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Distance Perception in Virtual Environment through Head-mounted Displays

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DISTANCE PERCEPTION IN VIRTUAL ENVIRONMENT THROUGH HEAD-MOUNTED DISPLAYS

By

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List of Abbreviations

AMOLED	Active-Matrix Organic Light Emitting Diode
API	Application Program Interface
CG	Computer Graphic
FOV	Field of View
FPS	Frames per Second
HMD	Head-mounted Display
IMU	Inertial Measurement Unit
OpenGL	Open Graphics Library
sRGB	Standard RGB Color Space
VE	Virtual Environment
VR	Virtual Reality
VRPN	Virtual-Reality Peripheral Network

Abstract

Head-mounted displays (HMDs) are popular and affordable wearable display devices which facilitate immersive and interactive viewing experience. Numerous studies have reported that people typically underestimate distances in HMDs.

This dissertation describes a series of research experiments that examined the influence of FOV and peripheral vision on distance perception in HMDs and attempts to provide useful information to HMD manufacturers and software developers to improve perceptual performance of HMD-based virtual environments.

This document is divided into two main parts. The first part describes two experiments that examined distance judgments in Oculus Rift HMDs. Unlike numerous studies found significant distance compression, our Experiment I & II using the Oculus DK1 and DK2 found that people could judge distances near-accurately between 2 to 5 meters.

In the second part of this document, we describe four experiments that examined the influence of FOV and human periphery on distance perception in HMDs and explored some potential approaches of augmenting peripheral vision in HMDs. In Experiment III, we reconfirmed the peripheral stimulation effect found by Jones et al. using bright peripheral frames. We also discovered that there is no linear correlation between the

stimulation and peripheral brightness.

In Experiment IV, we examined the interaction between the peripheral brightness and distance judgments using peripheral frames with different relative luminances. We found that there exists a brightness threshold; i.e., a minimum brightness level that's required to trigger the peripheral stimulation effect which improves distance judgments in HMD-based virtual environments.

In Experiment V, we examined the influence of applying a pixelation effect in the periphery which simulates the visual experience of having a peripheral low-resolution display around viewports. The result showed that adding the pixelated peripheral frame significantly improves distance judgments in HMDs.

Lastly, our Experiment VI examined the influence of image size and shape in HMDs on distance perception. We found that making the frame thinner to increase the FOV of imagery improves the distance judgments. The result supports the hypothesis that FOV influences distance judgments in HMDs. It also suggests that the image shape may have no influence on distance judgments in HMDs.

Chapter 1

Introduction

1.1 Visual-based Virtual Environments

A virtual environment (VE) or virtual reality (VR) system is a computer-generated simulation that provides the sensory experience of being present in a non-physical environment. The virtual environments have a wide variety of applications, such as training, prototyping, presenting and entertainment. Most immersive virtual environment systems focus primarily on simulating and presenting visual information to users. Most visual-based virtual environment systems consist of one or multiple displays that provides users with stereoscopic imagery. There are two types of displays commonly used in virtual environments including large-screen displays and

Figure 1.1: A wall-display virtual reality system. This picture is in courtesy of https://commons.wikimedia.org/wiki/d/6d. It is created by Davepape. Davepape grants anyone the right to use this work for any purpose, without any conditions, unless such conditions are required by law.

head-mounted displays (HMDs). Large screen displays usually present 3D information through wall-like displays along with 3D glasses to provide depth cues (shows in Figure 1.1). Virtual environment systems commonly consist of multiple sensors to capture users' head movements (position and orientation), which enable users to look around or even move around in the virtual environment. Modern sensory technologies also enable users to interact with the virtual environment through hearing, touch and smell. A well-known application is a virtual surgery simulator, which uses a haptic sensor to provide users with a realistic haptic force feedback. Figure 1.2 shows an example of a virtual surgery system using haptic technologies. Other than this, some virtual reality game system use controllers to transmit sensations to users through

Figure 1.2: A virtual surgery system for training of student doctor. This picture is in courtesy of http://www.scienceimage.csiro.au/image/3361. The image is created by CSIRO under Creative Commons Attribution 3.0 Unported (CC BY 3.0) licence, which allows free reuse with proper attribution.

vibration. For instance, a virtual driving simulator can allow users to practice driving without going to a real traffic road. Furthermore, a virtual tourism system can let users to see points of interests around world vividly without going out of their own house. The device manufactures and developers are still looking for more and more areas that the virtual environment system can be useful, and the number of the potential users and the future influence of the virtual environment system are immeasurable.

1.2 Head-mounted Displays

A head-mounted display (HMD) is a wearable display device that people wear on their head. It was first invented by Surtherland [36]. It usually consists of one or two displays. It may also use a lens in front of each eye to derive users' vision to specific area on the display. Each eye sees a different image and therefore the system can present 3D information to users. Many HMD systems also contain an inertial measurement unit (IMU) to capture users' head orientation, and use it to allow users to naturally look around in the environment by rotating their head. HMDs are becoming one of the most popular virtual reality display devices.

Figure 1.3: Oculus DK1 HMD. This picture is in courtesy of https://commons.wikimedia.org/wiki/OculusDK1. This image is created and own by Sebastian Stabinger. It is created and owned by Sebastian Stabinger. CC BY 3.0 allows free reuse with attribution.

The Oculus Rift HMD was created by Oculus VR LLC (a company owned by Facebook). It is inexpensive compared to many HMDs that were previously available. The first generation of the Rift HMD is the Oculus Rift Development Kit one (DK1) shown in Figure 1.3. It has a resolution of 1280×800 pixels (640×800 per eye) and a high-speed IMU. It also has a horizontal field of view of around $100 degree$. The field of view is notable because it almost double that of other HMDs such as the NVIS nVisor ST60 HMD that has a horizontal field of view of around $47°$. The second generation of the Oculus HMD, known as the DK2 HMD, is similar to the DK1 in terms of design and properties, but has an improved display and an additional positional tracking. The latest release of the Oculus HMD, known as the CV1, is a version targeted at consumers. It inherited the design of the older versions, improved the display resolution, and added stereo audio support.

Figure 1.4: Microsoft HoloLens, an augmented reality display. This picture is in courtesy of https://www.flickr.com/photos/jiff01/16486271861. It is created and owned by Jorge Figueroa. CC BY 2.0 allows free reuse with attribution.

In addition, some HMDs feature a see-through function that enable users to view

both the virtual scene and the real world. These are often called augmented reality (AR) displays. The Microsoft HoloLens (Figure 1.4) is an example of an AR display.

1.3 Egocentric Distance Perception

Egocentric distance perception or depth perception usually refers to people's ability to perceive the distance between themselves and an object in the world. Egocentric distance perception is an important ability in both real world and virtual environments, as it provides strong guide to people's actions. In general, we need to be able to perceive distances correctly in order to reach for an object, throw an object at a target, and jump to a location. Egocentric distance perception is also important when people are driving a vehicle. They need to perceive the distances to cars and objects in the environment around them to safely avoid accidents.

Although it is difficult to measure perceived distances directly, we can ask people to perform certain actions which depend on the perceived distance and measure their performance. We describe common ways of measuring perceived distances in Section 2.1. It is known that people are can judge distances accurately using these action-based methods in the real world [25, 33, 44]. However, numerous research studies found that people typically underestimate distances in virtual environment through HMDs [2, 16, 19, 34, 38, 41, 42, 43, 44, 48] and also in large-screen virtual

environments [1, 7, 14]. This performance difference then became a popular research direction in virtual environments. Detailed information about distance perception in HMDs is discussed in Section 2.1.

1.4 Field of View

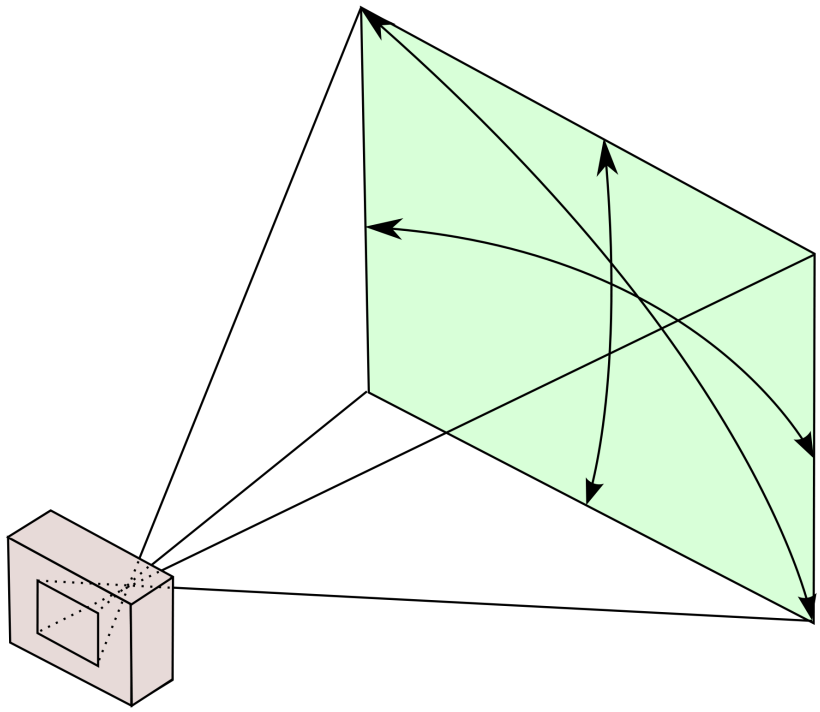

Figure 1.5: Device field of view demonstration

Field of view (FOV) or field of vision refers to the full range of the observable world. It is represented by two angles (horizontal $\times$ vertical) or one diagonal angle, shown in Figure 1.5. It is known that the human natural field of view is around $180° \times 130°$ [4].

In this document, we will mention two types of FOV: device FOV and the geometric or rendering FOV. The device field of view depends on the display device. For example, if you are watching TV, the screen size and your distance from the screen will impact the display's FOV. An HMD also limits the field of view because of the limited size of the display and/or because of the lenses and optics of display. The device FOV is one of the key specifications of a HMD. It is challenging to make an HMD which provides a large FOV because the optics are difficult to construct and a larger FOV requires higher display resolution to keep the visual angle of pixels to remain constant. The second field of view is called the geometric field of view or gFOV. It is used when we are rendering the virtual environment. The larger the rendering FOV is, the more geometry there will be displayed on the screen. Therefore, objects become smaller on the screen as the gFOV increases.

Device field of view is typically constrained in most modern HMDs. It is possible that the limited FOV being a contributing factor to the distance underestimation commonly seen in HMD-based virtual environments. Although there is significant research into the influence of FOV, there is still no agreement on whether FOV can influence distance judgments. By simulating the FOV-restricted experience in real-world environments, some studies found that limiting the device FOV does not influence distance judgments in real-world environments [5, 16], while some other studies found different results [22, 41, 45]. In Chapter 2.1.3 we describe previous research on the influence of field of view in both real world and virtual environments.

Chapter 2

Background

2.1 Distance Judgments in HMDs

Many HMD-based applications require or at least benefit from users' ability to judge distance in a similar manner as they do in the real-world. Three examples are listed below:

1. A sports simulator where users try to earn points playing basketball. In this application, users need to judge distances as they do in the real world to successfully throw the ball and score points.

2. A driving simulator that's designed to improve users' driving skills. The simulator might provide virtual roads, vehicles, and traffic scenarios and give users hands-on experience to practice driving in a realistic setting. If users can't judge distances correctly, or if their distance judgments differ from those in the real world, then we can't expect users virtual driving practices to improve their real-world performance.

3. An immersive interior-design software. This software, when combined with HMDs, allows users to conveniently and intuitively make interior design decisions. It also allows them to view the results in a vivid and realistic way. When the designer later recreates the design in the real world, they need it to match the appearance that they saw in the HMD. However, if designers can't judge relative or egocentric distances correctly in virtual environments, the design decisions made in the virtual environment might not be translated correctly to the real world. Any inconsistencies between the perception of the virtual world and the real world would negatively impact the system effectiveness.

2.1.1 Perceived Distance Measurements

Since distance judgments are important for many applications, we need a way to measure perceived distances to study it. Although we can't measure it directly, we can ask people to judge distances by performing actions or answering questions which

will indicate their perceived distances. Many methods are used to measure perceived distance. They include methods which involve walking, reaching, aiming, throwing and verbal reports. This subsection describes most of these methods in detail.

2.1.1.1 Verbal Reports

Verbal report is a simple way of measuring perceived distances. It requires participants to observe a target and then verbally report the distance. Ideally, the participants can choose which unit (e.g., feet, meters, yards, etc.) they wish to use in their reports. One shortcoming of this method is that the ability to convert the visual distance information to measurement units can vary greatly and may heavily depend on personal experience. People are also more consciously aware of their verbally reported results. Many studies try to ensure that participants are familiar with the lengths by showing them a meterstick or yardstick prior to the experiment to familiarize the participants with the type of unit used for the experiment.

Previous research using verbal report suggests that people tend to underestimate distances in both real world and virtual environments [2, 13, 23, 29, 43]. On average, people reported 65% to 75% of the actual distances. Previous research conducted by our lab found that people significantly underestimated distances (74%) in virtual environment through HMDs with verbal reports [48].

