공학석사 학위논문

Exploring the Front Touch Interface of Virtual Reality Head-Mounted Displays

가상 현실 디바이스의 정면 터치 인터페이스 연구

2016 년 08 월

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이 논문을 공학석사 학위논문으로 제출함

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이지현의 공학석사 학위논문을 인준함

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ABSTRACT

Virtual reality (VR) refers to three-dimensional realities implemented with stereo viewing goggles and reality gloves. The immersive experience that the VR technology provides entails a wide range of potential usages, and has attracted attentions from both the industrial and the academia for the last decades. Mobile VR headsets, VR head-mounted displays powered by smartphones, have recently been introduced, making VR more accessible and affordable than before. However, VR is not embraced by a broader scope of audience as much as the field expects. One of the reasons would be a lack of natural yet effective ways to interact with the VR world.

This study introduces a new HMD-embedded interface, with which users can interact with the virtual world via a touchpad placed in front of the VR headset, namely "front touch interface." This new interface has the potential to expand the design space of VR interactions, introducing new possible interaction methods. A prototype device was built on which a series of user studies were conducted to evaluate the fidelity of this new interface. Equations that map the coordinates of the 2D touchpad to that of the 3D virtual scene were made based on the data collected from a short pilot study.

In addition, preliminary interviews were conducted to find how intuitive the interaction of touching the front space of headset is. And in the next study, the design space of the VR interactions, which was expanded by the introduction of the front touch interface, was explored. Then, two selection tests were conducted to find out how effective the front touch interface is with (1) menu interface and (2) keyboard. During this process, two new selection techniques, Two-Fingers and Drag-n-Tap, were proposed to explore an appropriate input method for the front touch interface. Each technique was devised to provide different types of benefits in terms of usability: Two-Fingers to help users make quicker selections, and Drag-n-Tap to achieve more accurate selections. Lastly, a short case study on VR media player was conducted, and how the front touch interface can provide with other alternative solutions was discussed.

As a low-cost, light-weight, and low power-budget technology, a touch sensor makes a good medium for VR interaction. Also, the touch sensor could be embedded to the currently available VR headsets, requiring no extra devices. Such aspects of the front touch interface make it even more suitable for the mobile VR headsets, which attains highly portable and affordable characteristics.

In future, further tests on unexplored design spaces and interaction gestures such as swiping and pinching will be conducted. This work is envisaged to shed light on a range of unexplored design possibilities.

Keywords : Virtual Reality; Touch Interface; HMD-embedded Interface; Input Techniques; Selection Techniques; Text-input; Keyboard.

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1. Introduction

1.1 Background and Motivation

Since its introduction, the field of virtual reality (VR) has revolved around the head-mounted displays (HMD) (Lantz, 1996). The immersive experience of VR has entailed a wide range of potential usages, and has attracted both the industry and the academia (Stein, 2015). In particular, the development of mobile VR HMDs such as Samsung Gear VR, Zeiss VR One and Google's Cardboard well illustrates industry's efforts to make VR more accessible to the public. Mobile VR HMDs are VR headset devices that use smartphones as the power source of the VR display, and are good medium for various leisure activities. Examples include gaming, movie-watching (Oliver, 2015), photo-curating and reading (Ryan, 2001). Mass media applications such as Netflix, Hulu, and Twitch are continuously being introduced to mobile VR HMDs (Cox, 2015). Facebook's acquisition of Oculus even highlighted the excitation of the media that VR device might be the next big platform of social network (Panzarino, 2014). Such phenomenon denotes that VR is starting to infiltrate our daily lives.

With the introduction of mobile VR HMDs, VR technology starts to attain low-cost, light-weight and highly-portable characteristics. With VR being never as accessible and affordable as now, it is an ideal time to develop VR as the next communication interface and establish it as a new metamedium (Biocca and Levy, 1995). For VR headsets to support mass media applications for a wide range of people, easier interaction methods should be developed to serve generic tasks such as menu selection, file navigation and keyboard application.

<Figure 1> A concept art of the front touch interface for the head-mounted displays. Users use their proprioceptions to locate the VR objects with respect to their bodies using the touchpad placed around the face.

1.2 Research Goal

This study proposes the front touch interface: a new HMD-embedded VR interface where people use the touchpad placed in front of the headsets to interact with 3D virtual world. <Figure 1> illustrates a concept art of the front touch interface. In order to explore the fidelity of this new interface, a series of user studies were conducted using a prototype device. Then, what contributions the front touch interface can make is discussed based on the results.

First, a pre-study was performed to demonstrate how intuitive the front touch interface is. In the second study, how the front touch interface expands the design space of VR interactions was discussed new design spaces that were introduced by the front touch interface were explored. Next, two experiments on selection tasks were conducted using a menu interface and a keyboard application. For the front touch interface, two new selection techniques - Two-Fingers and Drag-n-Tap - were introduced, and tested in those experiments. Lastly, a VR media player application was developed for a case study, and its usage in various conditions was discussed.

Introduction of the front touch interface has several meanings in the field of VR interactions. This new interface has expanded the design space of VR interactions, and makes a type of interaction that was not possible with the precedent techniques. Also, with a wider touchpad that covers a user's face, richer interactions such as drag-and-drop, and pinching can be explored with the front touch interface. Furthermore, the front touch interface has some unique characteristics that make it especially suitable for the mobile VR headsets, and fit the current trend of VR industry. For instance, the touch sensor is embedded to the headset so that no external controllers are needed, supporting high mobility. Also, the haptic feedback of the touchpad interaction can help users manipulate the UI events more easily and precisely (Mine et al., 1997). The low-cost, light-weight and low power-budget characteristics of the touch sensing technology makes the front touch interface a practically viable and portable solution as well. Further details on what contributions the front touch interface can make will follow in the rest of this paper.

2. Related Work

There has been a plethora of research and commercially available products on virtual reality devices and interactions. However, an (in)ability to provide precise and intuitive input signal is still identified as an issue among the VR users (McGill et al., 2015). In this section, prior works on VR headset interactions experimented in academia and industry are reviewed to get a status-of-art of the VR field. More specifically, ways through which prior studies approached to solve selection tasks, especially with the menu interface, and text-entry, are addressed.

2.1 Interaction Methods and Devices

Bowman (Bowman and Hodges, 1999) characterized the four universal interaction tasks of virtual environment systems: selection, navigation, manipulation, and system control. Although a simple interaction method would be adequate to support selection task on static menu layouts, a more sophisticated interaction method is needed to leverage delicate motions such as drag-n-drop, pull-down, sliding and resizing. Such motions often help users to manipulate complex user interface with smaller and packed buttons (e.g. keyboard) and navigate through the hierarchy of the menus. Thus, a number of approaches has been made to come up with a method that can support a variety of techniques in virtual environment. This section mainly focuses on interaction methods proposed to support selection tasks.

2.1.1 Gestural Interaction

The most obvious selection technique in VR would be the gestural interaction where users use their body to interact with VR objects (Bowman and Hodges, 1995; 1997). Users would stretch their arms and use their hands to interact with virtual objects they see in front. The virtual objects then react in the manner that the real objects would have, as it is with the natural mapping. Gestural interaction provides a natural user interface in VR as they select objects using their proprioceptive senses (Mine et al., 1997). However, it is limited in a way that users need to physically navigate through the space to contact with distant objects (Bowman and Hodges, 1997).

To overcome this limit, ray-casting (Jacoby and Ellis 1992; Mine, 1995; Bowman and Hodges, 1997) can be used. It is another way of interacting with virtual objects where a ray extends from user’s hand to point at an item to select. Therefore, users are able to select distant items without having to move their positions in the virtual environment. Often it is accompanied with other VR devices such as gloves (Bowman and Wingrave, 2001) to allow more delicate inputs and enhance the user experience. Also, motion capture cameras such as Leap Motion, Microsoft Kinect and Valve Lighthouse are needed to tract the positions of users’ hands and possibly the whole bodies. The motion capture technology using camera or photosensors (mounted on the headset (Steinicke et al., 2009) or in a room-scale) has shown its potential; however, it still suffers from technical issue to serve high precision (Carbotte, 2015), and needs to more time to support better user experience.

2.1.2 Gaze-based Interaction

Extensive amount of research has been done on the usability of gaze-based interaction in head-mounted displays (Jacob and Karn, 2003; Karn et al., 1999; Gepner et al., 2007). It tracks the eyes or the head orientation (Mine, 2007) to calculate the pointing direction. A crosshair positioned at the fingertip or at the center of the gaze (Cournia, 2003; Mine, 2007) helps to indicate where the selection will be made. Selection command is made by dwelling the gaze on item (Cournia, 2003) or other standard input signals such as pressing a physical button (Mine, 2007; Mine, 1997).

Mobile VR headsets in the market tend to prefer the head-oriented selection technique over the traditional input methods since it provides more simple and intuitive interaction (Mine, 2007; Mine, 1997). Selection commands are made by tapping on the touchpad (Gear VR) or by pulling a magnet button (Google Cardboard) positioned at the side of the headset. The fundamental idea of the gaze-based interaction is that people would interact with items that they see. This might the gaze-based interaction intuitive, yet it can also be a limitation in a sense that users cannot interact in items outside their field of views.

2.1.3 Handheld and other Assisting Devices

Other interaction types include but not limited to gloves (Bowman and Wingrave, 2001), pen and tablet (Angus and Sowizral, 1995; Lindeman et al., 1999), 3D mouse, standard keyboard, and other handheld indirect props (Kim, 2005). 3D mouse especially is appropriate for more delicate VR works such as industrial product design due to its resemblance of the computer mouse (Bowman, 1996, Kim 2005; Mine, 1997). In (Bowman and Wingrave, 2001), interaction with menus using the gloves was compared with pen and tablet menus, and floating menus. Its performance was less impressive but opened a new design space for VR menu selection. Speech recognition (Darken, 1994; Ferneau and Humphries 1995; Jacoby and Ellis 1992) is also an available option; however, both handheld devices and speech recognition have rooms for improvement to be the mainstream of the

VR input methods (Bowman and Hodges, 1995).

2.1.4 Conflicting Results

Most VR interaction researches are based on comparing different interaction methods to demonstrate the feasibility of the method a study is proposing. However, some methods have shown conflicting results when the conditions of experiments change. For instance, Tanriverdi and Jacob (2000) conducted an experiment where they compared gaze-based and hand-based pointing method on selection tasks. Their results indicated the gaze-based pointing was significantly faster when it comes to selecting distant VR objects. (No difference was found with close objects). In 2003, Cournia, et al. extended this work by comparing the gaze-based and hand-based pointing with two distinctions. One was that ray-casting method was employed for hand-based selection, and another was that they distributed the targeting VR objects in a 360-degree truncated sphere instead of doing it on a flat plane. Under such condition, their preliminary results demonstrated contradicting finding: gaze-based pointing was found to be slower than hand-based pointing for distance objects.

