이학석사 학위논문

Influence of Eye Position and Binocular Information on Torsion Control

안구 비틀림 제어에 관한 양안간 안구 위치와 양안 정보

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Abstract

Visual discomfort caused by visual distortion is a persistent issue facing Virtual Reality technology, illustrating the need for research into 3-dimensional eye movement. In this study, 3-dimensional eye movement is investigated to help understand oculomotor movement. Listing's law describes how the six muscles controlling the eye move in a horizontal, vertical and torsional direction to allow the eyeball to gaze in any direction. Through a controlled experiment, torsional movement was measured in three conditions: 1) comparing the eye's torsional movement in monocular vision compared to binocular vision 2) the effect of vergence on the eye's torsion, 3) the location of primary position, which is a reference position for eye movements when the head is fixed without the rotation of eyes.

Results suggest that 1) torsional amount between the monocular condition vision and the binocular condition vision do not show any significant differences 2) the effect of vergence in the eye conditions do not show any significant differences;

however, when the effect was compared within the left and the right side of each condition, the effect of vergence on the left eye was significant while the right was not significant. 3) the primary position is shifted in the downward direction from what is known in Listing's law.

Keyword : 3-dimensional eye movement, torsion control, Listing's law, primary position, virtual reality, user experience

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1. Introduction

In recent years the interest in the eye movements has increased as it can be implemented in many fields such as virtual reality (VR), advertising industry, medical fields and many more (Tanriverdi and Jacob, 2000; Lohse, 1997; Gallagher et al., 2005). The rising interest in the technology, especially in VR has revealed the importance of understanding eye movements to a further extent. As technology advances, the development of VR became the trend in the era of the Fourth Industrial Revolution. VR, which provides “a computer generated display that allows or compels the user (or users) to have a sense of being present in an environment other than the one they are actually in” attracted people immediately (Schroeder, 1996). However, soon after experiencing VR, people reported feeling discomfort and the technology struggled to attract users. Through many studies, it was found that one of the main reasons for this discomfort stems from the difference between the eye’s movements in the natural world in comparison to the virtual world (Koulieris et al., 2017; Howarth, 1999; Peli, 1995).

When experiencing VR, a device called a Head Mounted

Device (HMD) is widely used. Allowing for full body mobility, the HMD presents a real time interactive display in 3-dimension. The rendered images projected on HMDs trigger the human-visual system to perceive and to interact with the virtual world. Therefore, the importance of addressing visual and anatomical properties of the human-visual system in HMDs becomes crucial to help mitigate feelings of discomfort such as vertigo, eye strain, blurred vision and many more when experiencing VR (Rolland and Hua, 2005).

Many problems arise when trying to emulate visual information within a VR headset while being compatible with how human visual-systems perceive the natural world. One of these factors includes how humans have a pair of eyes in which each eye perceives images of the world from slightly different angles. This distance between the two eyes is referred to as the interpupillary distance (IPD)(Koulieris et al., 2017). The binocular fusion system processes these two images into a single stereoscopic image which facilitates depth perception along with several other cues such as texture gradient, shading, and occlusion (Bajcsy and Lieberman, 1976; Howard and Rogers, 1996; Otero Millan, 2014; Enright, 1990). In order for HMDs to use computerized 2-dimensional images to generate 3-dimensional images, two separate images are projected which are divided by the amount of a person's IPD. Although recent HMDs have adjustable IPDs to alleviate the issue of feeling disoriented, the realistic differences between the two eyes and the displays are yet to be accurately reflected as the image rendering procedure considers only the shifting identical images to each left and the right display screens. There are several key factors that needs to be addressed to resolve the discrepancy. The relative disparity cues such as texture, blurring effect, and the sizes of objects play crucial roles when it comes to accurately perceiving the depth and the distance between objects (Collewijn et al., 1991). The feeling of discomfort rises when the images with a limited number of pixels are stretched over a wide field of view (FOV) as bringing different texture of the real world inside the HMDs_(Rolland and Hua, 2005; Meng et al., 2006). In addition, the images in HMDs are displayed in a consistent texture which in reality the center of vision and the peripheral vision is textured differently. The human-visual system works where only the center of vision is in focus while the rest of vision is blurred to process visual information (Mercier et al., 2017). Furthermore, the sizes of objects need to be correctly calculated to accommodate the real distance between objects.