2.1.1.2 Direct Blind Walking

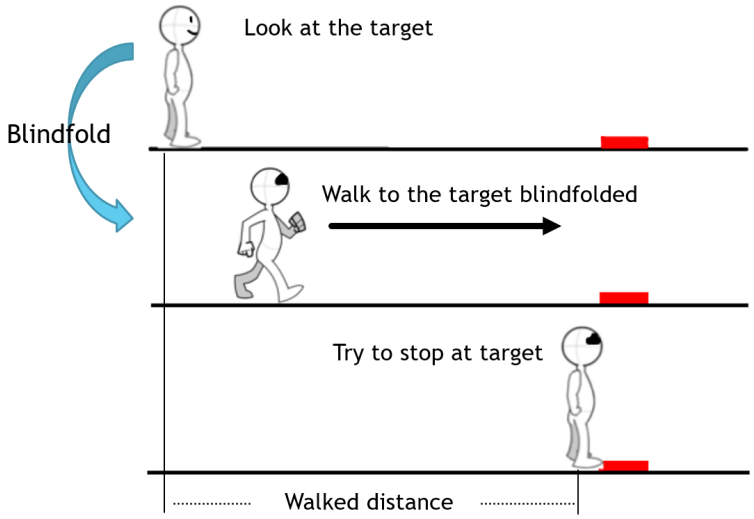

Figure 2.1: Demonstration of direct blind walking

Direct blind walking is one of the most common ways to measure perceived distance. In this method, participants view a target on the floor, close his/her eyes, and then walk to the target without vision (Figure 2.1). Participants are instructed to stop walking when they believe that they are standing on top of the target. The target is usually removed before participants reach it so they will not be able to feel it under their feet. The participants' walked distance is measured and treated as if it was the distance that the participants perceived. Unlike verbal reports, previous research using direct blind walking has shown that people are capable of judging distances accurately in real-world environments [25, 33, 44]. However, it is also well-documented that people typically underestimate distance by 20 to 50 percent in HMDs when measured by direct blind walking [5, 8, 11, 12, 15, 16, 24, 26, 30, 34, 38, 41, 42, 43, 44]. Previous

Table 2.1
Preliminary research in distance judgments using direct blind walking.

	Study	Environment	Walked Dist	Range
Real-world	Loomis 1998	Field	∼95%	4 ∼ 16 m
	Andre 2006	Gym	∼95%	1.5 ∼ 18 m
Virtual Environment (HMD)	Messing 2005	Field	∼73%	3 ∼ 7 m
	Kunz 2009	Classroom	∼78%	3 ∼ 6 m
	Kuhl 2009	Hallway	∼80%	3 ∼ 6 m
	Zhang 2012	Classroom	∼76%	2 ∼ 5 m

work by our lab showed that people significantly underestimated distances in an NVIS nVisor ST60 HMD, which is consistent with other studies [48]. Table 2.1 shows the results of previous research using the direct blind walking method.

In this dissertation, we conducted a series of direct blind walking experiments to measure how people judgments distances in response to different visual conditions with new Oculus HMDs. We conducted additional studies because previous work typically used older HMDs with FOVs of less than 50°. These experiments are described in Chapter 3 and 4.

2.1.1.3 Indirect Blind Walking: Repositioning

Indirect blind walking is another method of measuring perceived distances. Like the direct blind walking, this method also relies on the memory of a previously observed distance. However, indirect blind walking involves a repositioning of the participant before walking to the target blindly (Figure 2.2).

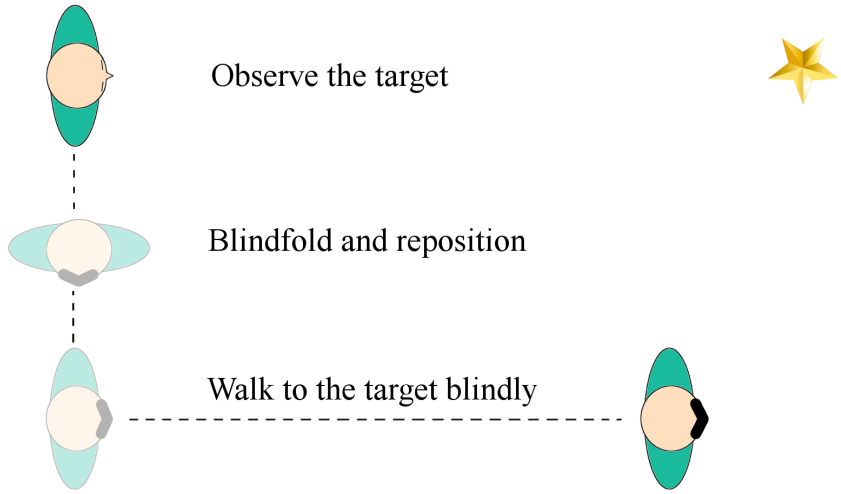

Figure 2.2: Demonstration of indirect blind walking

When conducting a blind-walking experiment, it is often the case that the examined distances are limited by the physical conditions, such as the size of the walking area and sensor-tracked area. The indirect blind walking method solves this problem by repositioning participants to a larger space before letting them walk. An example of the indirect blind walking is to let participants observe a target in a small laboratory, then bring them to a hallway and ask them to walk the distance they viewed in the laboratory. Figure 2.2 shows a demonstration of this method.

There are two major drawbacks of repositioning people. First, unlike the direct blind walking method, the indirect blind walking has a delay between the time that the distance is perceived and the time of the blind walking action. However, previous research showed that the time delay doesn't influence the distance judgments in walking tasks [33]. Second, this method requires a repositioning of the participants to another

location, which must involve some walking and turning. People must imagine that the target is still in front of them even though they have moved to a new location, which can lower the accuracy of the walking tasks.

2.1.1.4 Indirect Blind Walking: Triangulation

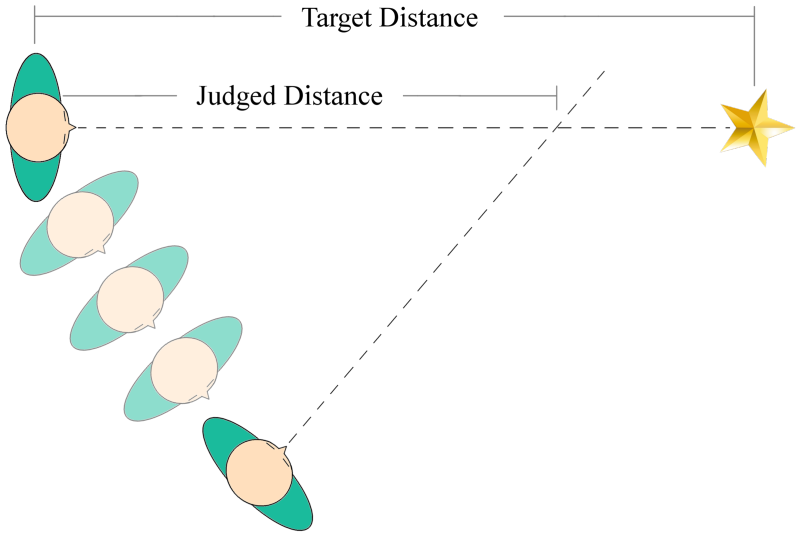

Figure 2.3: Demonstration of triangulated walking

Triangulated walking is another common way of measuring perceived distances. Like the blind-walking tasks, the triangulated walking requires participants act based on their visual inputs. The difference is that triangulated walking allows investigation of much longer distances by having participants form a triangle between standing positions and the target (Figure 2.3). An example of the procedures is that participants first view a target on the floor, turn right (or left) approximately 60°. Next, participants close their eyes or are blindfolded, walk straight for a short distance,

stop walking, then turn toward the target they previously saw. The judged distance is then calculated based on participants' positions and turning directions. Figure 2.3 demonstrates the triangulated walking procedure.

Previous research found that people are capable of judging distance accurately using the triangulated walking method [6, 38]. However, like the direct blind walking method, research has found that people significantly underestimate distances in virtual environments through HMDs measured by triangulated walking [38, 41].

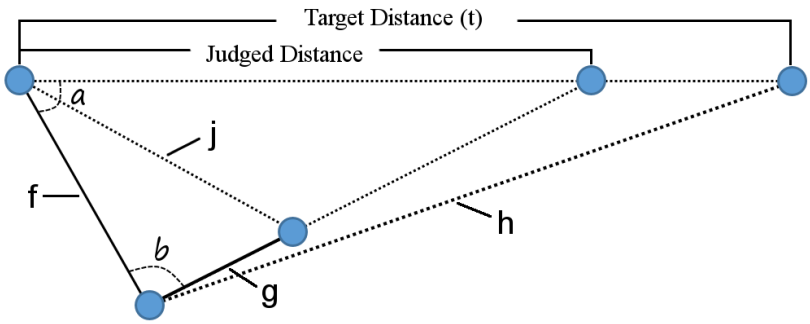

Figure 2.4: Calculating the judged distance

$$\angle a = arccos(\frac{t^2 + f^2 - h^2}{2 \cdot t \cdot f})$$
$$\angle b = arccos(\frac{f^2 + g^2 - j^2}{2 \cdot f \cdot g}) \tag{2.1}$$
$$JudgedDistance = \frac{f \cdot sin(\angle b)}{sin(180 - \angle a - \angle b)}$$

The judged distance can be calculated based on the law of cosines. The triangulated relation is shown in Figure 2.4. The equation for the calculation is shown in

Equation 2.1. First, we need to calculated two inner-angles using the first two equations. Next, the judged distance is calculated by using the last equation shown in Equation 2.1.

2.1.2 HMD Limitations & Distance Underestimation

Distance underestimation has resulted in a large volume of research aiming to find an explanation for the phenomenon. Every HMDs limitation could contribute to distance underestimation. These limitations include the quality of the graphics, latency, inaccurate tracking, limited field of view, poor color reproduction, limited resolution, insufficient screen brightness, etc.

There is no lack of previous research on examining the potential influence factors to distance perception in HMDs, and some factors have been shown not to influence distance judgments in virtual environment through HMDs. A study by Thompson et al. showed that the quality of the graphics does not significantly influence distance judgments in HMDs [19, 38]. Another work by Willemsen et al. showed that the physical properties of the HMD, such as the mass and moments of inertia, are also not significantly influence distance judgments [41]. Another study showed that enhancing users' sense of presence by exposing them to a similar real-world environment can improve distance judgments [9]. Finally, other studies have reported that displaying a

co-located virtual avatar can significantly improve distance judgments [27, 28, 31, 32].

In this discussion, we primarily focus on examining the influence of field of view and peripheral vision.

2.1.3 Field of View and Peripheral Vision

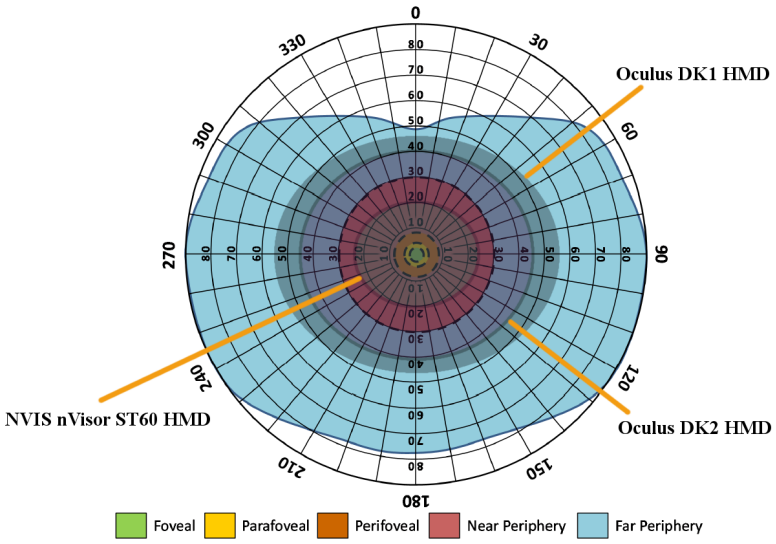

Figure 2.5: Division of human binocular field of view. Figure adapted from [10]

Limited FOV could be the main or a contributing factor to the distance compression in HMDs. Most HMDs are unable to provide the entire human natural binocular field of view (FOV) spans around 180 degrees horizontal and 130 degrees vertical [4] (Figure 2.5). Until 2011, most HMDs used for research seldom provided FOVs more than 60 degrees diagonally. To examine the influence of the FOV, many research studies have used a real-world approach where participants judge distances while wearing

mock HMDs which creates a FOV-restricted experience that is similar to HMD-based virtual environments. However, previous studies found conflicting results using the real-world approach. Figure 2.6 demonstrate the simulated or mock HMDs commonly used for examing the influence of FOV in real world. Some research found that field of view did not influence distance judgments. For example, Knapp and Loomis et al. asked participants to judge distances in real world while wearing a simulated HMD that limits their field of view [16]. They found no statistically significant difference between the condition with the mock HMD and the real-world condition with no restrictions.

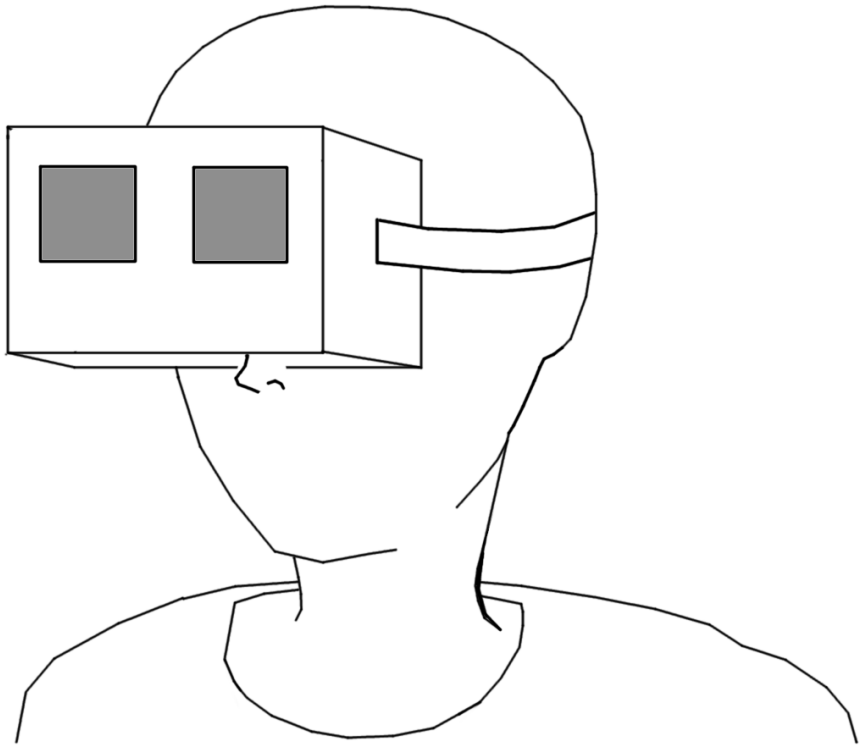

Figure 2.6: Demonstration of a simulated or mock HMD used for FOV research. The image was created specifically for this document by the author.