Such conflicting results make it difficult for VR community to decide which method should be the most representative method. Furthermore, the absence of universal framework for VR experiments makes it even more difficult to compare two methods, or compare with itself to see whether it has made any technical progress. A model where VR selections tasks can be based on is needed to make the outputs from different VR interaction researches more thorough and comparable.

2.2 Design Spaces

Virtual world is an artificially create environment, and how the VR objects will behave is a critical design choice. In particular, how VR objects should be positioned often has been discussed since the inception of virtual reality. The most intuitive way would be placing the objects at their absolute positions – just like in the real world. Yet, researchers in the field of VR have suggested different design options to meet various needs.

2.2.1 Relative Positions

In 1993, Feiner et al. introduced the 2D windows into 3D environments. During this process, they identified three different types of windows by what the window is fixed to, namely surround-fixed, display-fixed, and world-fixed. Lindeman et al. (1999) later re-coined these names to world-fixed, view-fixed, and object-fixed. (Note: for the sake of consistency, the terms coined by Lindeman will be used in this paper):

(1) **World-fixed windows** have absolute position in the virtual environment. They work just like any objects in real world. That is, if users move their heads around, surround-fixed windows go out of, or come into, their views.

(2) **View-fixed windows** are fixed to those of users' viewpoints. That is, if users move their heads around, display-fixed windows will follow them, and be always within the viewing angles. Since view-fixed windows are always present in the field of views, they may be suitable for interface with controlling attributes such as system manipulation.

(3) **Object-fixed windows** are fixed to a specific object in virtual environments. So, if that object moves, relevant object-fixed windows will move along with it. Each type of windows has its own advantages and disadvantages, and thus it should be used appropriately for better VR user experience.

2.2.2 Design Choices Applied to Menu Interfaces

Menu items can be floating in the air (Jacoby and Ellis 1992), or positioned relative to the user's head (Bowman, 1996; Chung 1997), hand (Bowman and Wingrave, 2001) or whole body (Mine et al., 1997). Lindeman et al. (1999) coin them as world-fixed windows for menus at their absolute position in VR, and view-fixed window for menus that follow the head movement. Pros of having the menus relative to the body is that users can take advantage of their proprioceptive cues during the interaction (Bowman and Wingrave, 2001), and have menus always within sight. It is asserted that exploiting proprioceptive feedback helps users to perform better than just relying on visual feedback (Mine et al., 1997). This design option, however, cannot be used with head-oriented interaction which has a cursor fixed at the center of the window. Also, even though the view-fixed menus solve the issue of losing the items from sight, a new challenge can be met as the items start to block over VR objects (Mine, 2007). This can be solved by making the menus to pop up on need-base, but it would require users to do extra work such as pressing a physical button on the device or giving a special gesture to make the menu to appear.

2.3 Interface Designs

Just like the 2D space menus, various designs of virtual interfaces have been experimented. These ideas are then applied to make menus, and other application interfaces in the virtual world. There has been an attempt to apply the desktop metaphor on VR, but it is often asserted that VR needs its own metaphor for optimal design (Nielsen, 1993). In (Bowman and Hodges, 1994), for instance, proposed a design option of using widgets instead of WIMP in virtual environment.

2.3.1 Menu

A computer menu is a collection of items from which users can select to issue command, begin dialog sequences, change the mode of interaction, and so on (Jacoby and Ellis, 1992). Menu interface is an integral component of any computer-generated medium to enhance the system feasibility by providing a series of options to users. The layout of menu items largely depends on the purpose of using VR. For instance, the realistic quality would be the focus for training while the usability would be the priority for mass media applications where a series of rudimentary tasks would be conducted (Bowman and Wingrave, 2001). Various layout designs have been proposed to support high usability, which include drop-down (Bolter et al., 1995; Darken 1994; Jacoby and Ellis 1992) and circular layouts (Deering, 1995). In general, menu system takes advantage of its one degree-of-freedom operation (Bowman and Wingrave, 2001; Mine, 1997; Liang and Green, 1994) to enable simple interaction. 3d widgets have also been tried out to give affordance but suffer from lower precision as the menu items have volumetric shape (Mine, 2007).

2.3.2 Keyboard

Text entry, a courses of key inputs, is a natural extension of simple menu system, and is an integral component of any advanced applications. VR keyboard application has been tested with various means such as gestural interactions with gloves (Bowman et al., 2002), tablet + stylus combination, (González, 2009) and a standard keyboard in mixed reality (McGill et al., 2015). Gaze-controlled interaction was also found to be viable for the motor- or speech- impaired users (Ding et al., 2009; Bates and Istance, 2005). However, gestural interactions suffer from high power budget and cannot support delicate inputs yet. Also, interactions using external devices supports low portability, and restricts the distinguishing characteristic of the mobile VR headsets.

At the current stage, within the best knowledge, no interface with a touchpad in front of VR headsets has been proposed, let alone evaluated. The purpose of this study is to propose this new way of interacting with VR world, and evaluate its fidelity through a series of experiments.

3. Interaction Design Space

3.1 Expansion of the Design Space

As discussed in the Chapter 2 above, there are various design choices available to VR application makers in how they will position and manipulate the VR objects. These works have become the fundament for a VR interaction design space. This section explains how the front touch interface could expand the current design space, and how the new options may be applied to making VR applications.

Expanding on the concepts of **world-fixed** and **view-fixed** windows (Lindeman et al., 1999), a design space that layouts the relationships between the *selector* and the *selectee* are constructed (see <Table 1>). The term, *Selector,* refers to the items that are used to select objects in VR world. Examples include but not limited to virtual cursors, users' fingers in gestural interface, and the tip of stylus on tablet. *Selectee,* on the other hand, refers to the VR object that is being selected by a *selector*. Examples of *selectee* are menu buttons on system console, play button on a VR media player and so on. Conceptually, anything in the virtual environment can be *selectee*. So, designing a VR interaction is about how a user will use a *selector* to manipulate *selectee(s)* in virtual world. For instance, in gaze-based interaction, users use the virtual cursors (i.e. *selector*) fixed at the center of their gaze to pick VR objects (i.e. *selectee*) by moving their heads. It is important to point out that the view-fixed window cannot be supported for the gaze-based interaction since the virtual cursor is always fixed at the center of the sight.

Relative Position of *Selector*	**Relative Position of *Selectee*: World-Fixed**	**Relative Position of *Selectee*: View-Fixed**
World-Fixed	Both *selector* and *selectee* are at their absolute positions in virtual environment e.g. motion capture interaction	(Unexplored)
View-Local	*Selectee* is fixed to the World; s*elector* is fixed to the View, but movable on demand e.g. front-touch interaction (Front-World)	Both *selector* and *selectee* are fixed to the View, but *selector* is movable on demand e.g. front-touch interaction (Front-View)
View-Fixed	*Selectee* is fixed to the World; *selector* is fixed to the View with no flexibility e.g. gaze-based interaction	Impossible interaction dimension with both *selector* and *selectee* fixed to the View

<Table 1> Design space matrix based on the relative placements of *selector* and *selectee*. Note that, in gaze-based interaction, since *selector* is fixed at the center of the scene, *selectees* must stay fixed in world space to allow users to look at *selectees*. However, since users can move *selector* in front touch interaction (i.e. view-local), they can now make *selectees* to move with the view (head). This allowed the design space expansion.

By introducing the front touchpad, the design space of VR interactions could be expanded naturally, now that the cursor becomes movable relative to the view. Users can control the virtual cursor using their hands, and the cursor movement is no longer bound to that of the head orientation. In other words, they can work in an eye-off manner (Bowman and Wingrave, 2001; Mine et al., 1997). The middle row in <Table 1> demonstrates this expansion of design space with the introduction of the front touch interface. This new design option is named view-local because the virtual cursor is fixed to the center of a user's viewpoint as default, yet it can be freed from this constraint if the user uses his/her finger. Until now, users needed to bring external devices such as gamepad or handheld controllers to work in an eye-off manner in VR world. But since the front touch interface can be embedded to the headset, it has allowed expansion of the design space in low-cost and highly portable manner, making it especially suitable for mobile VR headsets.

3.2 Application Area

For the gaze-based interaction, the VR objects need to be positioned relative to the VR world and cannot be positioned relative to the users' views. However, with the introduction of the front touch interface, the virtual cursor is liberated from the head movement and users can work in an eye-off manner. With the front touch interface, view-fixed interface is now possible, which means menu interfaces can be designed to follow the users' views. Current VR applications such as Netflix and Gear Cinema provide view-fixed mode (i.e. void mode) where users can fixate the cinema interface to the current head orientation. This allows users to watch movies laying in any position they find comfortable. However, with just gaze-based interaction, users need to exit from the void mode to perform interactions such as controlling the play button or changing between movies. With the front touch interface, however, users can interact with the view-fixed cinema interface by moving the virtual cursor with fingers. In this sense, front touch interface has expanded ways in which VR applications may be developed, and as a result, users can now use their mobile VR devices at any comfortable postures.

4. User Study

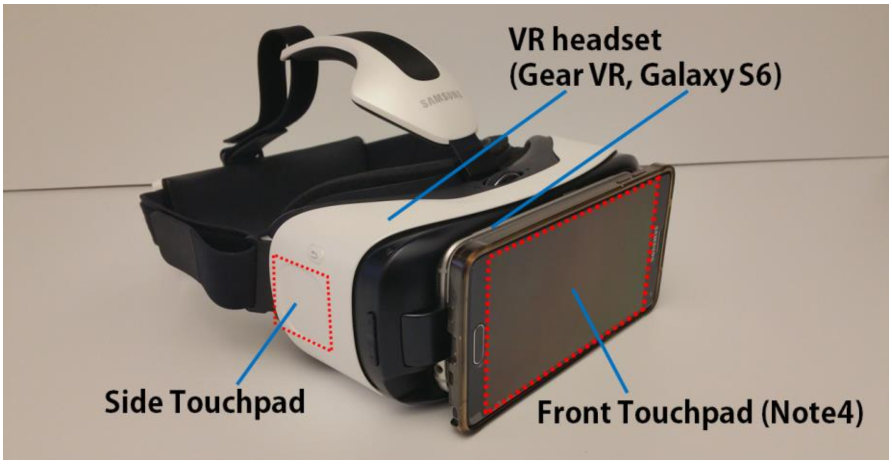
A series of user studies were conducted to evaluate the fidelity of the front touch interface in comparison to the gaze-based interaction. Gaze-based interaction was chosen because just like the front touch interface, it does not require external controllers, and the selection signal is made by touching on the headset. Also, many mobile VR headsets such as Samsung Gear VR and Google Cardboard use the gaze-based interaction, making it as an appropriate comparison target.

4.1 Implementation

For the user studies, a prototype version of the front touch interface was built using commercially available devices. Details on graph engine used to build VR applications is also explained.