In addition, as the distance between the eyes and the display screens are approximately 50 mm, the synchronized systematic mechanism of accommodation and vergence is disrupted, which leads to feelings of sickness (Hoffman et al., 2008; Shibata et al., 2011). Accommodation is an act of bringing objects into focus by controlling the crystalline lens, while vergence is the act of moving both eyes inwardly or outwardly depending on the distance of the object. These are tightly linked and work synchronously as changes in accommodation will cause changes in vergence. This cross-link interaction is called AC/A ratio, which describes the changes in vergence due to accommodation to the changes in accommodation when the retinal disparity is absent (Lambooji et al., 2009; Rolland and Hua, 2005). In the case of experiencing VR through HMDs, the AC/A ratio is disrupted, which eventually causes discomfort. In natural viewing conditions, the focal and vergence distances are cross-linked (figure 1a); however, when viewing with the HMD, the focal distance is blocked by the display screen while the vergence distance is set beyond the screen (figure 1b).

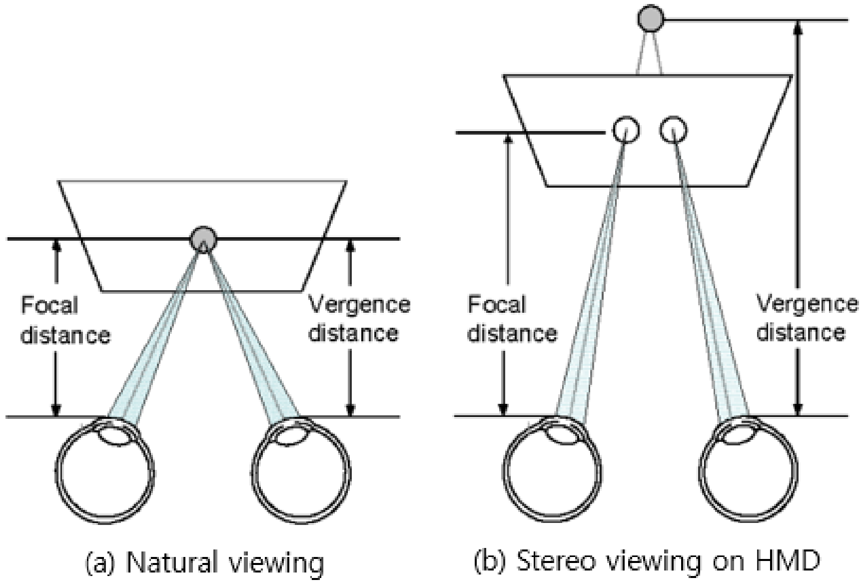

Figure 1. The relation between accommodation and vergence in natural viewing and the HMD condition. (a) the equidistant of vergence and focal distance in natural viewing (b) disrupted link between vergence and accommodation due to the display screen in HMD. The ratio of focal distance and vergence distance does not match the ideal AC/A ratio (Shibata et al., 2011).

Lastly, the angle of the eye's rotation used to bring an object into focus needs to be considered. The images that are reflected on each side of the eyes can be different due to the different orientation of the perceived images (Mok et al., 1992; Somani et al., 1997). This difference, which is referred to as interocular torsional difference (IoTD) must be considered since the degree of torque in both eyes are not accurately accounted for and diplopia, or double vision, may occur when experiencing VR using an HMD (Blaha and Gupta, 2014).

Previous research has primarily focused on the eye's 2-dimensional movements to resolve the issue with HMDs; however, users still report feelings of discomfort when experiencing VR (Salvucci and Goldberg, 2000; Anliker, 1976). Therefore, a promising way to approach this issue to examine the eye's 3-dimensional movements, which have not been implemented in the field of VR due to the technical limitations of HMDs. HMD devices with eye trackers mostly only track the gaze of the eye and do not provide information on how the eyes are positioned and aligned to perceive images. Unlike this 2-dimensional method to track the eye gaze, the 3-dimensional method will be able provide valuable information on the eye's movements in HMDs such as the rotation of eyes during depth perception, the impact of FOV, IPD and many more to develop VR that is more comparable to the natural world (Rolland and Hua, 2005; Koulieris et al., 2017)

In order to apply this novel method to VR, it is important to understand the 3-dimensional movement of the eyes. First. The eye has three degrees of freedom which helps the eyes to move in an infinite number of directions for any position of gaze. Horizontal eye movements are made by rotating around a ground-fixed vertical axes and vertical eye movements are generated around axes on the horizontal plane. Finally, torsional eye movements rotate around a point fixed within the center of the eye and can be explained through a third ambiguous axis which aligns with the line of sight, the torsional axis (Ferman et al., 1987; Wong et al., 2004). These axes help the eyes to move in the most muscle efficient way, allowing the movement of eyes to meet its superlative moving trajectory. The commonly known law which explains 3-dimensional eye movement is called Listing's law.