However, there are also some research that found different results. Research by Willemsen et al. showed that the limiting FOV did impact distance judgments, by using a mock HMD. They also mentioned that the influence they observed was not sufficient towards explaining the entire distance underestimation commonly reported by research [41]. In addition, Wu et al. found that limiting vertical FOV, when combined with head-orientation restriction, can significantly impact distance judgments in real-world environment [45].

It is well documented that human peripheral vision is essential to daily activities, such as guiding orientation, detecting motions and understanding spatial relationships (for a review, see [35]). However, little was known about how peripheral vision influences spatial perception in virtual environments. Jones et al. found that light or stimulation in users' peripheral vision could improve distance judgments [10, 12]. Figure 2.7 demonstrate the idea of adding LEDs inside HMDs. This peripheral stimulation was reconfirmed by our Experiment III described in Chapter 4, but the reason behind this effect still isn't clear. These findings raise questions which require additional study: How does peripheral vision influence distance perception? What triggers this peripheral stimulation and how can we use it to improve spatial perception? Another study conducted by Microsoft found that adding a set of LEDs in the periphery can enhance situational awareness, reduce motion sickness, and is generally preferred by users [46]. Other work showed that peripheral vision can influence sensation of illusory self-motion (vection) in HMDs [40].

For several years, HMD development has steadily improved sensory technologies and display components. HMDs commonly used for older research studies, such as the NVIS ST, only covers human near periphery that is within 60° diagonally. With technological improvements of HMDs, newer devices such as Oculus Rift and HTC Vive are capable of providing a diagonal FOV of approximately 100°. This made it possible to examine the influence of FOV and peripheral vision directly in virtual environments. In this dissertation, we examined the influence of FOV in both real and virtual worlds.

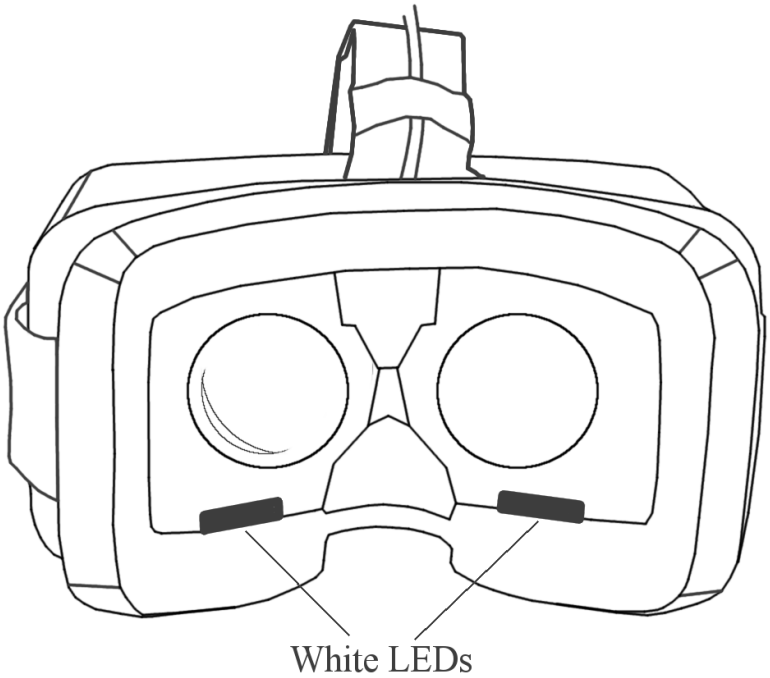

Figure 2.7: Demonstration of adding white-LEDs inside a HMD. The image was created specifically for this document by the author.

Chapter 3

Research: Distance Judgments in Oculus HMDs

In Section 2.1 we described how accurate distance perception can be important for some virtual reality experiments. Previous research suggests that people typically underestimate distances in virtual environment through HMDs [5, 8, 11, 12, 15, 16, 24, 26, 30, 34, 38, 41, 42, 43, 44]. Previous work from our research lab indicates that minification, or rendering the imagery smaller than a correctly calibrated image, increases the perceived distance to objects. It can be used as a correction to the underestimated distances that are commonly observed in virtual environments through HMDs [17, 18, 39, 48].

Until 2011, HMDs commonly used for research seldom provided FOVs more than 60° diagonally. In 2013 Oculus Inc. published the first generation of the Rift HMDs. The first generation of the developers' version (DK1) provides a diagonal FOV of around 110°, which is significantly higher than many HMDs commonly used in research. Therefore, it is worthwhile to re-examine how people judge distances in virtual environments through Oculus HMDs.

3.1 Experiment I: Distance Judgments in Oculus DK1 HMD

Table 3.1
FOV of HMDs used in previous research and our research.

Research	Environment	HMDs	Device FOV
Knapp 1999	Hallway	VR FS5	44° horizontal
Loomis & Knapp 2003	Laboratory	VR FS5	44° horizontal
Thompson et al. 2004	Hallway	Datavisor HiRes	42° horizontal
Sahm et al. 2005	Hallway	nVisor SX	47° horizontal
Interrante et al. 2006	Laboratory	nVisor SX	47° horizontal
Mohleret al. 2006	Hallway	nVisor SX	47° horizontal
Jones et al. 2008	Hallway	nVisor ST	47° horizontal
Kuhl et al. 2009	Hallway	nVisor SX	47° horizontal
Williams et al. 2009	Laboratory	nVisor SX	47° horizontal
Kunz et al. 2009	Classroom	nVisor SX	47° horizontal
Jones et al. 2011	Hallway	nVisor ST	47° horizontal
Exp. I of this work	Classroom	Oculus DK1	100° horizontal
Exp. II of this work	Classroom	Oculus DK2	90° horizontal

As shown in Table 3.1, most HMDs used in these research seldom provide a field of

view that is larger than 65 degrees, and little was known about how people would perform in larger field of view HMDs, and how minification might affect distance judgments. Oculus Rift HMDs are inexpensive HMDs that are primarily designed for gaming purposes. Oculus HMDs are becoming more and more popular, and have a large group of potential users and developers, with many types of applications. The first generation of the developer's edition, known as the DK1, provides a FOV of 110 $\times$ 90 degrees, which covers human's entire near periphery and part of the far periphery vision, and almost double the field of view of many HMDs that are often used for research, such the NVIS nVisor ST60 HMD that has a field of view of 47 $\times$ 40 degrees. Thus we did a direct blind walking experiment with two different conditions using an Oculus Rift DK1 HMD. The description for direct blind walking can be found in Section 2.1.1 of this document. We have two primary goals for this research. First, we want to collect baseline information for how people judge distances in Oculus Rift HMDs. Second, we want to confirm if minification influence wide field of view HMDs similarly as it does to other HMDs.

In this study, we used the Oculus Rift DK1 HMD to display the stereo image to users. We also used a four camera WorldViz PPT-H system to track user's head position. For graphics rendering, we used the WorldViz Vizard 4.0. There are two experiment conditions. In the calibrated condition, we let people judge distances in a calibrated normal virtual environment, where objects are rendered in the same size as they should appear in the similar real-world environment. In the minified condition,

we again let people judge distances in a virtual environment where we rendered by applying a minification factor of 0.7. We used the number 0.7 to match the scaling factor that has been used in our previous research [17, 18, 39, 48]. This work has been published at ACM SAP in 2014 [21]

3.1.1 Equipment & Calibration

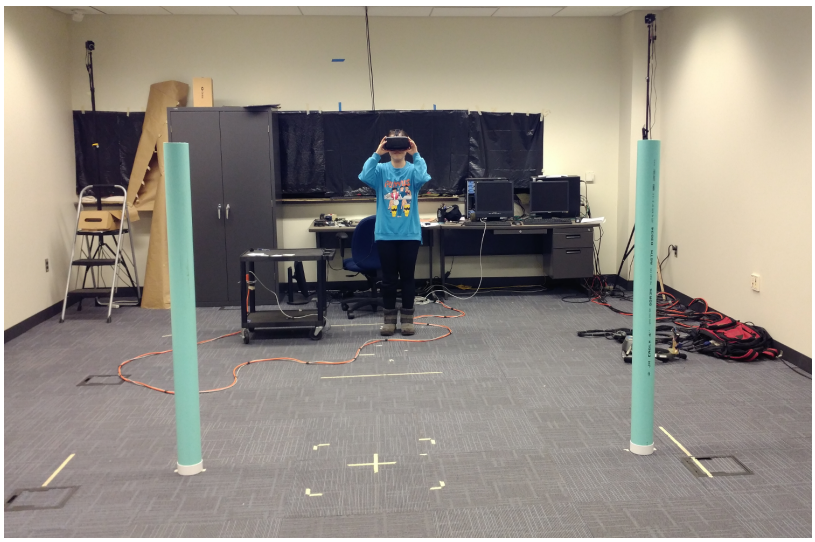

Figure 3.1: Demonstration of HMD field-of-view calibration. The image was created specifically for this document by the author.

The experiments in this study either used HMDs, such as the Oculus DK1 or DK2, for experiments in virtual environments, or used simulated HMD for real-world experiments. A tracking system captures users' head movements including their head positions and orientations. This information is then used to generate an interactive

user experience. Many modern HMDs include an IMU to sense users' head orientations. Although IMUs' fast and responsive, many suffer from a yaw drifting problem which can cause inaccurate measurements. This drifting occurs if the magnetic compass in the sensor is disabled or if it is unable to reliably detect magnetic north. Thus, in our experiments, we use a Vicon multi-camera tracking system to provide a yaw drifting fix the yaw drifting problem by combining the IMU data with the tracking system data to maintain a fast and reliable orientation measurement.

To render virtual world correctly, we need to ensure that we render objects in the virtual environment in the same size as they should appear in the real world. Previous studies showed that HMD miscalibration could significantly influence distance judgments [18, 48]. To achieve this, we need to render the graphics with a geometric field of view, known as the rendering field of view, that matches the device field of view of the Oculus DK1 HMD. We calibrated the HMD by placing two PVC tubes straight up on the floor and rendered two virtual poles at the same position as the real tubes (Figure 3.1). We then asked the user to stand in front of the two tubes, and repeatedly raise and lower the HMD on and off their head and compare positions of the real tubes to the virtual-world tubes. The users then adjusted an image scaling factor with a remote control until the virtual poles and real world PVC tubes were aligned. After averaging the results, we decided to apply a scaling factor of 0.87 on the default Oculus SDK rendering setting to make our normal calibrated condition. To reduce variability throughout the calibration and experiment, we adjusted the eye

relief screws on the DK1 HMD to maximize the eye-to-display distance.

3.1.2 Method

A total of 32 participants in the age between 18 to 30 were recruited for this study. Each participant was assigned to only one viewing condition (between subject design). We examine distance judgments of targets placed at 2, 3, 4 and 5 meters away from the participants. Each target distance was repeated three times during the experiment. There are two main reasons that we choose these distances. First, we use a 6×9 *meters* laboratory to conduct the experiments, and about 80% of the area is well-covered by the tracking system. Thus, testing distances longer than five meters can be difficult, given the limited lab space. Second, historical research on distance perception measured by direct-blind walking usually tested distances up to six meters, and we want to test distances that match those previous studies and match our previous experiments [18, 48].

To correctly measure participants' perceived distances, we want to ensure that participants make full use of the visual information they get from the HMD, and not to treat this task as a math problem. Specifically, the room had floor tiles and we don't want participants to calculate the distance based on tile numbers, and judge distance by counting steps. Thus, in an oral instruction before the experiment, we tell

participants to not count their steps or using any mathematical skills, and we also encourage them to use a mental-image strategy, which is relying on their memory of a previously viewed environment.

In addition, we want to prevent some influence factors that can impact distance judgments, such as the sound cues. Thus, we give participants a pair of noise-cancelling headphones with white noise looping inside to mask any environmental sounds that might influence participants' judgments. Since a previous study by [10, 12] found that the light in the periphery might influence distance judgments, thus we also keep the laboratory dark to avoid any potential influence from the environmental light sources. We also want to prevent participants from memorizing the repeated target distances. Thus we inserted target distances at 2.5, 3.5, and 4.5 meters, one time for each, and we randomly shuffle all 15 target distances throughout the experiments. For the same reason, we also move the virtual room position, without moving the target for each walking task. The end result is that people start from different locations in the virtual environment.

Here is the experiment procedure that we carefully designed and used for all the experiments described in this dissertation.

1. Prior to experiment, participants are assigned to one of the experiment conditions.

2. Give participants an oral instruction and ask them to read a written instruction.

3. Collect participant's information including name, age and interpupillary distance.

4. Blindfold participants and practice walking with them in the hallway for around five minutes.

5. Bring participants to the laboratory with their eyes closed.

6. Put the HMD on participants and then perform 17 blind-walking tasks, including 2 practice tasks and 15 recorded tasks.