4.1.1 Prototype Device

Samsung Gear VR for S6 and Samsung Galaxy S6 smartphone are used for the VR headset, and Samsung Galaxy Note 4 as the touch sensor (see <Figure 2>). Gear VR uses gaze-directed selection technique and a side touchpad to signal the selection as its built-in interface. As a prototype device, Galaxy Note 4 was physically tied behind Galaxy S6. The touch events from Note 4 were then transmitted to S6 via Bluetooth. Note 4 supports a resolution of 2560 by 1440 pixels, and thus the x- and y-point on the touch sensor ranged from [0,2559] and [0,1439] respectively. The touch sensor will send what kind of touch action (e.g. touch-down, scrolling, lift-up) was done and the touch point coordinates (x, y) to the VR system, so that corresponding changes can occur in the scene.



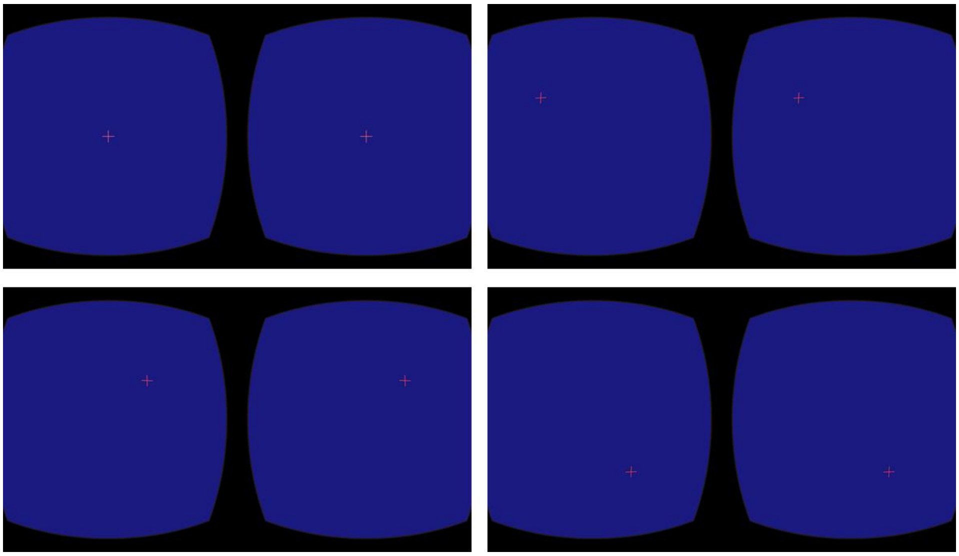
<Figure 2> **An apparatus setup for a prototype device used throughout the experiments.** A smartphone (Note 4) was physically tied at the front of the headset, and used as a touch sensor. Since a smartphone was used as a touch sensor, an extra weight penalty was given on the front touch interface during the experiments.

4.1.2 VR Scene Graph and Picking for UI Events

A scene graph engine was implemented using OpenGL ES 3.0, Android NDK (Native Development Kit), and Oculus SDK. Standard material shading model (Blinn-Phong) was used for rendering scene and geometry shapes in the virtual reality world. All necessary components in the interface such as buttons and cursors were generated procedurally. Furthermore, the STB library was used to generate text geometry.

To generate UI events, it is necessary to know which objects are intersecting with the ray starting from the scene camera and pointing the cursor, and which intersecting object is at the closest distance. This is commonly known as an object picking problem. Since VR renders two scenes for two eye positions that are generated from the scene camera, by displacing the camera location to the left and right, the scene camera location is equivalent to the center between the two eyes.

The rest of picking is straight forward. Computation starts from the root of scene graph clipping the ray by bounding box of each node. If UI elements are hierarchically organized into the scene graph, hierarchical bounding boxes are generated automatically. Since all nodes that belong to a bounding box will not be visited when the ray does not intersect with the bounding box, lots of computations can be saved. If the ray clipped by bounding box is not empty, full ray/triangle intersection test is performed. If the object, i.e., UI button, intersects with the ray, the button object is reported so that a UI event associated with that button can be generated.



<Figure 3> VR scenes given to the participants to collect data to make mapping equations. These are used to map 2D coordination system to that of 3D space. Each image shows the cross-shaped object that appear at different positions. Participants were asked to touch on the front touchpad if as they were touching the cross in VR world.

4.1.3 Matching Coordinates between Touch Sensor and VR Scene

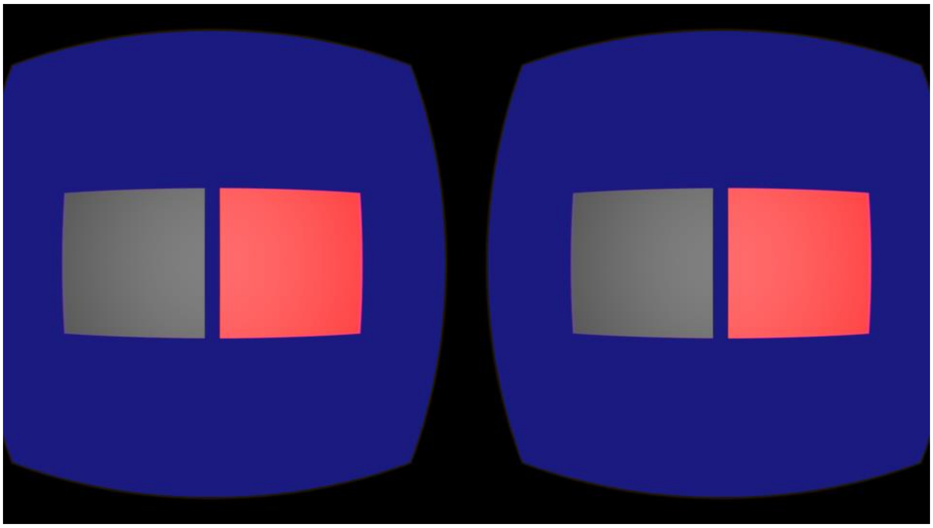
Equations that map the 2D coordination system of the touchpad to 3D space of VR are computed using the data from users. Ten participants were given a cross-shaped object positioned randomly on a 13-by-9 grid in VR scene, and were asked to touch on the front pad to select on it. <Figure 3> illustrates the scenes given to the participants. The grid was designed by varying the horizontal angle (i.e. θ_1) and the elevation angle (i.e. θ_2) from the viewpoint. Each participant was asked to perform 6 sessions, and thus s/he made $13 \times 9 \times 6 = 702$ selections in total. With this data, linear regression was performed to model the equations. The linear correlation coefficient for x and θ_1 was 0.998; that for y and θ_2 was 0.989. Also, the central point (the sample mean of the observed points) for each cross was measured, and the results demonstrate that the average distance between the central point and each observed point is approximately 184 pixels long.

From this brief analysis, it could be induced that people are reasonably good at interacting with the front touch using their proprioception without visual cues of their hands. However, since there is an offset of 184 pixels when trying to select the same target, well-designed selection control mechanism was needed.

4.2 Pre-Study: How Intuitive is the Front Touch Interface?

While using VR headsets, users sometimes click the front of the headset (i.e. click what they see) even though they know that the touchpad is on the side of the headset not on the front. So, a pilot user study was conducted to inquire users about what interaction techniques are most intuitive to click one of two rectangle objects in the VR scene. For this short pilot user study, 10 study participants were recruited.

All of them have never used VR headset before and do not have any prior knowledge or experience with the latest VR input technologies e.g. gaze-based interaction or the side-touch interaction on VR headsets. Study participants include 9 males and 1 female, and the age ranges are four participants in 20-30, four participants in 30-40, and two participants in 40-50.



<Figure 4> VR scene given to the participants in the pre-study.
Participants were asked how they would interact with the virtual world if they were to select the red square.

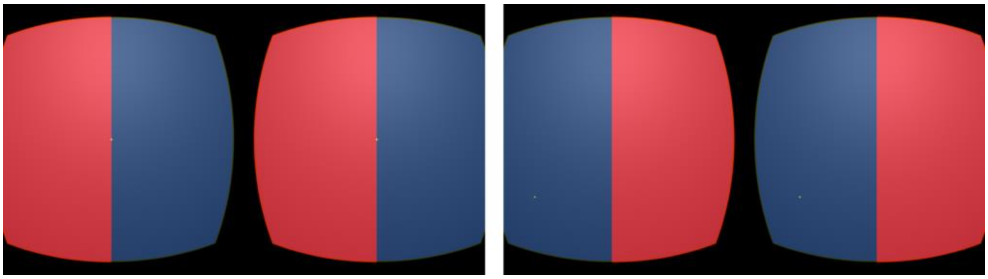
Participants were helped to wear the headset so that they do not see the side touchpad on VR headset. Participants were given a VR scene which consists of two square objects, one in red and the other in grey as in <Figure 4>. After checking with participants whether they can see those two square objects, a following open question “*How would you interact with the red square shaped object that you see in the virtual scene?*” was asked. Out of the ten participants, five participants answered front-touch on the headset, three said mid-air gesture, and two said side-touch on the headset. <Figure 5> illustrates some of the participants' gestures as they were answering this question.

<Figure 5> Participants doing intuitive test. All had no prior VR experience. To interact with VR objects as their first attempts, in the first two columns, people touched on the front of the headsets. The top right shows a case of mid-air, and the bottom right shows a case of touching the edge of the headset. Seven out of ten participants responded with the front touch to interact.

For three study participants who mentioned mid-air gesture, the second question was asked: *"What if the input technology is on the headset, where can be the most intuitive place?"*. Among the three, two participants said front of the device and one participant said side of the device. From this study, seven participants said it is intuitive to have the front input device while three participants said somewhere on the side of VR headset. This pilot study results show that people had a natural inclination to use their proprioceptions to touch what they see in front by placing their hands onto the front of the headsets. And the front of the headset is more intuitive place for study participants than the side of the headset for the input device on the VR headset.

4.3 Design Space Exploration

In this experiment, three design spaces with four different interaction methods were explored using the built-in side touchpad of the headset, and the newly proposed front touch interface. The bold text is the name of an interaction method, and text in a bracket is its corresponding design space as (*selector*, *selectee*).



<Figure 6> VR scenes given to the participants in design space exploration test. The left image shows the scene where the left plane is red; the right image where the right plane is red.

4.3.1 Study Design

The following four interaction design space were explored in this study:

(1) **Side-Gaze** (View-Fixed, World-Fixed) is a gaze-based interaction where people use their heads to move view-fixed cursor onto world-fixed VR objects. They tap on the side touchpad to signal the selection. This is also the default interaction method of Samsung Gear VR.

(2) **Front-Gaze** (View-Fixed, World-Fixed) is the same as Side-Gaze except that users tap on the front touchpad instead of the side touchpad.

(3) **Front-World** (View-Local, World-Fixed) is a selection method tested to find the feasibility of the front touch interaction. VR cursor is fixed to the view, but its position can be moved in the scene by using the front touchpad.

(4) **Front-View** (View-Local, View-Fixed) is another front touch method with *selectee* relatively positioned to the view.