Listing's law explains the eye's movements in 3 different contexts: monocular condition, binocular without convergence condition (version) and binocular with convergence condition. From the recent issues with HMDs, it became important to understand the eye's movements in the natural world and how this is different from the VR world. Therefore, an interesting research question was raised: "Do torsional movement, which rotates around the line of sight, follow Listing's law in VR?" To answer this research question, information about the eye movements in relation to Listing's law will be reviewed.

This experiment tests three hypotheses regarding the eye's torsional movement in different contexts as defined in Listing's law. The first hypothesis is that an eye's torsional movement will not be the same for monocular vision compared to binocular vision. As Listing's law is confined to only monocular movement, finding whether this law holds for binocular vision is an important step to understanding the eye's 3-dimensional movement. The second hypothesis is that the eye's torsional movement will be different when they are looking an object at an infinite distance compared to when they are converging at a nearby object. This is an extension from the first experiment to examine the effect of vergence on eye's torsion. The third hypothesis is that the primary position which indicates zero torsional movement will not be placed at where the straight eye gaze is made from the head fixed position. Since the eyes move in the most muscle efficient way, it is possible that repeated torsional eye movement can have an impact on one's primary position (Miller, 1958; Crawford et al., 1991). Therefore, it can be hypothesized that people's primary position will not be the same among individuals.

1.1 Eye Movements

Inside the eye, there are six muscles that are responsible for moving the eyes in an infinite number of directions. Of these six muscles four are rectus muscles and two are oblique muscles (Leigh & Zee, 2015). The four rectus muscles: lateral rectus (LR), medial rectus (MR), superior rectus (SR), and inferior rectus(IR) each move in the direction for which they are named. Considering the sagittal plane as a midline, the lateral rectus moves away from the midline whereas the medial rectus moves towards the midline. The superior rectus and inferior rectus each move the globe upward and downward (Leigh & Zee, 2015;

Iskander et al., 2018). The oblique muscles move the globe in direction of either intorsion or extorsion. These muscles each contract and relax to help move the eyes to their destined target place. With these muscles, eyes are not constrained to 2-dimensional movements but can move in 3-dimensional orientations. These principles which govern the 3-dimensional eye movements are called Listing's law, and provide promising explanation to different types of eye movements.

1.2 Listing’s Law

Listing’s law describes the eye’s movements using 3 axes of rotation. The first is the vertical axis(y) which generates horizontal eye movements, the second is the horizontal axis(x) which generates vertical eye movements and the third is the line of sight (z) which generates torsional movements (Wong, 2004). This paper will mainly discuss the torsional movements of eyes as the focus of the eye movement will be in 3-dimension. Listing's law states that when the head is fixed, there exists an eye position called the primary position in which the eye from the primary position can reach an eccentric position by a single rotation about an axis which is confined to a common plane (Somani et al., 1997; Wong, 2004). This common plane is called Listing's plane and it is orthogonal to the line of sight when the eye starts moving from primary position.

The primary position is defined as "the position where the line of sight is perpendicular to Listing's plane and from which any purely horizontal and purely vertical movement is initiated that does not have any torsional amount" (Iskander et al., 2018). The primary position must be discussed when it comes to 3-dimensional eye movement. It is an anatomical landmark to define any direction of torsional axis as looking straight into the infinity distance with the head fixed in position will create a condition where the torsion movement becomes 0 (Mok et al., 1992; Haustein, 1989).