7. Participants fill out a short post-experiment questionnaire.

3.1.3 Results and Discussion

Figure 3.2 shows the results for the normal calibrated condition. Appendix B described how we make the result plots. The blue line represents the ideal target distances. The green line is the results from our previous research, using the same walking method, and share the same procedure, but using a NVIS nVisor ST60 HMD [48]. Surprisingly, we found that people judged distances remarkably accurate from 2 to 5 meters in the Oculus Rift DK1 HMD. On average, participants judged distance at 99% of the actual target distances. This results contradicts numerous previous research that typically

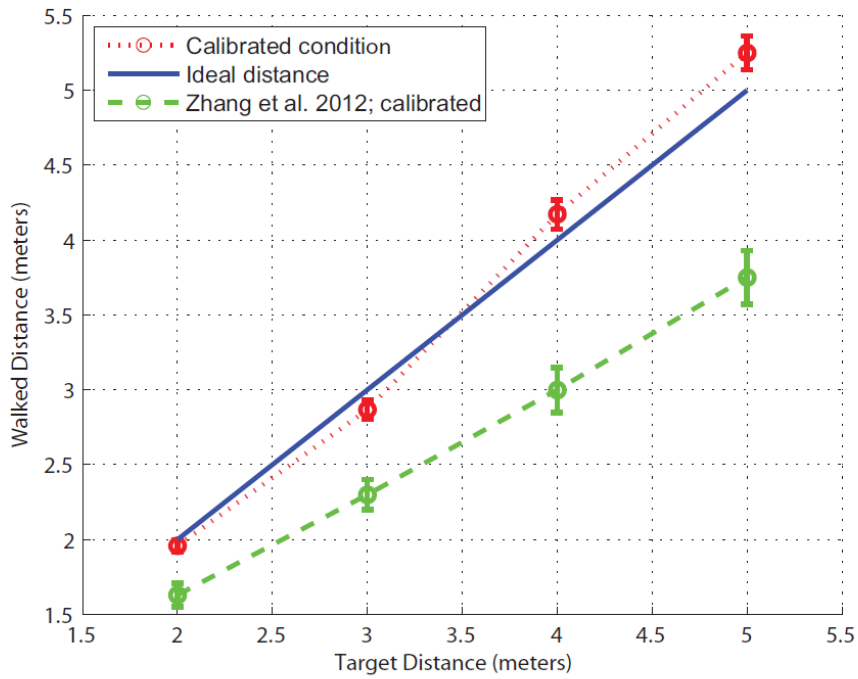

Figure 3.2: Results from the normal calibrated condition. [21]

reported distance underestimation in virtual environments through HMDs, including our previous research that shared great similarity with this research [48].

The results for the minified condition are shown in Figure 3.3. The green line shows the results of distance judgments in virtual environment with minification (a scaling factor of 0.7). As we can see that the minification actually lead to distance overestimation in the DK1 HMD. On average, participants judged distance at 111% of the actual distances. A 2 (condition) $\times$ 4 (distance) analysis of variance (ANOVA) showed a statistically significant difference between judged distances in the normal calibrated condition and the minified condition ($F(1, 30) = 5.097, p = 0.0314$).

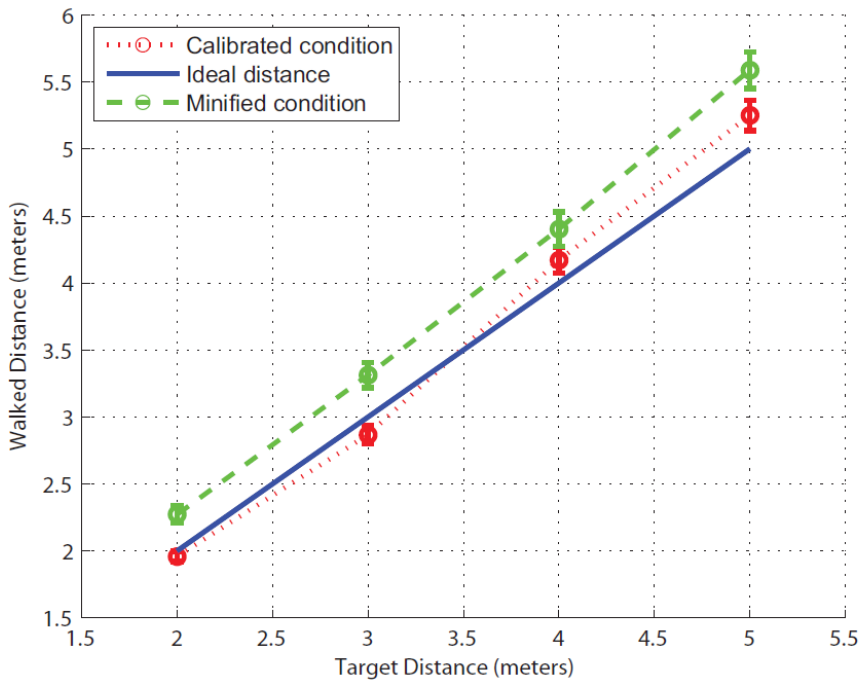

Figure 3.3: Results from the minified condition. [21]

To summarize, we found that people are capable of judging distances accurately in a normal calibrated condition inside an Oculus Rift DK1 HMD, which contradicts numerous previous research that found distance underestimation in virtual environment through HMDs. The question then becomes: What causes this performance difference between Oculus DK1 HMD and some other HMDs, such as the NVIS nVisor ST60 HMD? One hypothesis is that the Oculus Rift DK1 HMD has a relatively high field of view comparing to many HMDs that are commonly used by research. In addition to that, the results for the minified condition showed that minification significantly influenced distance judgments in Oculus DK1 HMD, which implies that minification also influences distance judgments in other HMDs with high device field of view. It

also showed that an accurate device calibration is necessary to avoid any undesired impact on distance perception in HMDs.

3.2 Experiment II: Distance Judgments in DK2 HMD and in Real world

Experiment I showed that people are capable of judging distance accurate in an Oculus Rift DK1 HMD in a normal calibrated condition [21]. At a similar time, the improved distance judgments in Oculus DK1 HMD were also observed by some other research groups [3, 47]. This is a surprising result, as it contradicts with a lot of previous research. Thus, it is important to understand the causes of this performance difference between Oculus HMD and some other HMDs that are commonly used for research. The findings can then be used by manufactures to make better devices, and help improve the perceptual performance of some other devices, such as the NVIS nVisor ST60 HMD.

There are a few possible explanations. First, it is possible that the high device field of view of the DK1 HMD increased its system performance. A few research conducted by Jones et al. showed that adding light in people's peripheral vision can actually improve distance judgments, which supports the field of view hypothesis, since high field of view HMD will display image in people's peripheral vision and make it relatively

brighter [10, 12]. Second, since our calibration for DK1 HMD was relied on the device IMU. The yaw drifting of IMU may have impacted the accuracy of our calibration. A miscalibration would cause minification which would then make people judge distance further away [17, 18, 21, 48]. It is possible that some unintentional minification caused by incomprehensive calibration could also lead to the improved judgments.

In this subsection, we described two direct blind walking based experiments that we conducted to further examine distance perception in Oculus HMDs and the influence of the device field of view.

3.2.1 Distance Judgments in DK2 HMD

The Oculus Rift Development Kit 2 (DK2), is the successor of the DK1 HMD. It has similar mechanical properties, in terms of weight and size, compared to the DK1 HMD. It also used a different display, which increased the screen resolution and slightly decreased the device field of view by around 20 degrees horizontal. However, it is still larger than many other HMDs that are commonly used for research, such as the NVIS nVisor ST60. In Experiment I, we let people judge distances in a virtual environment through an Oculus DK1 HMD with a much precise field of view calibration. Each participant was assigned to either the normal calibrated condition or the minified condition. In the normal calibrated condition, everything was displayed

with its correct size. We calibrated the HMD using a similar method described by Section 3.1.1. However, we used a precise and low-latency Vicon T20S 12 camera tracking system to get both user's head position and orientation, instead of the orientation sensor of the Oculus HMD, which eliminated the yaw drifting problem of our previous calibration process. For the minified condition, we applied a scaling factor of 0.7 to the displayed image, which matches our previous minification research [17, 18, 21, 48].

There are three primary goals for this experiment. First, we want to reconfirm the results that we saw in Experiment I, using the Oculus DK2 HMD. Second, DK1 and DK2 are different in multiple ways. For example, FOV. By doing another experiment, we can hopefully determine if the difference between the devices will influence distance judgments. Third, we also want to check the influence of minification on distance judgments in DK2 HMD, and compare the results to the DK1 minified condition.

We recruited 32 participants for this experiment, 16 for each condition. All participants were in the age range of 18 to 30, which we picked from the same subject pool as our previous research. The experiment setup and procedure are the same as our previous research. Detailed description about the procedure can be found in Section 3.1.2.

Figure 3.4: DK2 HMD (right); Simulated HMD with minification lenses and neck collar (left). The image was created specifically for this document by the author.

3.2.2 Distance Judgments in Simulated HMD

We have done some study about minification influence on distance judgments in virtual environments, which made us curious about how minification influence distance judgments in real world. To further examine the influence of the device field of view, we conducted another direct blind walking experiment with two conditions in the real world. For the first condition, instead of using a HMD, we made a simulated HMD from a safety goggles and an inner cardboard frame (Figure 3.4). The field of view is limited by the inner cardboard frame, which matches the device field of view of the DK2 HMD. In the second condition, we used the same simulated HMD and added a pair of minification lenses (Canon WC-DC52 0.7x) to create a real-world minified scenario. The lenses minified the image by a ratio of 0.7, which matches the scaling factor used by our previous minification research [17, 18, 21, 39, 48].

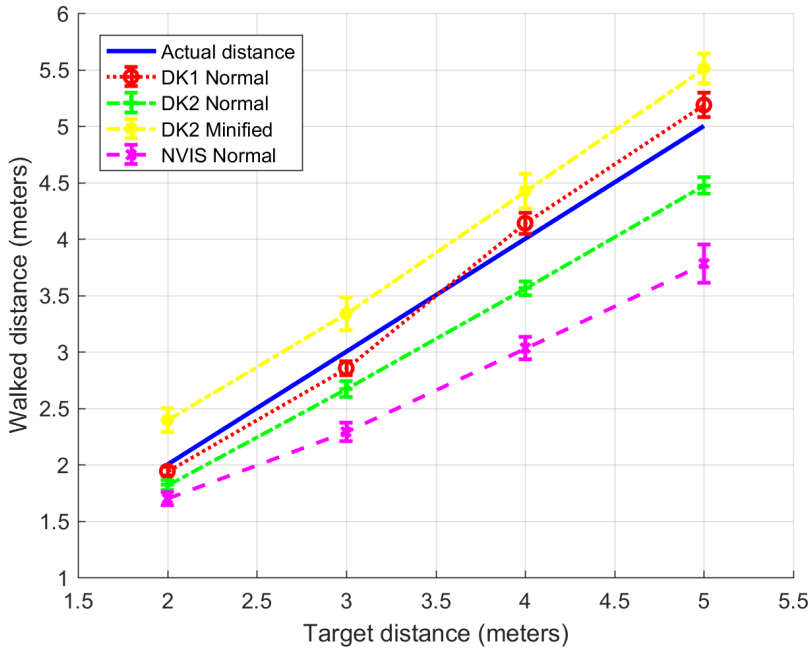

Figure 3.5: Results of distance judgments in DK2 HMD [22].

We recruited another 33 people for this experiment, 16 for the calibrated condition and 17 for the minified condition. The experiment setup and procedure are adapted from our previous research. More details can be found in Section 3.1.2. In addition, since in our previous experiments, people can't see their body in virtual environment through HMD, we put a collar around participants' neck to prevent them from seeing their body in the real-world space. Previous research has shown that the collar won't influence distance judgments in real world [5, 38, 41]. Figure 3.4 shows a participant wearing the simulated HMD and the collar.

3.2.3 Results and Discussion

The result for the DK2 experiment is shown in Figure 3.5. The green line represents the result of our previous research using the Oculus DK1 HMD, which is described in Section 3.1 of this document. The red line represents the result of distance judgments made through the DK2 HMD in a normal calibrated condition, and the purple line represents the result from the minified condition. Finally, the blue line represents the result of our previous research using a NVIS nVisor ST60 HMD [48]. We found that, unlike in the DK1 HMD, people significantly underestimate distances in a DK2 HMD in the normal calibrated condition. On average, participants judged distances at 89% of the actual distance. A 2 (condition) $\times$ 4 (distance) analysis of variance (ANOVA) showed a statistically significant difference between judged distances in DK1 and DK2 ($F(1, 27) = 15.15, p < 0.001$). However, the results are still significantly improved from what we commonly observed in many other research, including our previous research using the nVisor ST60 HMD.

In addition, we found that minification caused participants to overestimate distances. A 2 $\times$ 4 ANOVA showed a statistically significant difference between the calibrated condition and the minified condition ($F(1, 22) = 47.13, p < 0.001$). The result from the calibrated condition supports the hypothesis that the relatively high field of view

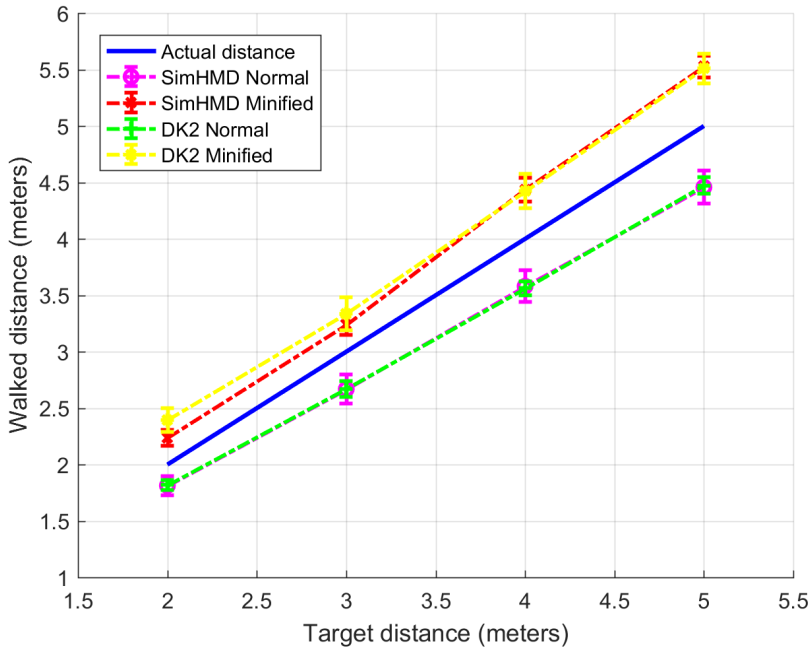

Figure 3.6: Results of distance judgments in the simulated HMD

of Oculus HMDs contributed to their high performance. As to the performance difference between DK1 and DK2, there are two possible explanations. First, since the high device field of view might be one of the main contributing factors to the high performance of Oculus HMDs, the lower field of view of DK2 might be the reason that caused distance underestimation in DK2. Second, yaw drifting of IMU may have natively impact our calibration in Experiment I, any unintentional miscalibration might also cause the performance difference between DK1 and DK2.