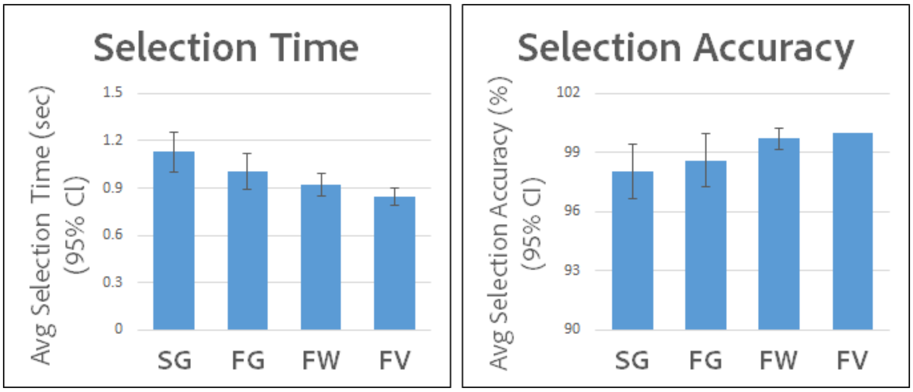
Experiment was conducted with a user interface that resembles a typical binary UI with two options (e.g. yes / no). Here, two equally-sized planes (left and right) divided by a center vertical line was given, where one plane was red and the other blue (See <Figure 6>). Each task begins with a participant selecting the red. Once s/he selects the red plane to begin the task, the selected plane becomes blue and the other becomes red for selection. Each experiment was composed of a series of 20 tasks, and 18 participants (13 males, ages ranging from 20's to 40's, all right-handed) were recruited.

Measurements were done on how quickly and accurately participants can select from one plane to another. In total, the collected data consists of 20 tasks × 4 methods × 18 participants = 1440 selections. Both the choice of the starting the red plane and the order of selection methods were randomized.

4.3.2 Performance Results

Participants were quickest and most accurate in the order of Front-View, Front-World, Front-Gaze and Side-Gaze. One-way repeated-measures ANOVA was used on both the average selection time ($F_{3,51} = 9.658$, $p < 0.00005$) and accuracy ($F_{3,51} = 260.764$, $p < 0.05$). As demonstrated with the low p-value, significant differences among the tested interaction methods were found. The values are shown in the graph in <Figure 7>.

Performance results reveal that users can make selections more quickly and accurately with view-local *selector* in a relatively simple user interface (binary selection test). It was especially high performing when the UI elements were fixed to the view as well (See <Figure 7>).



<Figure 7> Average selection time and accuracy of each method. Side-Gaze (SG), Front-Gaze (FG), Front-World (FW) and Front-View (FV). Front-View where the front touch interaction with View-fixed scenes was used outperformed in both selection time and accuracy.

To have a better understanding on the front touch with more complex user interfaces, in-depth experiments were conducted to compare Side-Gaze and two other refined front touch techniques.

4.4 Menu Selection Study

In this study, two selection techniques were introduced, especially devised for the front touch interface, and were evaluated via a user study to test their fidelity in comparison to a gaze-based VR interaction. Therefore, three different HMD-embedded input techniques were tested in total under a simple menu interface in VR. The tested techniques were named as Side-Touch, Two-Fingers, and Drag-n-Tap:

(1) **Side-Touch**: It is a gaze-based interaction where the virtual cursor is fixed

at the center of users' views, and they move their heads around to orient the cursor. To signal the selection, users tap on small touchpads placed at the side of the headsets. This is one of the widely used HMD-embedded interaction technique of mobile VR HMDs.

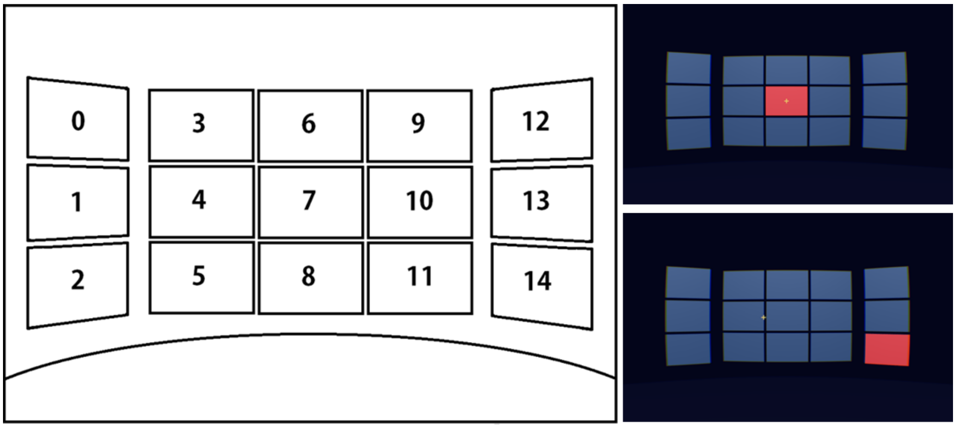
(2) **Two-Fingers**: This is a selection technique for the front touch interface, where users can move the virtual cursor with their fingers. In this technique, a pair of fingers work together on the front touchpad: one finger drags the VR cursor by moving across the front touchpad, and with this dragging finger still on the touchpad, the other finger makes a tap to initiate the selection.

(3) **Drag-n-Tap**: This is another selection technique developed for the front touch interface. Here, one finger does both the moving and tapping. Users will move the cursor by dragging it on the front touchpad and make quick taps on the pad to signal selections.

4.4.1 Study Design

A home screen interface of Gear VR application was replicated and used for the experiment. <Figure 8> shows the actual home screen of Gear VR, and <Figure 9> shows the layout of VR application used for the experiment. It consisted of fifteen equal-sized buttons: nine in the middle and three slightly tilted on each side. Each study task began by selecting the button in the middle (button no.7), and then one of the buttons except the middle button. Buttons turned red for selection, and green to indicate success. All tasks began from the middle button in order to make the total traveled distance consistent for all participants.

<Figure 8> The Oculus Home screen. This is the starting scene for accessing VR applications. The little blue that appears in the middle of the screen is the virtual cursor that is fixed to the center of gaze.



<Figure 9> The left image illustrates the user interface used for the experiment, and the number assigned to each button. The top-right and bottom-right images are sample snapshots; the top-right one shows a case where the button no.7 is the target, and the bottom-right a case where the button no.14 is the target.

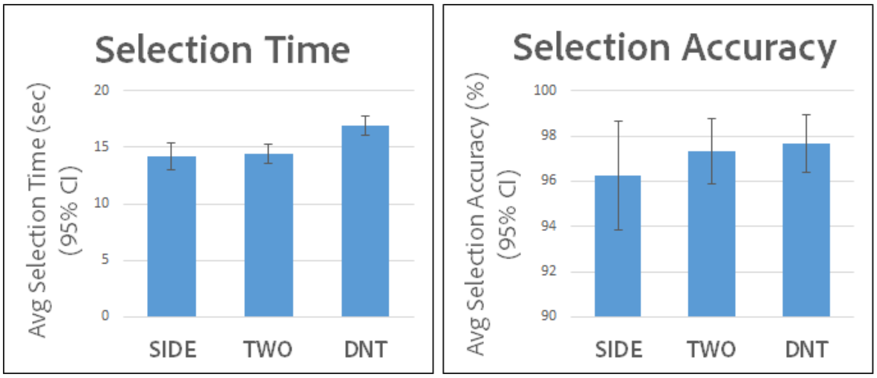
	Post-Questionnaires
1	How easy was it to learn the technique?
2	How easy was it to locate the touchpad?
3	How efficient was this technique at completing the given task?
4	How confident were you that the correct target button will be selected?
5	How tired did your arm become while using this technique?
6	How tired did your neck become while using this technique?
7	Did you experience nausea/dizziness while using this technique?
8	Overall, to what extent did you like this interaction technique?

<Table 2> Post-Questionnaire questions. The answers were in 7-point Likert scale, and this set of questions was asked on every tested method.

Each session consisted of a series of 14 tasks where users selected every button, except the middle button, in a random order. Each participant completed 3 sessions for every technique, with the order of the techniques randomized based on a Latin square design. A post-questionnaire (see <Table 2>) and short interview followed the experiment. A total of 20 participants (16 males, all right-handed, ages ranging from 20's to 40's) were recruited.

4.4.2 Performance Results

Again, one-way repeated-measures ANOVA was used to analyze the average selection time and accuracy, and a post-hoc analysis using the paired t-tests with p-values adjusted by Holm-Bonferroni correction (Holm, 1979). Average selection time and accuracy are shown in <Figure 10>. Users took 14.18, 14.42 and 16.87 seconds to finish tasks using Side-Touch, Two-Fingers and Drag-n-Tap respectively with significant difference ($F_{2,38}$ = 14.312, p < 0.00005). Pairwise t-tests revealed that Side-Touch (t_{19} = -4.510, p < 0.001) and Two-Fingers (t_{19} = -4.386, p < 0.001) were faster than Drag-n-Tap, but no significant difference between the first two (t_{19} = -0.489, p = 0.631). For accuracy, participants achieved 96.25% for Side-Touch, 97.32% for Two-Fingers, and 97.68% for Drag-n-Tap, but no statistical difference was found among the three ($F_{2,38}$ = 0.702, p = 0.502).



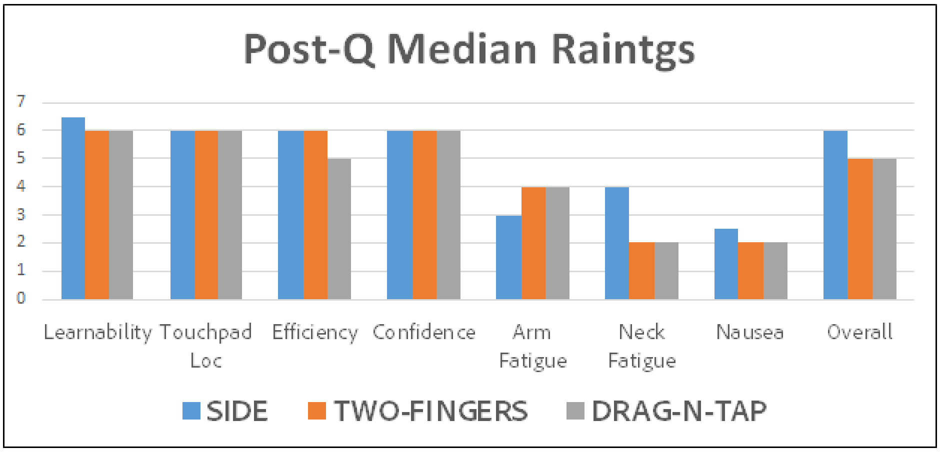
<Figure 10> Average selection time and accuracy of each method: Side-Touch (SIDE), Two-Fingers (TWO) and Drag-n-Tap (DNT). Side-Touch and Two-Fingers were faster than Drag-n-Tap while Two-Fingers and Drag-n-Tap were more accurate than Side-Touch.