1.3 Half-angle Rule

The Listing's half angle rule discusses the case where the eyes are gazing at an object that is at a distance of infinity. Listing’s law does not discuss the movements of both eyes but is confined to the movement of one eye. Since eyes do not always move from the primary position, the situation in which the eye starts its move to an eccentric position is also a factor to consider. In this situation, unlike the Listing's plane that is orthogonal to the line of sight, the plane tilts half as much as the listing's plane in the same direction as the line of sight (Wong, 2004). This new plane is called a velocity plane. The rotation axis that starts from the eccentric position lies in this velocity plane and this allows all eye movements to rotate in various directions. For example, when the eye starts its movement from right to left, its rotational axis is a vertical axis which generates horizontal movements and can say this vertical axis lies in velocity plane. If the eye is moving from top to bottom, its rotational axis will be a horizontal axis which generates a vertical eye movement and this will lie in a newly defined a velocity plane.

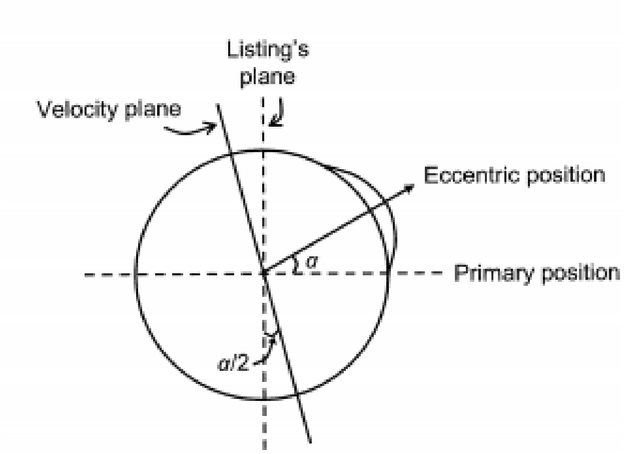

Figure 2. Listing' s half-angle rule: The dashed horizontal line represents the line of sight and the dashed vertical line represents the Listing' s plane, which is orthogonal to the line of sight. When the eye moves to the eccentric position with the amount of α angle, the plane tilts only half as much as the line of sight, $\alpha/2$ (Wong. 2004).

1.4 Binocular Extension of Listing's Law

The Binocular Extension of Listing's law explains the eye's movements when they converge to see near distance objects. When the eyes converge at a near distance object, the Listing's plane that is orthogonal to the line of sight makes an outward temporal tilt as much as a quarter of the vergence angle. This becomes a new velocity plane and is called the binocular extension of Listing's law (figure 3). When the convergence angle increases, the velocity plane tilts more outwardly from the

Listing's plane. This temporal tilt of the velocity plane occurs roughly symmetrical in each eye (Rijn & Van den Berg, 1993, Porrill et al., 1999, Mok et al., 1992).

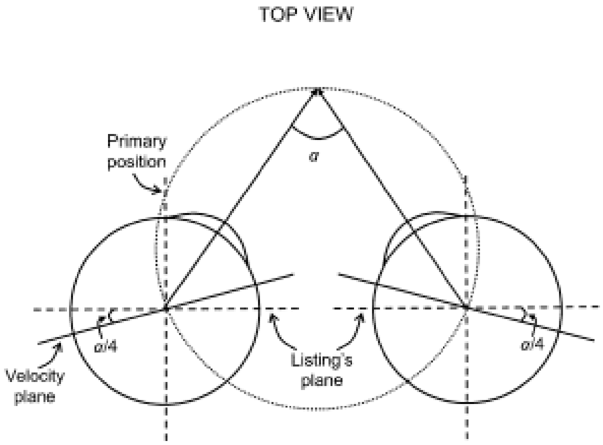

Figure 3. Binocular extension of Listing's law: The binocular extension of Listing's law applies when the eyes converge to see near objects. Given the vergence angle being α, the Listing's plane tilts temporally and symmetrically in each eye about a quarter ($\alpha/4$) of the vergence angle (Wong, 2004).

2. Methods

2.1 Participants

A total of twenty−nine participants [9 women, 20 men; mean age 29 (SD 3.6) yr] took part in this experiment. All participants had normal vision of at least 20/40 and did not have any medical history of a neurologic or ophthalmic disease. A 5−Item dry eye questionnaire (DEQ−5) (refer to appendix) was given to each participant prior to the experiment. As only the recording of a participant's eye movements was required in this experiment, it was important to prescreen those who often felt discomfort in their eyes. The scores were categorized into 4 different groups, severe (14.9±2.3), moderate (11.4±3.3), mild (8.6±3.1), and none (2.7±3.2), and those who did not fit into the none group were subsequently disqualified (Chalmers et al., 2010). In this experiment, three subjects scored higher than 6 on a DEQ−5 and were dismissed from the experiment.