Figure 3.6 shows the result for the simulated HMD. The green line represents the result of distance judgment in simulated HMD without minification lenses. The blue line represents the result with minification lenses in front of each viewport. Surprisingly,

we found that people judged distances are almost the same in the simulated HMD and DK2 HMD in calibrated condition. This result again supported the hypothesis that the field of view influence distance judgments in virtual environment through HMDs, and the distance underestimation can be explained by its limited field of view. In addition, we found that minification made participants overestimated distances in the real-world space, and the degree of overestimation is similar to what we observed in virtual environment through DK2 HMD. A 2×4 ANOVA showed a statistically significant difference between the calibrated condition and the minified condition ($F(1, 29) = 26.99, p < 0.001$). This result suggests that the effects of minification on distance judgments are not unique to HMD-based virtual environment, it also has a similar impact on distance judgments in real world.

Chapter 4

Research: Effects of Field of View and Peripheral Stimulation

4.1 Experiment III: Artificially Reduced FOV and Peripheral Frames

Our previous research observed a performance difference between Oculus HMDs and an NVIS nVisor ST60 HMD. The research results prompted a new question: what caused the performance difference between Oculus HMDs and the NVIS HMD? There are many differences between Oculus HMDs and the NVIS HMD, including the weight,

size, display resolutions, and device field of view. Among all these properties, the device field of view interests us most. Historical research about the field of view's influence on distance judgments in HMDs yield no solid conclusion. Detailed information about previous research related to field of view influence and distance judgments can be found in Section 2.1.3. To deeply examine the influence of field of view on distance judgments in HMDs, we conducted a direct blind walking based experiment with artificially rendered peripheral frame. The frame cover the peripheral vision and reduce the FOV of the DK2 HMD. There are three different conditions, BlackFrame, WhiteFrame, and GreyFrame. We then compared the results to our Experiment II.

4.1.1 Method

In this experiment, we used the Oculus DK2 HMD to display virtual environment to participants. We used the orientation sensor of the DK2 HMD for participant's head orientation, and a WorldViz four camera PPT-H system for the head position. The experiment used the same direct blind walking method described in Section 2.1.1.2. The experiment was also designed to match Experiment II described in Section 3.2. We can compare the result to Experiment II and use that as a noFrame reference condition.

In the BlackFrame condition, participants judged distances in virtual environment

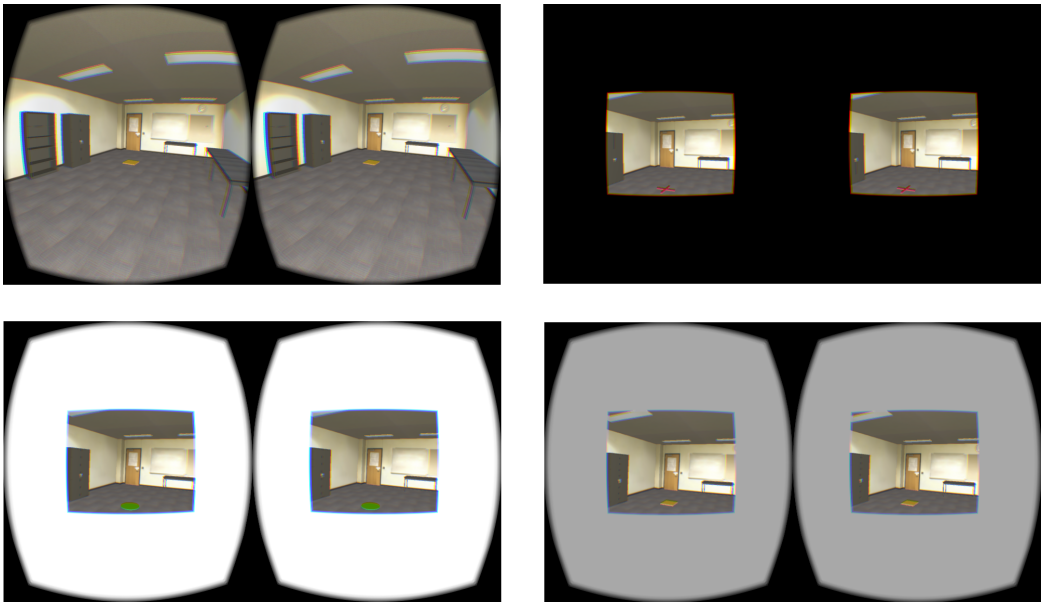

Figure 4.1: Screenshots for NoFrame condition, BlackFrame condition, WhiteFrame condition and GreyFrame condition

through DK2 HMD, where we rendered a black frame in front of each viewport inside the HMD. The black frame blocked participants' peripheral vision and artificially reduced the device field of view of the DK2 HMD (approximately 90° vertical) to match the field of view of the NVIS nVisor ST60 HMD (approximately 47° vertical) used in our previous research [48].

In the WhiteFrame condition, we changed the frame color from black to white to make the peripheral frame brighter (Figure 4.1). Research conducted by [10, 12] discovered that adding light to people's peripheral vision can actually improve distance judgments in HMDs, which supports the field of view hypothesis. Since large field of view HMDs can display images in people's peripheral vision, they make the periphery brighter.

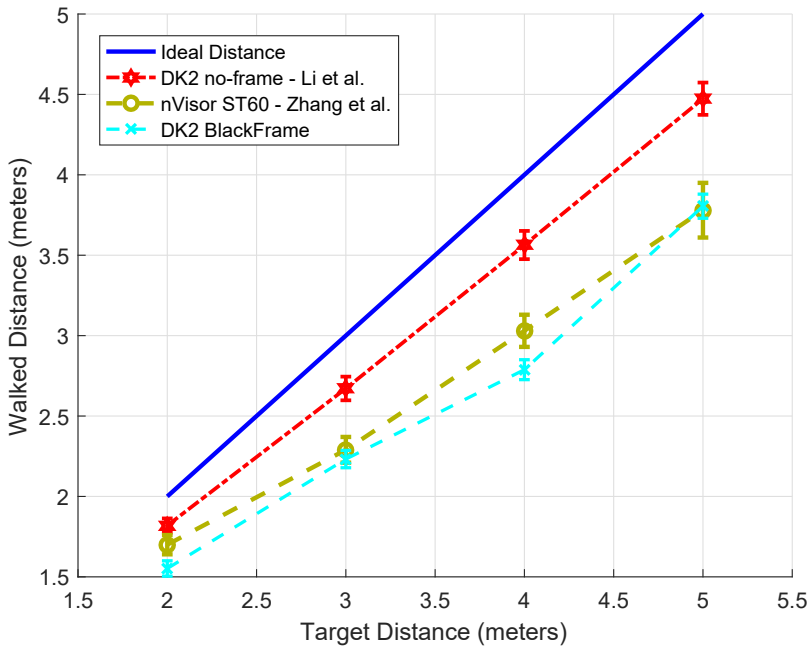

Figure 4.2: Result of the BlackFrame condition [20]

In the GreyFrame condition, we changed the frame color to a middle grey to examine the correlation between frame brightness and the peripheral effect. The relative luminance of the middle grey frame is 50% of the WhiteFrame. We accounted sRGB when rendering the middle-grey frame.

4.1.2 Results & Discussion

Figure 4.2 shows the result of the BlackFrame condition and WhiteFrame condition. The red line represents the DK2 HMD NoFrame result and the green line represents the previous result from Zhang et al. [48] using the NVIS HMD. Finally, the cyan line represents the result of the BlackFrame condition of this experiment. We found

that participants underestimated distances in DK2 HMD with the black frame. On average, participants judged distances at 74.5% of the actual target distances, which is significantly lower than what we observed in our previous experiment in the DK2 HMD under a calibrated condition without the frame [22]. The result is very similar to what was recorded in our previous research using the NVIS ST60 HMD. A 2 (condition) $\times$ 4 (distance) analysis of variance (ANOVA) showed a statistically significant difference between judged distances in the BlackFrame condition and NoFrame condition ($F(1, 24) = 28.54, p < 0.001$). This result shows that adding the black frame that blocks people's peripheral vision affects distance judgments in virtual environment through HMDs. The result supports the hypothesis that the device field of view could influence distance judgments in HMD-based virtual environments.

Figure 4.3 shows the result of the WhiteFrame frame condition. To our surprise, participants judged distances significantly better in the WhiteFrame condition than what we observed in the BlackFrame condition. On average, participants judged distance at 91.4% of the actual target distances, which is close to the 89% recorded in our NoFrame DK2 experiment described in Section 3.2. A 2 $\times$ 4 ANOVA showed a significant difference between the judged distance in the WhiteFrame condition and BlackFrame condition ($F(1, 24) = 42.6, p < 0.001$). One possible explanation is that even though the blocked peripheral vision did not provide any spatial information, making the peripheral frame brighter created a stimulation which led to more accurate distance judgments. The result confirms the findings of some previous research

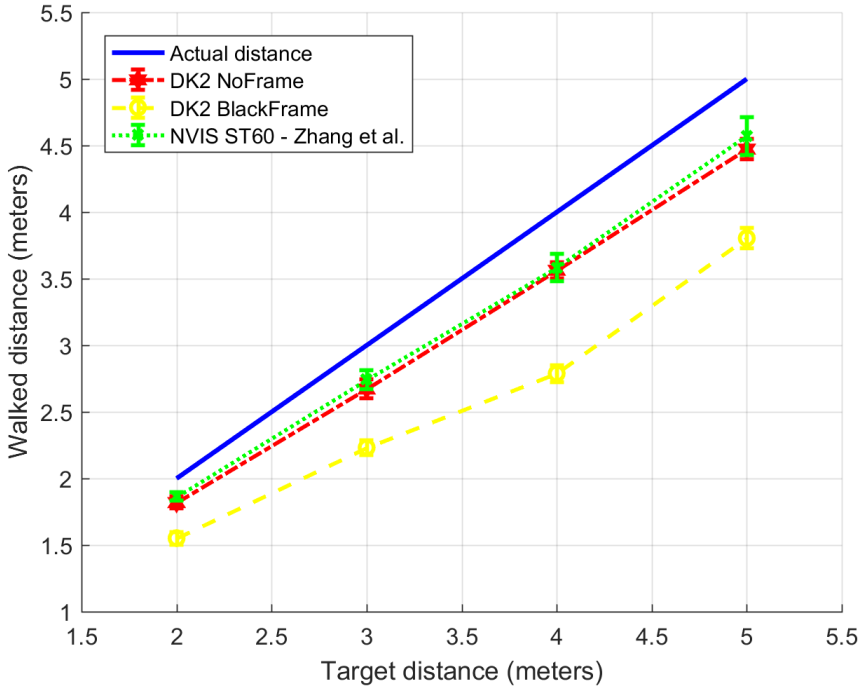

Figure 4.3: Result of the WhiteFrame condition [20]

conducted by Jones et al. [10, 12], which indicated that adding white LEDs around people's viewports inside the HMD improved distance judgments. More detail about the Jones study can be found in Section 2.1.3.

The result of the GreyFrame condition is shown in Figure 4.4. We found that the distance judgments made in the WhiteFrame condition were similar to those observed in WhiteFrame condition. A 2×4 ANOVA showed no significant difference between results in the GreyFrame condition and WhiteFrame condition ($F(1, 26) = 0.002, p > 0.1$). This result reconfirms the finding of our previous conditions, and suggests that the effect of this peripheral does not change proportionally to the frame brightness.

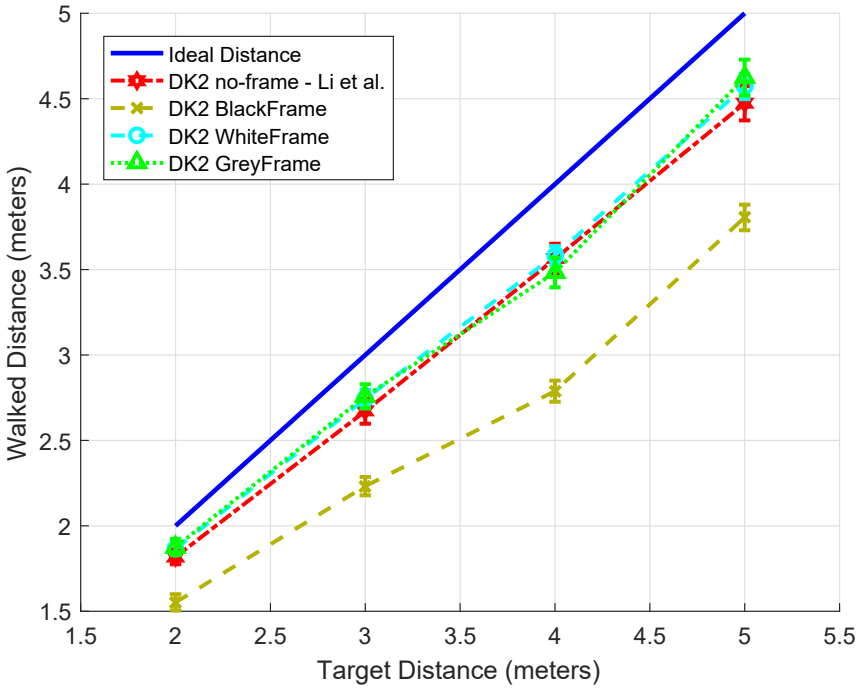

Figure 4.4: Result of the GreyFrame condition [20]

4.2 Experiment IV: Peripheral Frames with Various Brightness Levels

Our preliminary research found that adding a black frame in front of each viewport significantly decreased participants' judged distances (compared to the NoFrame experimental condition), and changing the frame color to a solid white or a middle grey eliminated this negative impact. One of the possible explanations is that, even though the white and grey frame didn't provide any spatial information, making the peripheral frame brighter created a stimulation that helped participants recalibrate

their eye position more accurately. Detailed information about the previous experiments can be found in Section 4.1. However, we also found no differences between GreyFrame condition and WhiteFrame condition, which implies that there is not a linear correlation between peripheral brightness and participants' distance judgments. The new question then becomes: How bright does the peripheral frame need to be to create this peripheral vision stimulation that improves distance judgments in HMDs? In our previous experiment, we tested a white frame, and a middle-grey frame that is exactly 50% of the brightness of the white frame. Thus, we decided to extend the previous experiments by conducting another direct-blind walking experiment to search the minimum effective frame brightness.