4.4.3 Post-Questionnaire Results

To analyze Likert scale scores of the post-questionnaire, Friedman rank sum test, and Wilcoxon signed rank test with Holm-Bonferroni correction for a post-hoc analysis were used. <Figure 11> demonstrates the median scores of each question, and <Table 3> shows the details of statistical results. Significant differences in users' responses for learnability (F_2 = 10.364, p < 0.01), neck fatigue (F_2 = 13.636, p < 0.005) and nausea (F_2 = 18.2, p < 0.0005) were found.

	Question	Median			F-value	p-value	Z-value (p-value)		
		Side-Touch	Two-Fingers	Drag-n-Tap			Side vs. Two	Side vs. DNT	Two vs. DNT
1	Learnability	6.5	6	6	10.364	< 0.01	2.840 (< 0.05)	2.111 (0.0670)	-1.265 (0.206)
2	Touchpad Location	6	6	6	1.037	0.5954	-0.575 (0.573)	-1.065 (0.573)	-1.414 (0.472)
3	Efficiency	6	6	5	5.1212	0.7726	1.752 (0.161)	1.929 (0.161)	0.838 (0.402)
4	Confidence	6	6	6	0.38298	0.8257	-0.660 (1.000)	-0.480 (1.000)	0.000 (1.000)
5	Arm Fatigue	3	4	4	4.4286	0.1092	-1.745 (0.162)	-2.070 (0.115)	0.378 (0.705)
6	Neck Fatigue	4	2	2	13.636	< 0.005	2.777 (< 0.05)	2.777 (< 0.05)	0.000 (1.000)
7	Nausea	2.5	2	2	18.2	< 0.0005	2.699 (< 0.05)	2.858 (< 0.05)	1.000 (0.317)
8	Overall Rating	6	5	5	0.78873	0.6741	1.256 (0.628)	0.670 (1.000)	-0.645 (1.000)

<Table 3> Statistical results of post-questionnaire for menu selection user study. Questions were asked on 7-poin Likert scale. Friedman rank sum test, and Wilcoxon signed rank test with Holm-Bonferroni correction were used. Friedman test showed significant differences in three categories: Learnability, Neck Fatigue and Nausea.



<Figure 11> Medians of the post-questionnaire results for each interaction method. Friedman test revealed significant differences in Learnability, Neck Fatigue and Nausea.

4.4.4 Learnability and Metaphors

Side-Touch was reported to be easier to learn than Two-Fingers (Z=2.840, $p < 0.05$), but Drag-n-Tap showed no significant difference with the other two. This result corresponds with the interview feedback that Side-Touch was more straightforward to use than Two-Fingers (P2, P11, P12, P16). Two-Fingers seems to be more difficult to learn as the two fingers serve different roles and users need to work them simultaneously (P16, P18). However, its resemblance to the motions of a mouse (P3, P13) or the trackpad on the laptop (P11) help them learn more quickly. Thus once they get accustomed to the technique, Two-Fingers could be quicker than Side-Touch (P13). In a similar fashion, Drag-n-Tap also reminded them of a trackpad on a laptop (P13) or a mouse (P17, P18, P19, P20), and this metaphor allowed the gesture be more intuitive to use.

4.4.5 Neck Fatigue and Nausea

Neck fatigue was raised as an issue with Side-Touch relative to Two-Fingers

(Z = 2.777, $p < 0.05$) and Drag-n-Tap (Z = 2.777, $p < 0.05$). Some experienced tension on their necks as they try to fixate them to target a small area (P2, P14). Also, when selecting the buttons on the 3x1 layout, some found it uncomfortable having to pan heads to reach for buttons far away from the center (P1, P18). This might have caused some nausea, another issue raised with Side-Touch. As shown in the post-hoc analysis, people experienced more nausea with Side-Touch than Two-Fingers (Z = 2.699, $p < 0.05$) and Drag-n-Tap (Z = 2.848, $p < 0.05$).

4.4.6 Control over the Cursor

By leaving their fingers in contact with the front touchpad throughout the interaction, users could see how the finger and the cursor are mapped with each other for Two-Fingers. This seemed to give users more confidence in making selections (P15, P16) as they could have a full control over the cursor until the final tapping is signaled. Stabilizing their necks seemed to be more difficult to achieve pinpoint precision than their fingers, and thus Side-Touch seems less suitable for delicate tasks (P2, P5, P13, P16, P25).

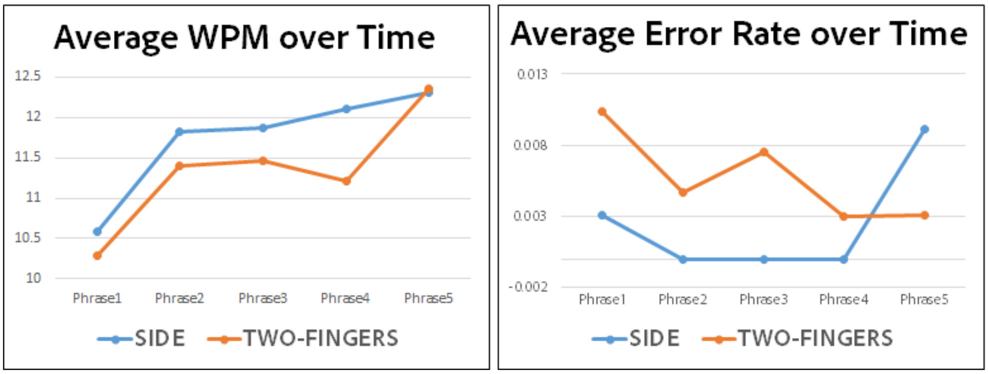
4.5 Text Input Study

In this study, fidelity of Side and Two-Fingers methods were further tested. Participants were now given VR keyboards and a set of text phrases, and were asked to type the phrase as quickly and accurately as possible. Two-Fingers was tested instead of Drag-n-Tap because Two-Fingers performed better than Drag-n-Tap in the previous menu selection test. Also, the hand gesture of Two-Fingers resembled that of the SWIFT keyboard, which demonstrates a great potential as a means of VR keyboard application.

<Figure 12> A snapshot of the VR keyboard used for the experiment. It illustrates a case where *"this is a very good idea"* is the presented phrase (i.e. text in green) and *"thi"* is the current state of the transcription (i.e. text in orange).

4.5.1 Study Design

<Figure 12> shows a prototype VR keyboard interface that was implemented for the text-input user study. It was in a QWERTY format, and a short clicking sound was provided to help users to know whether a letter was selected or not. For each test section, five phrases (each phrase 25 to 28 characters long) were chosen randomly from MacKenzie and Soukoreff corpus (MacKenzie and Soukoreff, 2003) and had a participant to transcribe a given sentence as quickly and accurately as possible. For a short practice session, each participant got to write two phrases, which were the same for all participants. A total of 25 people participated in the study. 19 of them were males, everyone aged from 20's to 40's, and all right-handed. According to their self-assessment, their English skills were all higher than 4 in a Likert scale of 7, where 7 being equivalent to a Native level.



<Figure 13> Average WPM and error rate measure over time for Side and Two-Fingers techniques. For both WPM and error rate, Two-Fingers performed better at the fifth phrase (i.e. the last phrase), hinting a sign of improvement of Two-Fingers as the time progresses.

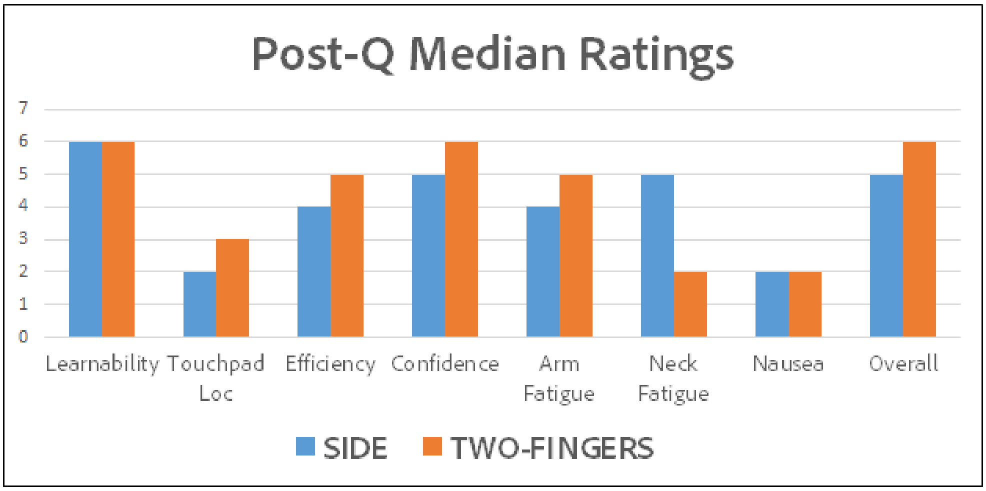
4.5.2 Performance Result

For each transcribed phrase, the text-entry rate in terms of words per minute (WPM) (MacKenzie and Zhang, 1999; MacKenzie, 2002), and error rates based on Minimum String Distance (Soukoreff and MacKenzie, 2004) were calculated. Paired t-test was used to verify any significant performance differences between Side-Touch and Two-Fingers. The average WPM of Side (11.738 WPM) was slightly higher than that of Two-Fingers (11.346 WPM), but with no significant difference (t_{24} = 1.246, p = 0.225). The average error rate of Side (*0.24%*) was lower than that of Two-Fingers (*0.57%*), but again with no significant difference (t_{24} = -1.913, p = 0.068).

Looking at the users' performance over time in <Figure 13>, these results suggest potential benefits in using Two-Fingers in a longer term. There was an increase in speed for both types of interaction method, and Two-Fingers outperformed Side at the fifth phrase. Similarly, the error rate of Side is bigger than

	Question	Median		Z-value	p-value
		Side-Touch	Two-Fingers		
1	Learnability	6	6	0.83205	0.4054
2	Touchpad Location	2	3	-1.5741	0.1155
3	Efficiency	4	5	-2.0126	< 0.05
4	Confidence	5	6	-1.4576	0.1449
5	Arm Fatigue	4	5	-2.3396	< 0.05
6	Neck Fatigue	5	2	3.6419	< 0.0005
7	Nausea	2	2	2.9575	< 0.005
8	Overall Rating	5	6	-2.5406	0.05

<Table 4> Statistical results of post-questionnaire for text-input user study. Wilcoxon signed rank test was used. Scores showed significant difference in five categories: Efficiency, Arm Fatigue, Neck Fatigue, Nausea and Overall Rating.



<Figure 14> Medians of the post-questionnaire results for Side and Two-Fingers. Wilcoxon signed rank test revealed significant differences in Efficiency, Arm Fatigue, Neck Fatigue, Nausea and Overall Rating.

Two-Fingers on the fifth. The initial underperformance of Two-Fingers could have been due to its lower learnability relative to Side (P5) and/or the performance of Side could have become worse over time as the neck fatigue and nausea accumulate. To confirm this hypothesis, it is necessary to conduct stress tests and observe how the Side-Touch and Two-Fingers perform with longer sentences in a longer term.