The process of eliminating participants' data was chosen in fastidious manner due to technical limitations. The experiment uses an eye tracker to achieve all data; however, due to its sensitivity to light contrast and effects of shadows, the data went through a quality analysis process. Each participant's data in which the average of torsional movement did not meet 0.75 percentile or above was eliminated. In addition, factors like the shape of eye and the iris pattern affected the reliability of the data. As participants must be able to keep their eyes open while the eye tracker scans the pupil to measure torsional movement, participants with visible ptosis were not able to keep the eyes wide open, therefore causing the quality of torsional movement lower than 0.75 percentile. Furthermore, participants without a clear iris pattern were eliminated as the eyes could not provide sufficient landmarks to calculate the eye's torsional movement. From these elimination processes, 17 participants' data were eliminated from the 29 participants.

2.2 Apparatus

The participants sat on an adjustable chair in front of a TV screen measuring 55 inches (width= 121.76cm, height=68.49cm) in size. The TV screen stood 40 cm away from the participants and stayed in the same position throughout the experiment. The head and chin rest were screwed to a table with an eye tracker attached in an adjustable way using wires (figure 4). The head and chin rest ensured greater experimental control in three ways: all participants could view the TV screen at a distance of 40 cm, all looked at the target in the same position, and all kept their head immobilized throughout the experiment. Red and blue cellophane sheets were positioned on the left and right eye, respectively, and were used throughout the experiment as a method to create stereopsis. Also, an IR light is placed in front of the participants to constrict the pupil size to capture the iris pattern (figure 4).

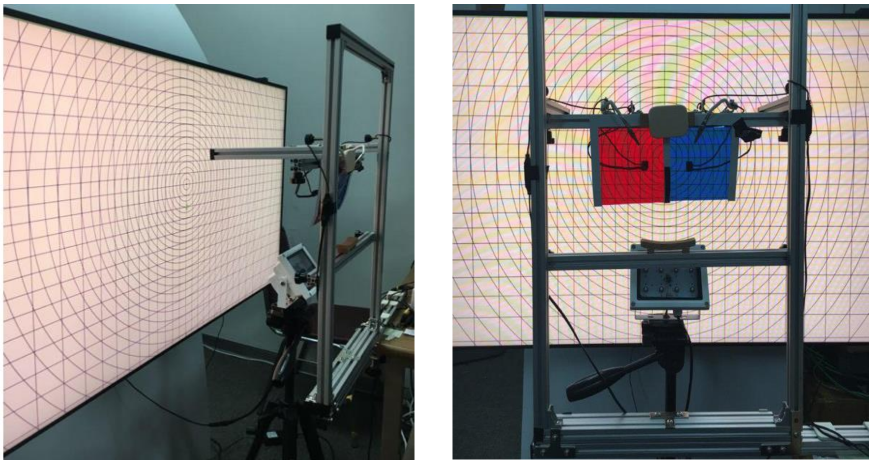

Figure 4. The setup of the experiment. The head and chin rest, red and blue cellophane, eye tracking cameras in each eye, and the infrared light (IR light) is used in the experiment.

2.3 Stimulus

The stimulus is presented on a TV screen using MATLAB 2018a. In all experimental conditions, a size slider was set to 0.5 degrees to generate black dots in a randomized order on the dartboard pattern combined with grid pattern background for the participant's eyes to follow. While participants are resting in the head and chin rest, the eye tracker is adjusted so it can fall into the square box on the screen (figure 5a). By placing the camera in each box, it prevents any blockage of the stimulus to participants. The center dot which appears 8 degrees above the center of the screen is used as a reference point in each condition for participants to fixate until each experiment session begins. The fixation point appears 8 degrees above the center of the screen because the line of sight which participants make while head is fixed in the head and chin rest was 8 degrees higher than the center of the screen. The fixation point was measured prior to each experiment condition. The participants move their eyes in four different directions (up, down, left, right) in 10 degree increments (figure 5b). This calibration process creates a reference position that calculates the amount of torsional movement when the eyes take off from a starting position to a target position.