In this experiment, we examined how people judge distance through peripheral frames with different relative luminances (brightnesses). The goal is to measure how bright the peripheral frame needs to be, to trigger the peripheral stimulation effect and to deeply examine the relationship between the distance judgments and the peripheral frame brightness, using frames with different relative luminances. This information could be useful when designing peripheral displays and developing HMD-based applications with better perceptual performance.

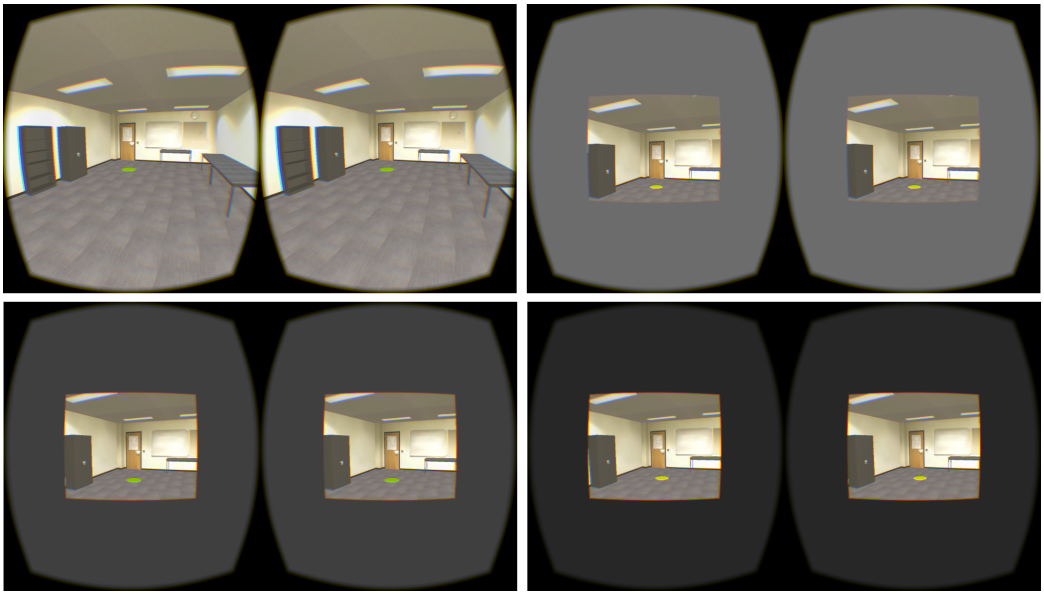

Figure 4.5: Imagery of virtual environments in different conditions. NoFrame condition (top left), 15% luminance peripheral frame (top right), 5% luminance peripheral frame (bottom left), 2% luminance peripheral frame (bottom right).

4.2.1 Method

In this experiment, we tested how participants judge distances in the virtual environment through an artificial peripheral frame with multiple brightness levels. The peripheral frame limited the FOV to a degree that matches the FOV of an NVIS nVisor ST 60 HMD (47×40 degrees in the horizontal and vertical respectively). Our previous work tested the distance judgments with frame set to 0%, 100%, and 50% of the screen relative luminance, and the hypothesis is that there exists a threshold or minimum brightness level that might trigger or help create the stimulation effect, which enables people to recalibrate their position in the virtual environment. In this

experiment, we tested three different experimental conditions, where frame brightness was set to 15%, 5% and 2% of the relative luminance. We also accounted sRGB gamma correction, as Oculus DK2 uses sRGB. For instance, to achieve a 50% relative luminance, the color displayed on the screen is (186, 186, 186) instead of (128, 128, 128). The size of the peripheral frame matched the frame used in previous experiment described in Section 4.1. Based on result of previous experiments, we decided to start the experiment with the peripheral frame set to 15% luminance, which was reasonably darker than the previous middle-grey (50% luminance) frame used in Section 4.1. Then based on the result of the current condition, we picked the next condition to be 5% luminance, and finally we decided to set the frame to 2% luminance. Figure 4.5 shows the virtual environments in different experimental conditions in Experiment I.

We recruited 42 participants for this experiment (14 for each condition). All participants came from a university subject pool, ages 18 to 26. Each participant was shown one of the three experimental conditions, and was either granted course credit or paid $10 for participation. Before the experiments, we used a stereopsis test, which involves identifying a random dot stereogram on a paper, to make sure that our participants were not stereoblind.

In this experiment, we used the same Oculus DK2 HMD as the previous experiment. We also will use a Vicon T20S 12-camera tracking system to capture participants' head position, and the high-speed inertial measurement unit (IMU) for their head

orientation. We also applied a yaw correction based on the Vicon orientation data to fix any yaw-drifting problem which might occur during the experiment.

The experiment procedure strictly followed that of the previous experiments that used the same direct-blind walking method. Detailed information about the procedure can be found in Section 3.1.2. Besides changing to a different position tracking system, the only experimental difference was the brightness of the frames.

4.2.2 Results & Discussion

As shown in Figure 4.6 and Figure 4.7, participants judged distances significantly better in the 15% brightness frame than in the 5% and 2% brightness frames. On average, participants walked to 92.6% of the actual target distances with the 15% brightness peripheral frame in a calibrated condition through an Oculus DK2 HMD. This result is similar to the result observed in our previous experiments using a solid white peripheral frame (Section 4.1). An analysis of variance (ANOVA) showed no significant difference between distance judgments measured in the 15% condition and the WhiteFrame (100%) condition described in Section 4.1 ($F(1,26)=0.104$, $p > 0.05$). This result shows that the peripheral stimulation effect does not change due to the brightness drop from 100% to 15%, which reconfirms, that the peripheral frame brightness and the judged distance are not linearly correlated. More importantly, a

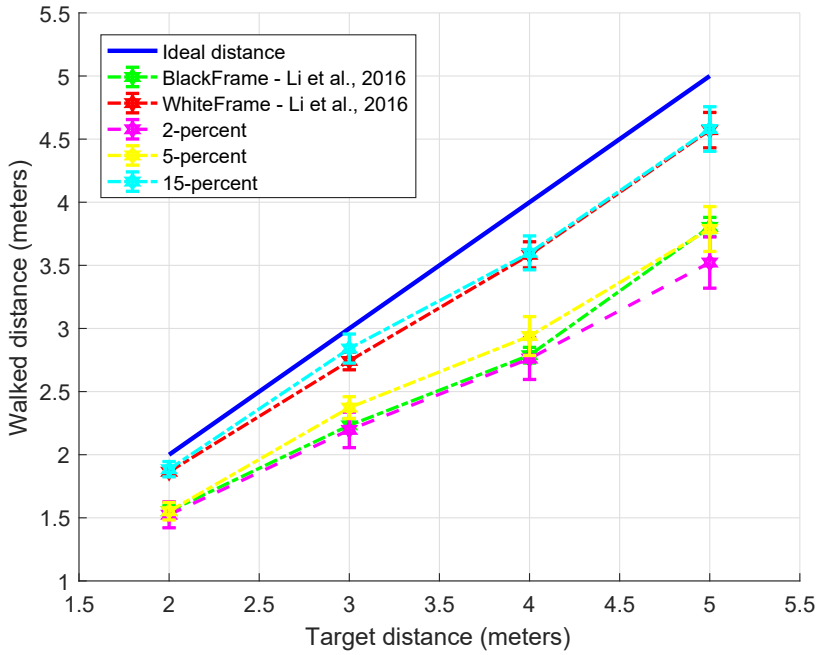

Figure 4.6: Participants' walked distances in different frame conditions. Note: results for BlackFrame (0%) and WhiteFrame (100%) conditions are from previous experiments described in Section 4.1

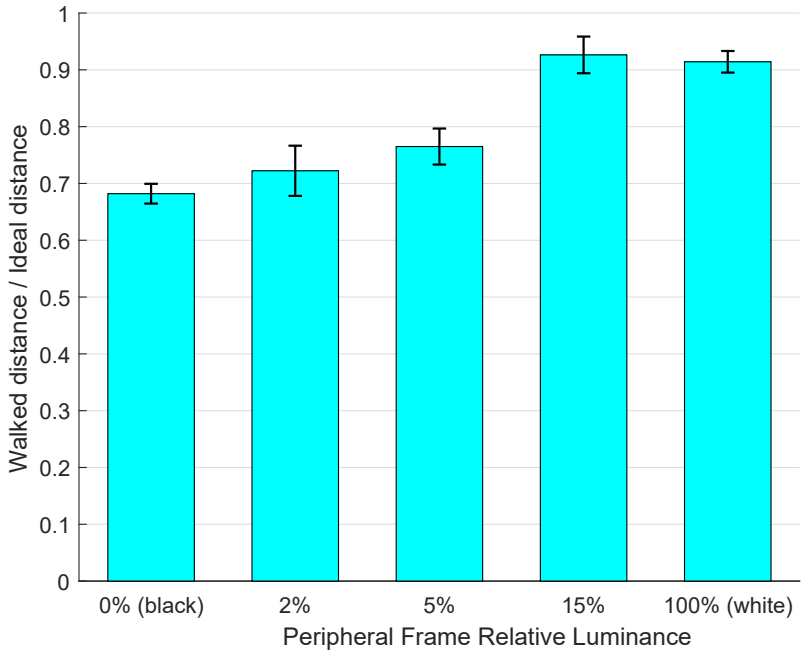

Figure 4.7: Average walked distance in different frame conditions.

significant distance underestimation was observed in both 5% and 2% conditions. On average, participants walked to 76.5% and 72.2% of the actual distances in the 5% and 2% brightness conditions, which matches the result of previous experiments conducted using a black peripheral frame (Section 4.1). A one-way ANOVA with the peripheral-frame brightness as a between-subject factor found a significant interaction between frame brightness and distance judgments (F(2,39)=6.68, $p < 0.001$). A post-hoc test using Tukey's Honestly Significant Difference (HSD) showed a significant difference between judgments made in 15% condition and 5% condition $p < 0.5$, and no significant difference was found between 5% and 2% conditions. The result confirms the existence of a threshold on peripheral frame brightness between 5% and 15% of the relative luminance, which triggers the peripheral stimulation that enables better distance perception. These results confirm the existence of a minimum brightness level that triggers the peripheral stimulation effect. The effect could significantly improve distance judgments in HMDs.

4.3 Experiment V: Peripheral Frames with Image Pixelation

Our earlier experiments found that rendering a black frame inside each viewport, which reduce the device field of view of an Oculus DK2 HMD to approximately 60°

diagonally, significantly decreased participants' judged distances. Furthermore, we found that making the peripheral frame look brighter created a peripheral stimulation, which significantly improved distance judgments. Experiment II & III (Section 4.1 and Section 4.2) focused on the peripheral stimulation effect that is triggered by a bright peripheral frame and grey-scale frames, such as white, black and gray. However, in real applications, peripheral vision may be augmented by adding peripheral displays or decorated specifically to match different virtual environments. For example, a secondary low resolution could be added to a HMD. Previous work by [46] showed that such peripheral displays can enhance situational awareness and reduce motion sickness.

In this experiment, instead of using a solid color, we applied a pixelation effect to the peripheral area that was originally covered by the frames in previous conditions. The resulting image had much larger pixel size in the peripheral-vision area, and a normal image in center area. This effectively simulated the effect of adding a low-resolution peripheral display inside a low-FOV HMD. Figure 4.8 demonstrates the imagery of the peripheral-pixelated frame used in this experiment. We then conducted another direct-blind walking experiment using the same Oculus DK2 HMD. The main goal of Experiment V is to further examine the peripheral stimulation effect, and to examine the influence of a secondary peripheral display on distance judgments in HMD-based virtual environments.

Foveated rendering, which selectively renders different part of the image with different quality level based on where people's eyes are staring at, is expected to lower computational cost [37] of HMD rendering. The resulted image will have better quality at the foveal area, and lower quality in peripheral area, which is similar to the image used in this experiment. Although we are not doing eye tracking and foveated rendering in this experiment, we hoped the result of this experiment can also provide some baseline information about the potential influence of foveated rendering on spatial perception.

4.3.1 Method

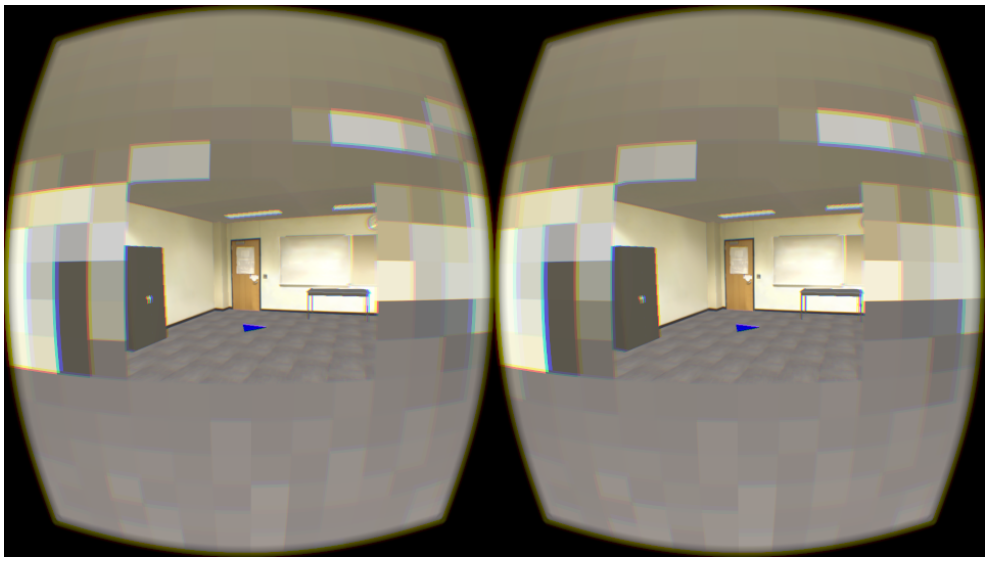

Figure 4.8: Imagery of virtual environment with pixelated peripheral frame.