4.5.3 Post-Questionnaire Result

Wilcoxon signed rank test was used to compare users' feedbacks on each post-questionnaire question. Five out of the eight features were found to be significantly different: Efficiency, Arm Fatigue, Neck Fatigue, Nausea and Overall Rating. Participants found Two-Fingers to be more efficient ($Z = -2.013$, $p < 0.05$), to cause less neck fatigue ($Z = 3.642$, $p < 0.0005$), and cause less nausea ($Z = 2.958$, $p < 0.005$). However, it also seemed to cause more arm fatigue ($Z = -2.340$, $p < 0.05$). The significant difference in overall rating statistically verified that users preferred Two-Fingers over Side ($Z = -2.541$, $p < 0.05$).

4.5.4 Efficiency of the Techniques to Text-entry

From the Likert scale analysis, it can be suggested that users found Side technique to be less efficient than Two-Fingers at text-input task ($Z = -2.013$, $p < 0.05$). Five participants answered that Side is inappropriate for the text-input task because moving head that much for a rudimentary task like text-input is tiresome, tedious and almost silly. Although moving head is generally faster, fingers catch up quickly as you get used to the technique (P23). Regarding the speed of interaction, people found moving head to be faster than moving their fingers across the touchpad to select a key on one end after selecting a key at the other end of keyboard (P11). This could be improved by accounting the velocity of finger movement to move the VR cursor, instead of simple linear mapping. Further discussion is done later in the paper.

4.5.5 Fatigue and Nausea: Head vs. Hand

As in the previous study, neck fatigue was a significant issue for Side ($Z = 3.642$, $p < 0.0005$). But with the keyboard, people also experienced arm fatigue for Two-Fingers ($Z = -2.340$, $p < 0.05$) in comparison to Side-Touch. Fifteen participants commented that they experienced arm/neck fatigue in their interviews. Users' preferences seemed to have been affected by this fatigue experience. For instance, five participants answered that they liked Two-Fingers because they regarded neck fatigue as a more severe issue while three liked Side better because they experienced arm fatigue with Two-Fingers. While users did not comment on getting neck fatigue for Two-Fingers, four users complaint on getting arm fatigue for Side as well since they have to hold their arms up anyway.

Also, since the head is in the course of constant movement, arm needs to stay aligned to the side touchpad not to lose its location, and this led to ergonomic annoyance. Three users additionally commented that their fingers were tired because their fingers were tense the way Two-Fingers make them to hold their fingers was unusual to them. (P4, P16, P20). In particular, P25 remarked: *"In choosing between these two techniques, there is a trade-off being made on arm and neck fatigue."* As the task gets more complex and courses of movements longer, the tolerance on moving hand/head becomes the major criteria on the preference between side and front. In general, users preferred Side or had no preference for writing short sentences while preferred Two-Fingers for long sentences.

4.5.6 Precision

Seven participants remarked that they were more prone to error with Side because they had to make a tap in a course of head movements. But if moving head and tapping did not synchronize well, they ended up selecting wrong keys: *"when you are in the middle of writing sentences, the momentum (of head movement) builds up. And if the timing is not right, you tap on the side too quickly or too slowly and make a typo."* (P24)

Some participants replied it is harder to achieve high precision with Side than Two-Fingers with small and packed buttons. It was because it was harder to travel a small distance and make a pinpoint precision with a neck than with a hand. When they tried to make a pinpoint precision with Side, they often experienced muscle tension on their necks. Also, they were more prone to losing the location of the side touchpad while using the keyboard as the head movements become more intense. However, two users still remarked that gazing was a better means to achieve high precision (P12, P17).

Two-Fingers, on the other hand, uses dexterity to control the cursor movement with ease and achieve higher precision (P6, P11, P23, P24, P25). Side may be faster, but when working with small buttons, clicking with higher precision becomes a priority than speed (P13). Also, with Two-Fingers, they could hold their fingers down on the touchpad to have a full control over the cursor throughout the interaction. However, four participants commented that Two-Fingers also leads to error by accidentally tapping twice during the interaction (P14, P15, P16, P21).

4.5.7 Limited Range of View

Some users preferred the front touch because they could have an overall view of both the keyboard and the sentence they were transcribing. With Side, however, the view became restricted as they move their heads to target at a specific key on the keyboard. This inability to get an overall view of the keyboard and the sentences they are writing seemed to be a concern especially for longer sentences.

4.5.8 Drag-n-Tap

Although not indicated in the post-questionnaire, participants who also participated in the previous selection test were asked how they would have liked Drag-n-Tap technique on a keyboard application. Many of them showed positive responses since the gesture is more straightforward (P4, P21, P22), less prone to the off-screen issue (P1, P13), and perceived to support higher precision (P25). But they also remarked that Drag-n-Tap will be less efficient in terms of performance than the other two techniques.

4.5.9 Like Neither

In general, Two-Fingers was more preferred over Side with a statistical difference. However, two participants responded that they had no strong preference over either of them and that neither of them looked suitable for text-entry for VR (P18, P19). For VR text-entry, they said that they would rather use the voice recognition or a standard keyboard connected to the device if they can. They envisioned an interaction that can support as high fidelity as the standard keyboard or that on the phone to be developed for VR in future. But there was also a positive feedback that the front touch clearly has a room to be explored for further optimization, and that it can be improved to give more pleasing experience (P3).

5. Case Study

One of the most distinguishing advantages of mobile VR headsets is that they are highly portable. This allows the VR users to bring the headsets around, and have VR experience at where they want. The goal of this case study is to explore how the front touch interface could leverage this aspect of mobile VR headsets. The problems with the current system is discussed and how the front touch interface may solve them is suggested with a media player as an example.

5.1 Motivation

As mentioned above, due to their highly portable design, people can bring mobile VR headsets to enjoy VR experience at anywhere. For instance, people might be watching a movie in their bed or playing a mini-game in a car with mobile VR headsets. In fact, an Australian airline Qantas Airways provided a pilot program where they handed out the Samsung Gear VR to their first-class passengers for in-flight entertainment (Simpson, 2015).

As shown, the mobile VR headsets are used in various situations, and this needs to be considered while designing interaction methods. In case of the gaze-based interaction, however, the VR objects always need to be fixed to the world position. This can cause some deterioration in VR user experience. For instance, it becomes difficult to interact with VR objects if users are in moving vehicles (e.g. in cars or on planes). This is because the world-fixed VR objects would come and move out of the viewpoints if the vehicles make dramatic turns. Also, users had troubles interacting in VR world when their heads are not free to move (e.g.

reclined in seats or lying in bed). However, with the front touch interface, users can now interact with the view-fixed windows at any comfortable posture, using their fingers instead of moving their heads. They can now manipulate the menus to select a film to have personal theatre in their beds. With the interaction liberated from the head orientation, VR application makers can provide a wider range of VR applications for various situations.

<Figure 15> Screenshots of Netflix application available on Samsung Gear VR. The top-left image is the starting screen of the app. the top-right image is the scene users see when they lay on their back, and they select the circle to enter the void mode. The bottom-left image shows the void mode, where only the movie screen is floating in the black background, and three options are available: “Back to Living Room”, “Turn on Travel Mode” and “Resize Screen.” The bottom-right image shows a film being played in the void mode, and the play/stop button and slide bar to control the play.

Also, the current design of side-touch technique does not provide sliding interaction, which is one of the most frequently used interaction methods in media playing application. (Note: it only supports swiping, which is a much shorter action compared to the sliding action.). Next section discusses how VR Netflix, one of the most prevailing media player available on Gear VR, has tried to handle these problems.

5.2 How Currently Available VR Products Are Doing

One of the most common use cases in VR platform is movie watching, and this is especially true for the mobile VR headsets due to its high portability and simple user interface. Some popular media streaming services such as Netflix and Hulu entered the VR industry. This often occurs while the users are lying on their backs, or in vehicles that are turning. Netflix, for instance, supports three modes – living room mode, void mode and travel mode - to meet users' needs at various conditions:

(1) **Living room mode** is the default mode of VR Netflix. It has a scene of a living room in a cottage, and the screen is fixed at the center of the view. The top-right image in <Figure 15> shows a scene of this living room mode. Since this screen is world-fixed, it moves out of the view, if users look away from it.

(2) **Void mode** is useful for the users who are reclined in seats or lying on their backs, since the screen is positioned in the ceiling, and it lets users to get reoriented on command. If users look up the scene, they see the left-top image in <Figure 15>, and they select on the circle to enter the void mode. The bottom-right image in <Figure 15> shows the void mode, which offers three options: one to go back to the living room, one to enter travel mode and another to resize the screen.

(3) **Travel mode**, which becomes available once users enter the void mode, is

useful for those who are watching movies in cars or on planes. VR objects are all earth-positioned, meaning if vehicles make turns, world-fixed objects will stay at their absolute positions, and move away from the field of view. In order to accommodate with this unintentional turn, the screen get repositioned to the front of users' view whenever users look away from the screen.

However, none of them is view-fixed because Netflix, and other similar services are aware that it is impossible to make interact with view-fixed screen with the gaze-based interaction and side-touch technique.

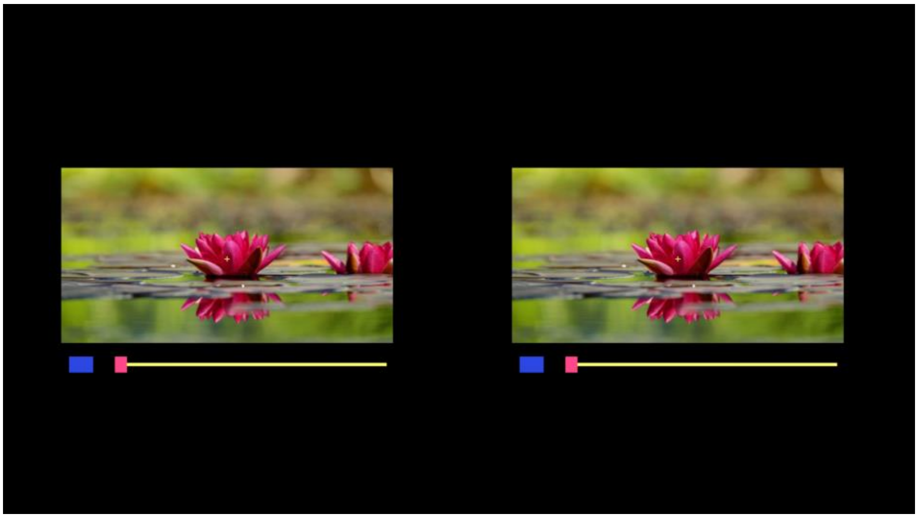
Moreover, Netflix makes users to point at the certain position on the slide bar and tap on the side touchpad to change to another timeframe. Brief swiping gesture is only used to move by a frame unit. No long sliding gesture is offered with the side touchpad. This may be a big downside of the current design, especially for people who are familiar to the sliding technique supported by mobile phones.