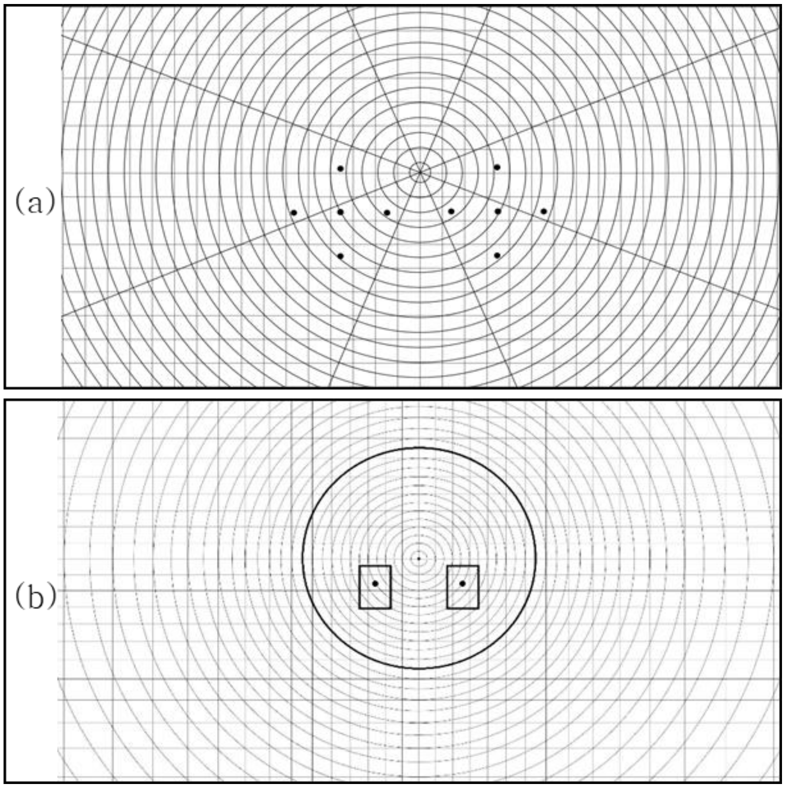

Figure 5. Calibration stimulus and the position of camera: (a) The position of camera to capture eye movements (b) Calibration stimulus plotted for each left and right eye

After the calibration process, the actual stimulus is projected on screen. The starting position, which is also the center position is always set 8 degrees above the center of the screen. From this position, a random dot appears at a distance of

9 degrees away at a speed of 1000ms±200ms before returning to the center position. The speed and direction were randomized in order to prevent any predictable movements. This process is repeated 16 times at different locations equidistant from the center position. After 16 repetition of saccadic movements, the center position shifts in total of five times in directions of left, right, and above from the center position in the distance of 9 and 13 degrees. From each shifted center position, the whole process of saccadic movements is repeated. The changes from center position did not shift to 9 and 13 degrees below the center position because the eye tracker could not capture the eye movement precisely due to the effect of shadows caused by the direction of IR light. The saccadic length of 9 degrees and 13 degrees were separately measured.

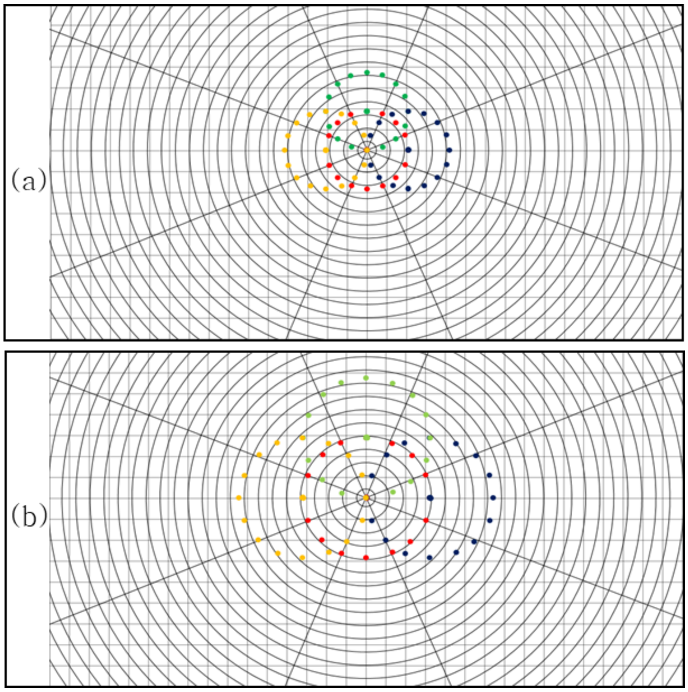

Figure 6. Stimulus: (a) All stimulus points when the distance between the fixation point and the target point is 9 degrees and (b) 13 degrees. Each stimulus point will appear one at a time in the order of center to the target position 1, then center again to another target position2.