We recruited 14 participants from the same university subject pool. Participants were

shown the same virtual classroom environment using the Oculus DK2. Then, we examined how participants judge distances with a peripheral-pixelated frame, measured by the same direct-blind walking method. We used a pre-rendering technique to apply a pixelation effect to the peripheral-vision area that was covered in peripheral frames in previous experiments. The size of the enlarged pixel in the peripheral vision was made of 82×85 of the normal pixel. The actual peripheral-pixel size may look different on the screen, due to pincushion distortion, as shown in Figure 4.8.

The experiment procedure will be strictly follow that of the previous experiments that used the same direct-blind walking method. Detailed information about the procedure can be found in Section 4.2.1.

4.3.2 Results & Discussion

As shown in Figure 4.9 and Figure 4.10, participants judged distances much better in the pixelated condition, compared to the result found in the BlackFrame condition in previous experiment (Section 4.1). The result was very similar to those found in the WhiteFrame condition and NoFrame condition in previous experiment (Section 3.2). On average, participants walked to 90.14% of the actual target distances. A one-way ANOVA showed a significant difference between distance judgments in the peripheral-pixelated condition and the black condition in our previous work ($F(1,26)=27.21$, $p <$

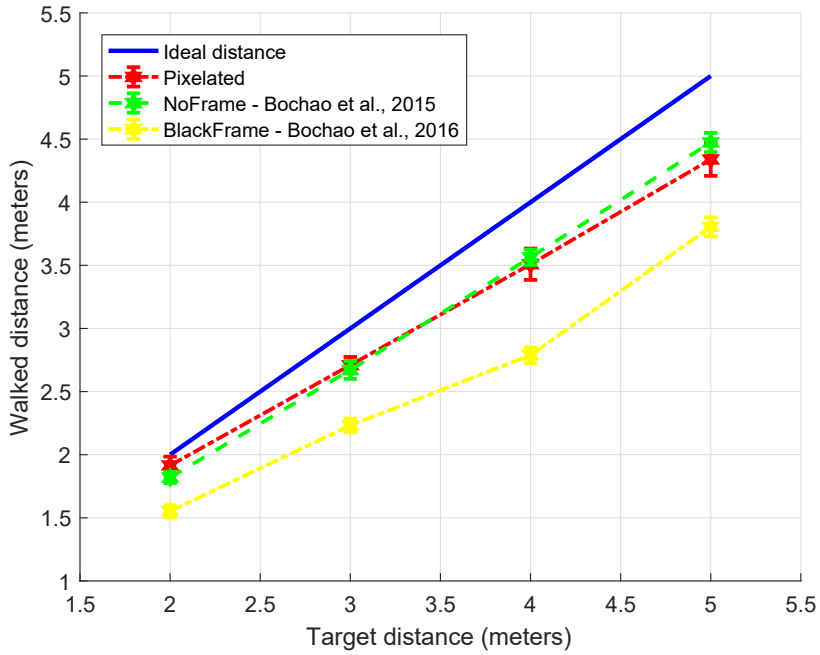

Figure 4.9: Participants' walked distances in different frame conditions. Note: results for BlackFrame (0%) and WhiteFrame (100%) conditions are from previous experiments described in Section 4.1

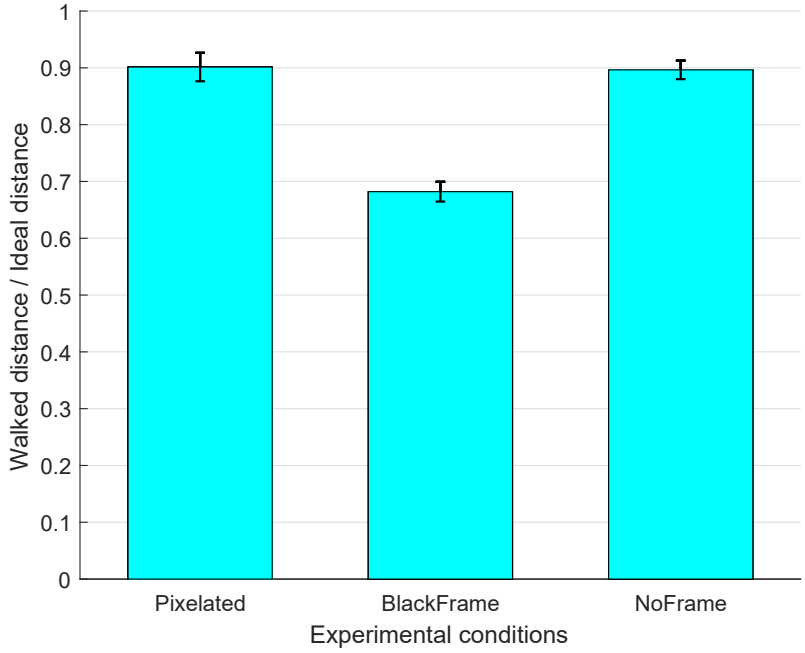

Figure 4.10: Average walked distance in different frame conditions

0.001). Another ANOVA found no differences between judgments made in peripheral-pixelated condition and previous WhiteFrame condition (F(1,26)=0.167, $p > 0.05$). The result indicates that, besides adding light-bars or peripheral frames with solid colors, the peripheral stimulation effect can also be triggered by a peripheral-pixelated frame. In this condition, the peripheral-vision area provided more spatial information, including object colors and depth cues. However, we found that the effect was similar to the WhiteFrame condition. These results suggest that adding a low-resolution peripheral display in a low-FOV HMD may improve distance judgments in HMDs.

4.4 Experiment VI: Peripheral-Frame Shapes and Sizes

In all of our previous experiments, our frames were rectangular. The frames were also all the same size so that they matched that of the NVIS HMD. However, in some situations, the frame could be a different shape or size. For example, an HMD manufacturer might want to provide a larger field of view with a rectangular black frame. Does changing the size of the black frame change people's distance judgments? To answer this question, we conducted another experiment which aimed to examine the influence frame size on distance judgments in HMDs.

We were also interested in how the frame shape might influence distance judgments. For example, we can maintain the same horizontal and vertical field of view with an oval frame and compare it to a rectangular frame. Thus, we can measure how frame shape influences distance judgments with minimal changes to field of view.

Our preliminary research has discovered that adding a bright peripheral frame could help participants judge distance more accurately. In the previous experiment (Section 4.1 and Section 4.2), we conduct a series of experiments to examine how does the brightness of the periphery might influence distance judgments in HMDs, and whether the peripheral low-resolution display could improve distance judgments in virtual environment through HMDs. In this section, we describe another experiment, which aimed to examine the influence of shapes and sizes of the peripheral frame on distance judgments in HMDs.

HMDs using different display technologies or lenses can often result in a different image experience. For example, Oculus HMDs are different from the NVIS HMDs. Because of different display mechanisms, Oculus HMDs provide a round-image experience, while the NVIS HMD provides a rectangular image experience. Thus, it is worthwhile to examine the influence of frame size and shape in HMDs on distance perception.

Currently, HMD manufactures and developers are aiming at creating devices with better specifications, such as decreasing the size and weight of the device, increasing

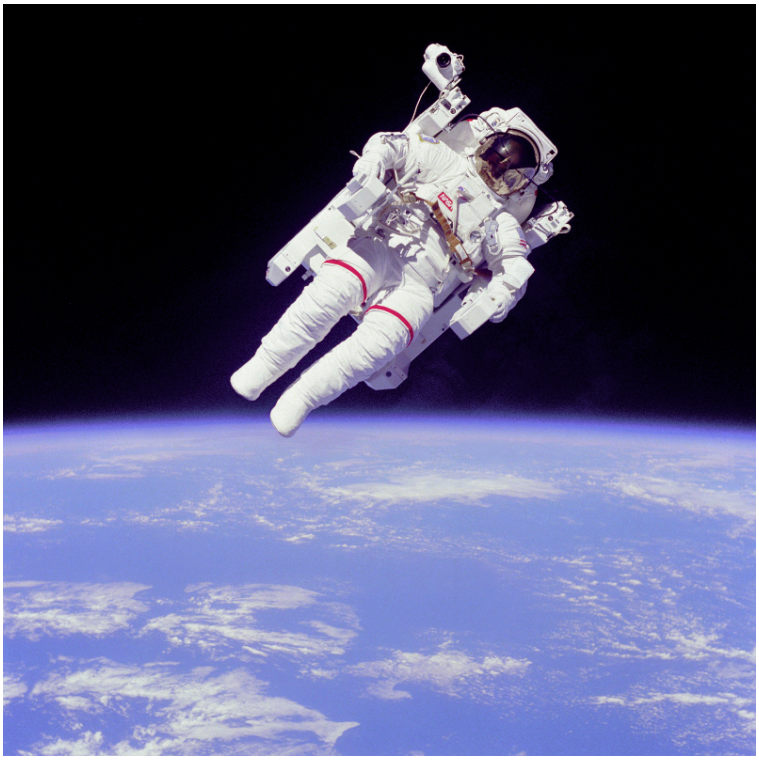

Figure 4.11: A space suit. This image is in courtesy of: https://en.wikipedia.org/wiki/Manned Maneuvering Unit/media/File:Astronaut-EVA in the Public Domain.

the display resolution, and minimizing the sensory delay and the device field of view. As the images provided by HMDs are becoming more and more realistic, users still must feel the physical presence of the HMD device by either feeling the weight of the HMD on their heads or the contacts between their skins and the HMD. This sensory conflict can greatly impact users experience in many HMD-based applications.

For instance, if we want to create an Astronaut Simulator, we can let the users to perceive the HMD as a part of the space-suit helmet (Figure 4.11) what they wear in the virtual environment by rendering a frame with well-designed texture, shape and size in user's peripheral vision. By doing this, the users will not only feel the

Figure 4.12: Pilot goggles (left); snorkel mask (right). This picture is courtesy of https://pixabay.com/en/photos/goggle/ in the Public Domain.

HMD, but also see that they are wearing something similar, which may help resolve the sensory conflict. Another example is that, if we want to create a virtual deep-water diving system, we can then design the peripheral frame or display as part of a swimming goggle or diving helmet 4.12.

In many situations, adding a peripheral frame or secondary display, will result in an altering of users' experience in the virtual environment through HMDs. To make use of the peripheral simulation, it will be useful if we can design the size and the shape of the peripheral frame or secondary display based on the needs of the applications. The question then becomes: how does different characteristics of the peripheral frame influence distance judgments in HMD-based virtual environments?

4.4.1 Method

We recruited 28 participants for this experiment, 14 for each condition. Each participant was shown either the LargerFrame condition or OvalFrame condition, and

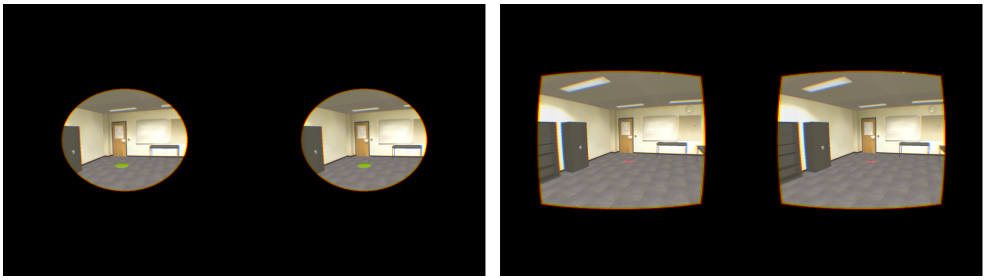

Figure 4.13: Imagery of virtual environment with circular peripheral frame on the left, and increased-FOV on the right.

performed 17 blind-walking tasks. We used two types of peripheral frames, which were similar to the FOV-restricting peripheral frame described in Section 4.1. In the first condition, we increased the size of the peripheral frame from the original frame described in Section 4.1 to approximately 75°. In the second condition, we changed the frame shape to oval while maintaining the same maximum horizontal and vertical FOVs as original frame. We used the same direct-blind walking method to measure participants' distance judgments, which involves letting participants blindly walk to a previously observed target on the floor. Detailed information about direct blind walking can be in Section 2.1.1.2. We also used the same Oculus DK2 HMD to provide participants with a 3D stereo image.