With the gaze-based interaction, these problems are inevitable because all objects need to be world-fixed. Also, the small touch pad on Gear VR is designed to support simple gestures only such as tapping and swiping. Next section tries to explain how the front touch interface may provide new ways to approach these problems in detail.

5.3 Designing VR Media Player for the Front Touch

In order to demonstrate how the front touch interface may solve the problems discussed above, a media player for VR platform was developed as a prototype application (see <Figure 16>). It was built using the same graph engine as the applications used in Chapter 4 user studies.

As shown in <Figure 16>, a screen is displayed at the center of the scene, and buttons that can control the playing behavior are set up below the screen. The blue button at the left is the playing button. The movie is stopped initially. Selecting it starts the movie and re-selecting the blue button pauses it. The red button is the slider button and the yellow bar behind it is the sliding bar. Changing the position of the red button on the yellow bar changes the timeframe of the film being played. This layout is a copy of the void mode of VR Netflix application. But it still needs to display the current timeframe and the total time length of the video.



<Figure 16> A screenshot of a prototype application that plays a video on the VR platform. The blue button is the player button; users can start and stop the video by selecting it. The red button is the slider button and the yellow bar is the sliding bar to move to a different point in video.

Although the basic framework is built, there are several design aspects that need to be considered. There are two main design options that may have critical influence on user experience. In particular, these two features are new features that are not present in the mobile VR headset that uses gaze-based interaction. Therefore, they will be designed based on the user feedbacks received from the previous studies.

5.3.1 View-fixed vs. World-fixed Windows

Gaze-based interaction did not have a choice, but to go with the world-fixed screens. However, now that the front touch offers a choice of the view-fixed windows, it is necessary to consider which window type would fix for the screen design. It is presumed that in cases where users are wearing VR headsets in moving vehicles, keeping the screen fixed to the front will be a better option. Should we keep the world-fixed windows or change to the view-fixed? Does the view-fixed window have clear benefits over the world-fixed in moving vehicles as expected? What are some side-effects resulted from using the view-fixed windows? These are all questions that need to be addressed via a user study.

5.3.2 Sliding Gesture

Technically speaking, Gear VR Edition 2 does not support “sliding” gesture. Only brief “swiping” gesture is offered to scroll between different items such as scrolling the available VR applications in home screen and selecting a film to watch. Therefore, VR Netflix users change the timeframe of a movie by selecting a specific point on a slide bar, or doing a brief swiping motion to change by a frame unit. But now that the front touch interface offers a wider touchpad covering the face, sliding gesture can be performed on it, just like how it is done on smartphones. Front touch interface will support a long sliding gesture, and it is presumed that this will enhance user experience. Also, another advantage of the front touch is that the direction of “sliding” is the same as the direction the slide button will move. In case of the side touchpad, users swipe towards their face to do playback, and away from their face to fast forward the film. Directions are perpendicular, and this could confuse users. Although this might be a minor point, it is definitely an improvement that could be achieved with the introduction of the front touch.

5.4 Future Work

For future work, fidelity of the front touch interface on VR media player will be investigated in comparison to the gaze-based interaction. Using the prototype application, two additional user studies will be conducted: one where the users are using the VR player in a vehicle, and another where they are doing it in reclined position as in bed. These two are typical situations that VR users frequently encounter when they are watching films wearing the VR headsets. Experiment will ask participants to perform tasks that VR users do while watching a film, such as selecting a specific film, starting/stopping the video, and changing the timeframe. Both speed and accuracy will be measured for performance measures, and interviews will follow to collect concrete user feedbacks. If the new features offered by the front touch help users to perform these tasks more easily, especially in unusual situations, this would definitely be an option to consider while designing VR media players.

6. Discussion

6.1 Which is more Efficient?

Quantitatively speaking, Side technique and Two-Fingers seemed to have no statistical difference in their speed and precision results from both menu and keyboard studies. From the interviews, it was found that users perceived they were moving faster with Side than Two-Fingers, but more difficult to control the cursor with high precision. It was because fixating to a small target area or moving a small amount of distance becomes more tedious with head than hand.

Even though it takes a little more time to learn for the front touch methods than Side, there is a higher chance of Two-Fingers outperforming Side once users become accustomed to (P9 from Study 1). Also, since fingers are more trained at performing delicate tasks than necks, this makes the front touch interactions more suitable for user interfaces with higher complexity like the keyboard in a long term. Performance-over-time results from the text-input experiment where Two-Fingers outperforms Side at the fifth phrase could be used to support this hypothesis. Further study should be conducted to find out the long-term performances of different techniques.

6.2 Preferences depending on the Tasks

There is a general tendency to like the front touch interactions for complex tasks while gazing for simpler user interface. We examined the reasons behind these tendencies in a more specific manner, and summarized several factors that influenced the users' preference over different selection techniques. These factors are not independent of each other but rather influence one another. For instance, if the task becomes sequential, it is more likely to get tired, and the tolerance level for arm and neck might differ for short and long tasks.

6.2.1 Complexity of the User Interface

Things like how small and spread out the buttons like in their field of view largely influenced their choices. In general, people liked to use their hands more than heads as the buttons get smaller, and more spread. It is because users found it easier to make pinpoint accuracy with hands than head. Also, they would have to pan their heads in a wider angle if the buttons are more spread out, which can be offloaded if they can use their hand along with the head to reach for items outside of their field of view.

6.2.2 Intensity and Length of Task

For consecutive tasks like text-input, front touch interaction was preferred over Side users because it is easier to control the cursor with hand than with head. For Side, they were more prone to making errors by selecting keys too quickly or too slowly in the course of head movement. Also, some even felt that it was tedious and almost silly to move head that much in VR.

6.2.3 Learnability of the techniques

Although it was not indicated in any of the Likert scale results, we observed users tend to take more time getting accustomed to Two-Fingers and Drag-n-Tap than Side. Unlike Side where they had to look at their target and tap, users took some time experimenting with the fingers postures for the front touch techniques. Some quickly learned the posture of due to its resemblance of that of using a mouse, but some suffered at the beginning being accustomed to separating the roles of each finger and control the cursor. Drag-n-Tap, in this sense, was found to be more intuitive than Two-Fingers. A natural inclination to touch what you see (as shown from the Pre-Study 1 results) also helped users be accustomed to the new front touch interaction techniques.

6.2.4 Engaging

We received a number of commentaries from users that they found the gazing interaction to be entertaining and fun to use. Gazing and tapping movements seem to remind them of a game, and made them to be more engaged in the interaction. This unique feature of Side can make it an appropriate interaction for VR application games such as First-Person shooting game where the goal is aiming at the target (gazing) and make a shot (tapping).

6.2.5 Fatigue and Nausea

As the complexity of user interface increases and tasks become longer, neck and arm fatigue issues start to play bigger roles. The ergonomic position of the arm locked to the side of torso for Side technique helped users feel less arm fatigue than the floating gesture of front. However, the courses of head movements for consecutive tasks and the tense they experience on their muscles to achieve high precision on smaller targets was more severe on the neck. So, there is a trade-off made between neck and arm fatigue in choosing between the techniques. The preference depends on the level of tolerance on arm and neck fatigue, which differs from person to person. Those who were more concerned about getting the neck tired would go for the front, while those more concerned about the arm for the side. But, Side is not completely free from arm fatigue issue either because users have to hold their arms up to touch the side pad anyhow.

Although we could summarize general tendencies based on the study results, these factors can vary at individual levels, and are difficult to measure them with absolute precisions. Thus, it would be ideal to give a hybrid of these techniques, compensating for each other's limitations instead of one replacing another. Just as in the work of Bowman and Hodges (1997), hybridized techniques would give distinct advantages in terms of use and efficiency. Fortunately, these techniques can be supported together as one embedded interaction for a VR headset without having a technical clash. With multiple interaction options available, they can choose the right one depending on their use cases.

6.3 Design Tips for the Front Touch Interface

6.3.1 Physicality of the Front Touchpad

Various textures of the screen need to be explored to overcome the finger-screen friction that builds up from moving across the touchpad for a long time. This especially could be an issue for Two-Fingers where one finger is in a constant contact with the surface of the pad. Furthermore, the prototype touch sensor device (i.e. Note 4) was flat, but it will be worthwhile to experiment how the front interaction can be improved with the curved touchpad that covers the temples as demonstrated in <Figure 1>. It can be hypothesized that such design would prevent users from experiencing off-screen issues (touching outside of the front touchpad during the interaction).

6.3.2 Coordinate Mapping between Touchpad and VR world

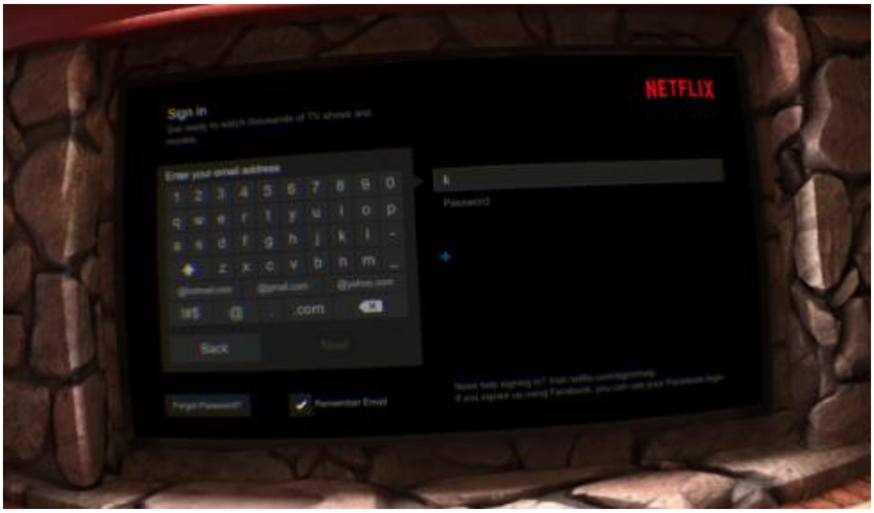
For the experiments, the coordinates of front touchpad and that of virtual environment scene was linearly mapped. So, a consistent amount of distance was traveled in VR for every unit of finger movement on the touch surface. This design choice can be further experimented with by applying the velocity of the finger movement to the VR. The faster the finger moves, the longer the distance the VR cursor travels. This feature should be designed carefully because there could be a trade-off made between the speed and accuracy. If users can make the cursor to travel a longer distance with a shorter finger movement, they could have more difficulty in achieving pinpoint precision.

Furthermore, the touchpad position could be mapped onto VR world in two different ways: (1) absolute and (2) relative. In absolute mapping, the touchpad position is directly scaled to the VR world, while in relative mapping, the touchpad motion is added to the current VR world location. From a short pilot study, relative mapping seemed to cause off-screen issues more frequently than absolute mapping. This was especially the case for Two-Fingers because the initial touch position is mapped to the center of VR world, and if users make initial touch off from the center of the touchpad, they were more likely to encounter this issue. But, with a wider touch surface as in <Figure 1>, the off-screen issue may be negligible. In case of absolute mapping, there is a jumping-cursor issue: some users reported confusion when the cursor suddenly jumped to the new touch position.