Due to the nature of this study, participants' eyes are required to stay open for a long duration, while minimizing the frequency of blinking. To minimize any feelings of discomfort, each experiment set lasted a maximum of 2 minutes and 30 seconds. After every session, participants can take up to 5 minutes to rest their eyes. Experiments comprised of four sessions requiring up to an hour to complete in total.

2.4 Experiment Conditions

2.4.1 "Monocular 2m"condition

In the "monocular 2m" condition, only the left eye was used to measure the torsional movement. The right eye's view was shielded by placing a cardboard sheet in front of the eye in order to obtain data from the left eye used for the monocular condition The Monocular eye perceives depth perception through relative disparity cues such as object sizes, motion parallax, and smaller visual angle (Saxena et al., 2007). However, since all stimuli given are in the same size, the monocular condition does not perceive any cues that is related to depth. Therefore, the line of sight in the "monocular 2m" condition is set at a default setting, which looks at the TV screen from 40 cm in distance. The experiment condition was divided into two sessions: 9 degrees and 13 degrees including a calibration process.

2.4.2 "Binocular 2m" condition

In the "binocular 2m" condition, +2 diopter lenses were inserted in front of both participant's eyes. By inserting +2 diopter lenses in front of the eyes, the eyes receive stimuli as if they are presented at a distance of 2 meters. The +2 diopter lenses push the vergence distance beyond the TV screen to 2m while the accommodation distance is fixed at the actual displayed screen which is 40cm in front of the eyes. This creates a condition where the amount of vergence angle is close to 0 which can be considered as a far distance in this experiment.

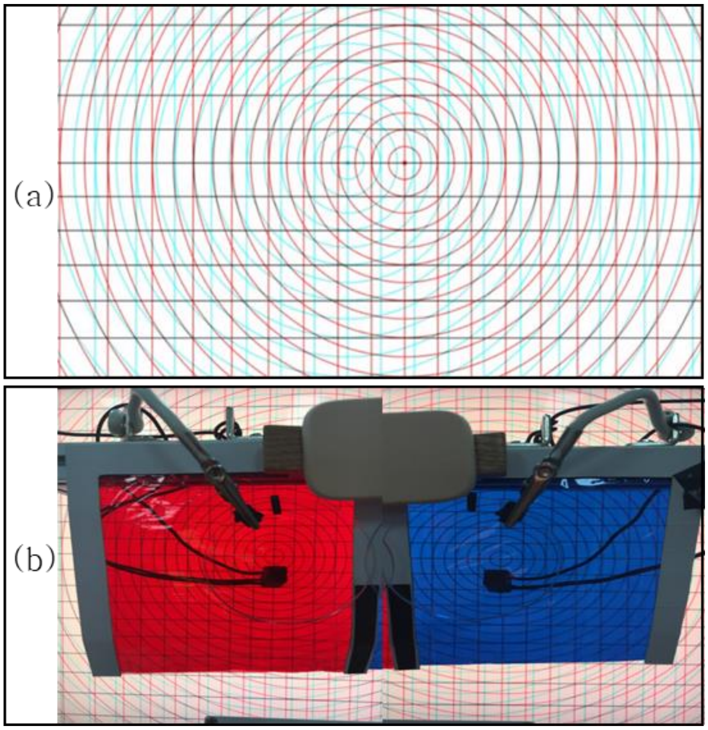

Figure 7. Binocular disparity: (a) The disparity is given by shifting the left and the right images. (b) Using the blue and the red cellophane and the +2 diopter lenses, the stereoscopic vision is created to see the objects in 2m distance.

2.4.3 "Binocular 0.4m" condition

In the "binocular 40cm (convergence)" condition, the participants looked at a screen without any lenses in front of them. This condition is considered to be the non−manipulated controlled condition where it displays stimulus where eye movements can move in a natural setting. The stimulus is the same as in *2.1.4.1* and *2.1.4.2*.