4.4.2 Results & Discussion

As shown in Figure 4.14 and Figure 4.15, participants judged distance significantly better in the LargerFrame condition relative to the result found in the BlackFrame condition by Li et al. [20]. On average, participants walked to 86.7% of the actual

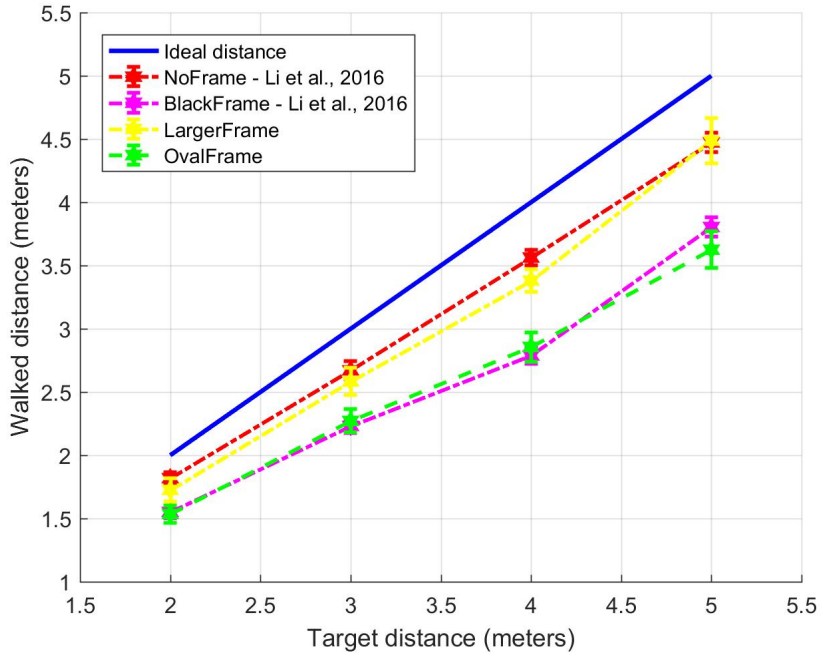

Figure 4.14: Participants' walked distances in different frame conditions. Note: results for BlackFrame (0%) and WhiteFrame (100%) conditions are from previous experiments described in Section 4.1

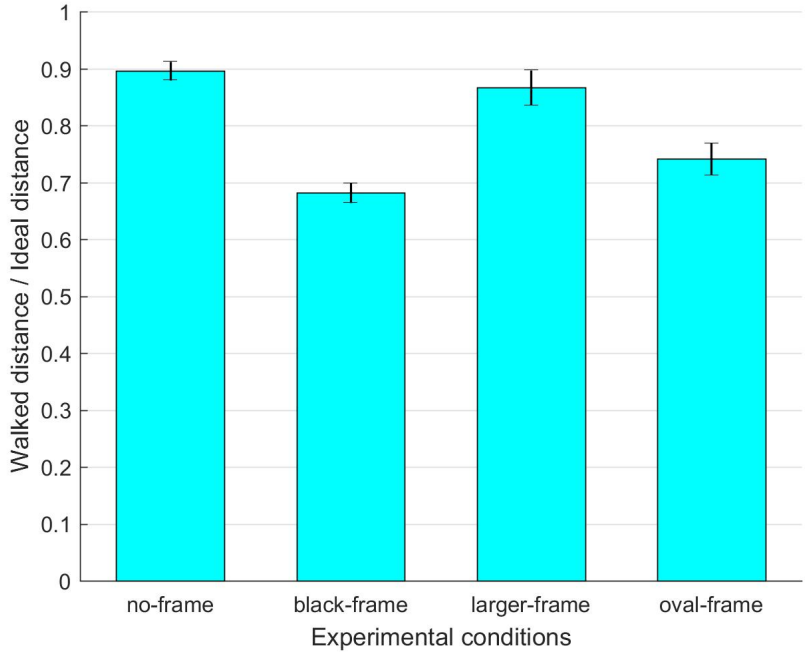

Figure 4.15: Average walked distance in different frame conditions

target distances, which is similar to the result found by our previous experiment with no peripheral frame [22]. Two one-way ANOVAs showed a significant difference between distance judgments made in the LargerFrame condition and the BlackFrame condition (F(1,26)=12.28, $p < 0.01$), and no difference between the LargerFrame condition and the NoF rame condition (F(1,25)=0.691, $p = 0.414$). Furthermore, we found that people significantly underestimated distances in the OvalFrame condition, with an average accuracy of 74.1%, and we found no difference between results of the OvalFrame condition and the BlackFrame condition (F(1,26)=0.011, $p = 0.917$).

The results for the LargerFrame condition provide a strong support to the hypothesis that the FOV could significantly influence distance judgments in HMDs. The results for the OvalFrame condition suggest that the shape of the image does not significantly influence how people judge distances in HMDs. Therefore, the performance difference found between the Oculus HMDs and the NVIS HMD is more likely to be caused by the change of FOV.

Chapter 5

Discussion & Conclusion

In this work, we conducted six experiments which focus on long-standing problems related to distance perception in HMDs. The first two experiments were focusing on collecting baseline information about distance judgments in Oculus HMDs using a direct-blind walking method.

Experiment III to V were aimed to provide information about the influence of FOV and peripheral vision on distance judgments, using artificial peripheral frames. The results suggest that people may judge distances accurately in wide-FOV HMDs and adding light in peripheral vision may improve distance judgments in small-FOV HMDs. This result is surprising because real-world studies which restrict FOV do not typically exhibit distance compression unless the field of view is exceptionally

small.

One possible explanation is that people may use the closest visible part of the ground or ceiling as a strong reference for their own position. However, the peripheral frame covers part of the ceiling and floor that is closest to the viewer. The frame brightness may change how people interpret the peripheral frame. A dark frame perhaps reduces awareness of the frame and makes participants think there is less floor between them and the target and thus judged the target as being closer to them. A bright peripheral frame might make people recognize that it is covering part of the ground or ceiling. Even if people can't see enough of the floor or ceiling, they may use the edge of the visible frame as a reference of where the ground plane or ceiling should be and adjust their judgments accordingly.

At last, Experiment VI shows that increasing the FOV can significantly improve distance judgments, which can be a potential solution to distance compression in HMDs. As new devices are developed which have larger fields of view, the distance compression problem may be reduced or perhaps eliminated. However, there are also other potential solutions which do not require hardware improvements. One solution is geometric minification which renders the image with an increased rendering field of view. Minification was showed to be able to increase the judged distances in both virtual and real-world environments [18, 21, 48]. Another solution is adaptation, which improves users' performance overtime by providing feedback based on their judgments.

Table 5.1
Summary of all experiments with different devices and conditions.

Experiment	Device	Condition	Walked Dist.
Experiment I	Oculus DK1	Calibrated	99.8%
		Minified	111.4%
Experiment II	Oculus DK2	Calibrated	89.6%
	SimHMD	Calibrated	90.4%
Experiment III & IV	Oculus DK2	0% (Black)	74.5%
	Oculus DK2	2%	72.2%
	Oculus DK2	5%	76.5%
	Oculus DK2	15%	92.6%
	Oculus DK2	50%	90.3%
	Oculus DK2	100% (White)	91.4%
Experiment V	Oculus DK2	Pixelated	90.1%
Experiment VI	Oculus DK2	Enlarged FOV	86.7%
	Oculus DK2	OvalFrame	74.1%

With technological improvements, these techniques might be less useful in the future.

5.1 Summary of Experiments

Table 5.1 gives a brief summary of all the experiments included in this research. In Experiment I, we examined how people judge distances using a direct-blind walking in virtual environments through an Oculus DK1 HMD, and found that people judged distances much more accurately than what we saw in a previous study using NVIS nVisor ST60 HMD which has a smaller field view. This result surprised us as it contradicts with many previous studies that suggest distance perception was significantly compressed in HMDs. We suspect that the wide device-FOV of the DK1 HMD might be an important contributing factor to this performance difference. In Experiment II,

we first conducted another experiment that was identical to Experiment I, but using a newer Oculus DK2 HMD. The result showed that people also judged distances much more accurately in the DK2 HMD than in the NVIS HMD, which re-confirmed the result of Experiment I.

To examine the influence of FOV, we repeated the same experiment using a simulated HMD which created a FOV-restricted experience like wearing an DK2 HMD. We found that people significantly underestimated distances in the simulated HMD, which suggested that the limited-FOV might influence distance judgments in real-world environment. The result also supported the hypothesis that the device FOV can influence distance judgments in HMDs. The later four experiments were focusing on examining the influence of device FOV and a peripheral stimulation effect found by Jone et al. [10, 12]. In Experiment III, we found that bright peripheral frames around viewport can improve distance judgments, which re-confirms the peripheral stimulation effect. In Experiment IV, we examined the interaction between the peripheral-frame brightness and the peripheral stimulation effects by using peripheral frames with varying brightness levels, and found that there is a threshold on the frame brightness which triggers the peripheral stimulation effect. In Experiment V, we examined the influence of changing the peripheral frame to a peripheral-pixelation effect, and found that the peripheral-pixelated frame also helped distance judgments like solid-color peripheral frames. In Experiment VI, we examined the influence of different shapes and sizes of the peripheral frame on distance judgments. The result

shows that people judged distances much better with an enlarged black peripheral frame and no influence found when changing the frame shape to oval. Based on the results of the preceding experiments, we reached five main conclusions:

- † Distance judgments made in wide-FOV HMDs, such as Oculus DK1 and DK2, are much less compressed compared to low-FOV HMDs, such as the NVIS ST HMDs.

- † Human peripheral vision can be utilized to improve distance judgments in HMDs by adding light to the periphery.

- † There exists threshold for peripheral-frame brightness between 5% and 15% relative luminance where distance judgments change from being compressed to becoming more accurate.

- † Adding a peripheral-pixelated frame significantly improved distance judgments in HMDs compared to the black frame condition. This suggests that adding a secondary peripheral display can help participants judge distances more accurately in HMDs.

- † The shape of the frame does not influence distance judgments in HMDs. The FOV restriction, such as that found in older HMDs like the NVIS nVisor ST60, is a more likely cause for distance underestimation.

5.2 Future Work

All of our experiments used the direct-blind walking method. It would be worthwhile to re-confirm this peripheral stimulation effect using different methods, such as triangulated walking or verbal reports. In addition, there is some speculation the peripheral stimulation influences distance judgments by causing a change on perceived scale of the virtual environments [10] or a change on perceived viewing position. More research is needed to understand the theories behind this effect. Lastly, our experiments used peripheral frames rendered graphically. It would be interesting to examine the peripheral stimulation effect using physically augmented peripheral displays, as described by Xiao et al. [46].

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Appendix A

Analysis of Variance (ANOVA)

In this document, we used two ways of running ANOVA tests. For the first three experiments, we used a mixed design. We set the condition as a between subject variable, as each participant is only assigned to one viewing condition. We also repeated the measurements for each target distances three times for each participant. A sample data is shown Table A.1.

Then, we use R to create a 2×4 ANOVA to test statistical difference between different conditions. The exact R commands are shown below. The DistWalked is the dependent variable. It depends on the TargetDist that is within-subjects variable, and Environment that is a between-subjects variable. A sample of the result from the ANOVA test is shown in Figure A.1.

Table A.1
Sample data used for 2 × 4 ANOVA.

Environment	TargetDist	Subject	DistWalked
env0	dist2	subj1	1.911840
env0	dist3	subj1	3.244472
env0	dist4	subj1	4.484748
env0	dist5	subj1	5.323795
...	...	...	...
env1	dist2	subj18	1.856603
env1	dist3	subj18	2.567321
env1	dist4	subj18	3.650291
env1	dist5	subj18	4.442818

```
my_aov = aov(DistWalked~TargetDist*Environment+Error(Subject
          /TargetDist)+(Environment), data=Rdata)
```

```
o  Error: Subject
           o  Df Sum Sq Mean Sq F value   Pr(>F)
o  Environment  1  9.563   9.563   27.93 2.03e-05 ***
o  Residuals   24  8.219   0.342
o  ---
o  Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

o  Error: Subject:TargetDist
                      o  Df Sum Sq Mean Sq F value   Pr(>F)
o  TargetDist              3  87.78  29.260 805.615  < 2e-16 ***
o  TargetDist:Environment  3   1.00   0.334   9.195 3.16e-05 ***
o  Residuals              72   2.62   0.036
o  ---
o  Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure A.1: Results from ANOVA test

For the last three experiments, we used another way of ANOVA test. The reason we changed to another method is that, for the last three experiments, we were focusing on analyzing the peripheral stimulation effect. It made more sense to normalize all measurements on different target distances for each participant. Thus, the data for each participant was a single value in the range 0 1, which indicate the general

Table A.2
Sample data used for one-way ANOVA.

Environment	Accuracy
env0	0.89
...	...
env1	0.75
...	...
env2	0.82
...	...

accuracy of the participant. A sample data is shown in Table A.2

A one-way ANOVA with Environment as a between-subject variable was used to test the statistical significance of examined environmental factor, such as the frame brightness. If ANOVA test find a statistically significant influence, a post-hoc analysis using Tukeys Honestly Significant Difference (HSD) was used to examined differences between pair-wise conditions. The R command used in this test is shown below.

```
my_aov = aov(Accuracy~Environment, data=Rdata)

summary(my_aov)

TukeyHSD(my_aov)
```

Appendix B

Results Plotting

To shows the result of each experiment, we use MATLAB to plot a linear graph. Figure xx shows an example of the graph. The x-axis represents target distances, and the y-axis shows the walked distances. There are four data points in the graph, which shows average walked distances for target distances of 2, 3, 4, 5 meters. At each data point, we also draw a vertical bar, which represents the standard error of the walked distances from all participants for the same condition. The equation for calculating the standard error is shown below, where the σ is the standard deviation of the population, and n is the number of samples.

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

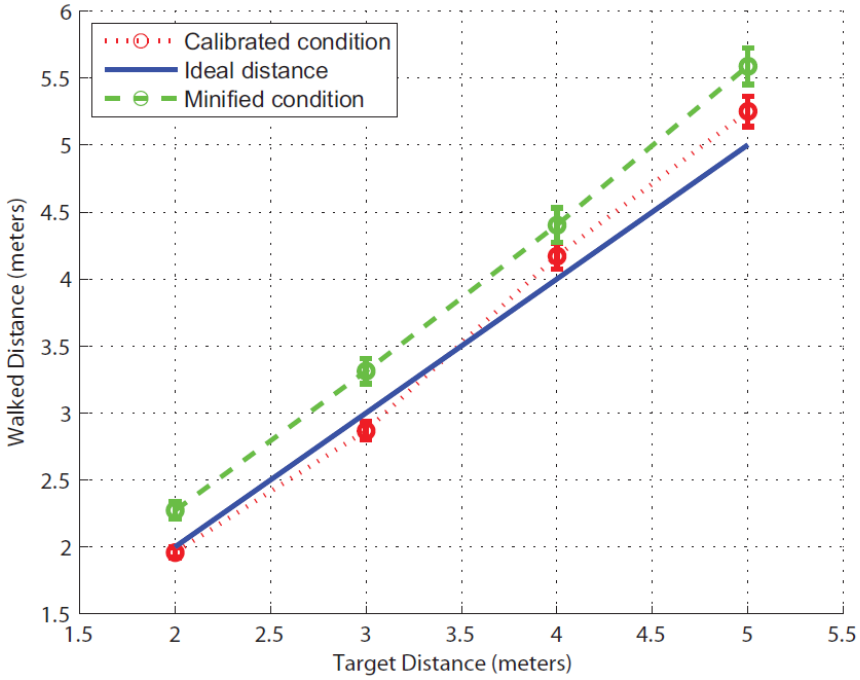

Figure B.1: Sample for the result plotting