Based on this insight, absolute mapping was used for Two-Fingers and relative for Drag-n-Tap. But a better solution needs to be proposed to handle this mapping issue e.g. a tentative solution is an implementation of the hybrid version of absolute and relative where the offset error is corrected by a fixed fraction for each touch event.

6.3.3 Size of Buttons for Front Touch

Users replied that they could have more control over the cursor with hand than head and move it to a precise location more flexibly. In this sense, it will be worthwhile to explore whether the front touch interface can afford smaller sized



<Figure 17> VR Netflix application released on 24 Sep 2015. It consists of a keyboard interface for login and movie searching. Such mobile VR application will be used ubiquitously often without additional peripheral devices nearby.

buttons than the side technique. If the front touch allows users to perform selections on small items without much trouble, then it will be possible to design interfaces with smaller UI buttons and keys. For instance, users might benefit from using the front touch interaction than the gaze-based interaction when it comes to interacting with more delicate interface such as keyboards where a group of small keys are clustered in a certain layout (see <Figure 17>). These suggestions, however, will need to be empirically proven to find out the exact threshold value on the button size.

6.4 Counterintuitive Interaction

Although Pre-Study showed the front touch is intuitive, it is also counter intuitive in a sense that users are pushing a UI button from behind. A short pilot study provided an insight. Two different ways of animating the button click were experimented: button is pushed (1) farther from eyes and (2) towards eyes. Note that (1) is opposite to the hand motion but consistent with conventional UI, while (2) is in the same direction as fingers but opposite to conventional UI. (1) was chosen over (2) since the former felt more natural. Also, throughout all user studies conducted so far, no user pointed out this discrepancy in finger and button motions.

Unlike the traditional VR interaction where users “reach out” their hands to interact with the objects, they instead “push towards” their face for the front touch interaction. This less familiar motion of the front touch initially confused some participants with prior VR experience, but they quickly adapted to it with their kinesthetic senses. Also, in order to achieve advanced interactions, there is a need to interact with items in multiple layers using the front touch interface. New gesture, such as pinching two fingers on the touchpad, can be developed to move the cursor across the z-index, or zoom-in and -out of the scene in VR. It is also possible to hybridize the front touch with the traditional motion capture interaction, e.g. VR game user can use the gestural interaction during play, and the front touch to navigate through menus.

In spite of its limit, the introduction of the front touch interface has opened a new range of design possibilities to VR interaction and its design space. Its practical and simple characteristics make the front touch interface appropriate for the newly-emerging everyday application, such as movie-watching and social networking.

6.5 Penalty on the Front Touch Interaction

When testing the side technique, the touch sensor device (Note 4) was always taken off from the headset, which implies there was an extra weight penalty on the front touch techniques. Even though neck fatigue was found to be more severe with the side than the front, this extra weight could have influenced negatively on the performance of the front touch. Also, there were occasional Bluetooth disconnections, causing latency in sending the touch position data to VR system. Some feedbacks indicated that these occasional bugs irritated users during the experiment, so there is a high chance of this technical issue negatively affecting on users' experience.

7. Conclusion

7.1 Future Work

There is a plethora of rooms for improvement to further explore and upgrade the front touch interface. Among the four universal VR tasks introduced by Bowman (Bowman and Hodges, 1999) - navigation, selection, manipulation and system control - only the selection part was examined in this work. To study those other three universal tasks, other rich touchpad gestures, such as drag-and-drop, pinching, and swiping, should be further explored using the front touchpad. The front touch interface can even be hybridized with others (e.g. side or gestural interaction) to find more enhanced interaction methods.

Also, the fidelity of the front touch interaction can be further explored by testing it on more complex user interfaces that might involve the delicate touch gestures suggested above. Especially for the text-input application, it will be interesting to implement SwiftKey keyboard or design other soft keyboards optimized for VR environment. Moreover, it will be an interesting challenge to find a natural way to use both hands instead of one with the front touch.

Lastly, the VR media player developed in the case study will need to be tested through thoroughly designed experiments. As discussed in the Chapter 5, future studies to investigate how the front touch interface can be used when users are watching VR movies in vehicles or in bed. This study suggests that the front touch interface may enhance the VR user experience by supporting the view-fixed windows, and the long “sliding” gesture. This hypothesis will need to be verified in future.

As demonstrated in <Figure 1>, the front touch interface is envisaged to be embedded to the mobile VR headset eventually, using the low-cost, light-weight and low power-budget touch sensing technology. Follow-up studies are expected to further enhance the VR interface and shed light on a range of unexplored design possibilities.

7.2 Summary

This study introduces the front touch interface to virtual reality headsets, where users exploit their proprioception to interact with VR via a touchpad at the front of the headset.

A series of user studies was conducted to explore its design space, tasks including menu selection and keyboard application. Results demonstrate this new interaction to be intuitive as shown in the first Pre-Study, cause minimal nausea, and was preferred by users when the complexity of user interfaces increases as shown in the keyboard study. Furthermore, two front-touch interactions, namely Two-Fingers and Drag-n-Tap, were developed and the results of the user studies demonstrate each technique’s advantages. Two-Fingers could support quick selection, and Drag-n-Tap could be used for accurate selection.

Finally, a prototype version of VR media player was developed as a case study. Some short-comings of the gaze-based interaction could be found when using the media player in a bed or a vehicle, and how the front touch interface can solve these issues will be tested in detail as future work.

The front touch interface can be naturally embedded to the mobile VR headset, with the low-cost, low-weight and low power-budget characteristics of the touch screen. Follow-up studies are expected to further enhance the interface and lead to other unexplored design possibilities.

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국 문 초 록

가상 현실 디바이스의 정면 터치 인터페이스 연구

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가상 현실(Virtual Reality, 이하 VR)은 컴퓨터로 제작된 3차원 세계로, 보통 스테레오 고글이나 머리에 착용하는 헤드셋을 통해 사람들은 경험하게 된다. 이는 마치 실제 세계에 있는 것과 같은 경험을 제공하며 다양한 사용 가능성을 제기하고 있다. 가상 현실이라는 개념이 소개된 지는 몇 십년이 된 상태이지만, 예전보다 VR 경험을 쉽게 할 수 있게 된 지금, 학계와 업계 양쪽에서 가상 현실 연구의 필요성을 중요시 하게 되었다.

이와 같은 관심은 모바일 VR 헤드셋의 등장으로 더욱 높아졌다. 모바일 VR 헤드셋은 스마트폰을 기반으로 하는 가상 현실 헤드셋으로, 시중에 나와있는 스마트폰을 가상 현실 기기에 장착하여 VR 경험을 사용자에게 제공하고 있다. 삼성에서 소개한 기어 VR 시리즈와, 구글에서 나온 구글 카드보드(Google Cardboard)가 그 단적인 예라고 볼 수 있다. 이처럼 가상 현실 경험이 그 어느 때보다 더욱 용이하게 되어, 그 사용자의 수가 늘어나고 있다. 그로 인해 다양한 가상 세계와의 인터랙션 방법이 소개되고 있지만, 기술적 한계 등으로 하나만을 고집하기에는 아직

이른다고 보여지고 있다.

이 연구에서는 새로운 헤드셋 기반의 인터페이스를 소개하고, 그 사용성을 실험을 통해 알아보고자 한다. 이 새로운 인터페이스에서 사용자는 헤드셋 앞면에 장착되어 있는 터치 패드를 이용하여 가상 현실 세계와 인터랙션을 하게 된다. 이 정면 터치 인터페이스(Front Touch Interface)를 통해 VR 인터랙션 디자인의 개념을 확장시키고, 새로운 인터랙션 테크닉의 가능성을 제시할 수 있게 되었다.

정면 터치 인터페이스의 사용성을 테스트하기 위해서 이 새로운 인터페이스를 사용한 프로토타입 기기를 만들고, 이 기기를 가지고서 다양한 사용자 스터디를 실행하였다. 본 실험에 앞서 짧은 파일럿 스터디를 통해 정면 터치를 사용하는 인터랙션이 얼마나 직관적인지를 알아보고, 정면 터치 인터페이스로 확장된 VR 디자인 스페이스를 탐구하였다. 그리고 나서 선택 테스크(selection task)에 있어, 정면 터치 인터페이스가 얼마나 효율적인지 알아보기 위한 두가지 실험을 진행하였다. 첫번째 실험에서는 기어 VR의 메뉴 환경을 구현한 환경에서 진행되었고, 두번째 실험에서는 QWERTY 자판의 키보드에서의 실험이 진행되었다.

이 과정에서 두가지 선택 테크닉(selection technique)이 소개 되었다. 하나는 Two-Fingers로, 한 손가락으로는 가상의 커서(cursor)를 움직이고 또 한 손가락으로는 탭핑(tapping)을 통해 선택을 마무리하는 기법이다. 또 하나는 Drag-n-Tap으로, 한 손가락이 움직이는 일과, 선택하는 일을 다 실행한다. Two-Fingers는 빠른 선택을 하는데 있어 효율적이었고, Drag-n-Tap은 정확한 선택을 하는데 있어 두각을 들어내었다. 이 연구의 선택 테스크 실험을 통해서 각 테크닉의 장점과 단점을 파악하였고, 여기서 얻은 인사이트를 바탕으로 하여 더 나은 방법을 고안할 예정에 있다.

마지막으로 VR 미디어 플레이어에 대한 사례 연구를 짧게 탐구하였다. 그리고 정면 터치 인터페이스를 가지고 가상 현실 세계 환경에서 제공 되는 VR 미디어 플레이어를 사용할 때 어떠한 장점을 가지게 되는지 이야기하였다. 이 연구에서는 프로토타입 버전으로 마무리를 지

었지만, 향후 연구에서는 본격적인 사용자 실험을 통해 장점을 입증해 보일 계획에 있다.

정면 터치 인터페이스는 가볍고, 저렴하며 대중적인 터치 패드를 사용하여 최근 더 가벼워 지고 있는 VR 디바이스의 트랜드에 맞는 인터랙션 방법을 제공하고 있다고 보여진다. 또한, 터치 패드를 디바이스 앞에 장착하여 타 기기 (예로 손에 쥐는 컨트롤러나 VR 장갑)를 필요로 하지 않게 되는 점 또한 장점으로 보여진다. 이 연구에서 얻은 결과를 토대로 하여 향후에는 단순 선택 인터랙션 외에도, 스와이핑(swiping)이나 핀칭(pinching)과 같은 다양한 제스쳐의 가능성 또한 정면 터치 인터페이스를 사용하여 알아볼 예정에 있다.

주 요 어: 가상 현실, 터치 인터페이스, 헤드셋 기반 인터페이스, 입력 테크닉, 선택 테크닉, 텍스트 입력, 키보드
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