2.4.4 "Primary Position"

In the "primary position" condition, the stimulus is presented differently compared to the previous three conditions. For this experiment, a vertical range of 26 degrees below to 6 degrees above from the center position and a horizontal range of 9 degrees left to 9 degrees right is set as a possible range where primary position might rely in (figure 8). Within the vertical range, points were arranged at an interval of 2 degrees, moving the center position up and down in a non−systematic manner, presenting the points that moves in horizontal direction in a distance of 9 degrees from each center position to the left and the right side. This repeats until stimulus in all intervals of 2 degrees in the vertical range and its related horizontal stimulus are presented.

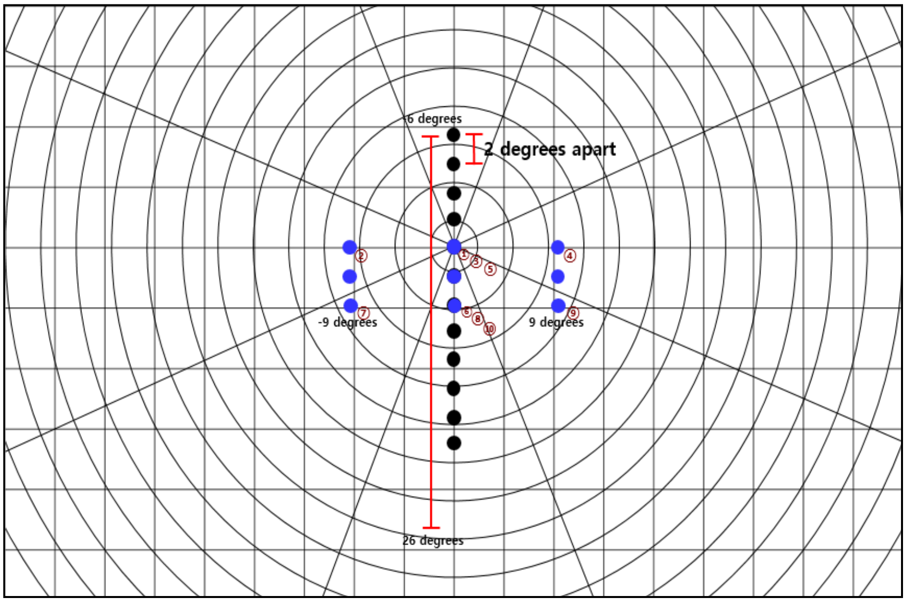

Figure 8. Primary position stimulus: Horizontal saccadic movement to measure the torsion of vertical position. A vertical range of 26 degrees down to 6 degrees above from the center point and a horizontal range of 9 degrees left to 9 degrees right is set as a range of the possible primary position. The order of the eye movement is as numbered: center → left →center → right → center → another center point (randomized) → continue.

2.5 Eye Movement Recordings and Data Analysis

The process of analyzing the eye's 3-dimensional movements is important to accurately collect data acquired using the eye tracker. This data is transferred to the Chronos Eye Tracking Device (C−ETD) which uses the iris segment tracking algorithm referred to as IRIS to analyze the eye movements. This program contains a calibration routine which uses the eyes' reference midpoints that become~~s~~ the reference position to all horizontal and vertical eye movements. This calibration routine estimates the reference position by capturing the eye movement after it moves across 4 different directions (up, down, left, and right) 10 degrees distance away from the midpoint. These movements are set as a reference position (figure 9a).

The IRIS program is based on the polar coordinates, which provides information on eye's torsion movement by exploiting the patterns of the iris. In order to capture landmarks of the iris, the detection of the pupil must occur in advance. The movement of pupil can be detected by using the luminance between the pupil and sclera. Once the detection of the eye movement is captured, exploring the landmarks of the iris process can begin. Landmarks are selected by capturing the most visible iris pattern that are not covered by the eyelid, eyelashes, or the reflection of infrared light in order to avoid any disruptions. Therefore, each side of the iris was used as a landmark in this experiment (figure 9b).

The torsional position of each ocular movement is reflected by the angular component rather than the radical component of the iris image. The coordinates of a circular sample in the iris are transformed from Cartesian to polar coordinates to convert the distance between the reference eye position and the shifted eye position to an angle of eye's torsional movement. As shown in figure 9b, the horizontal, vertical, and the torsional directional movements are given in degrees.

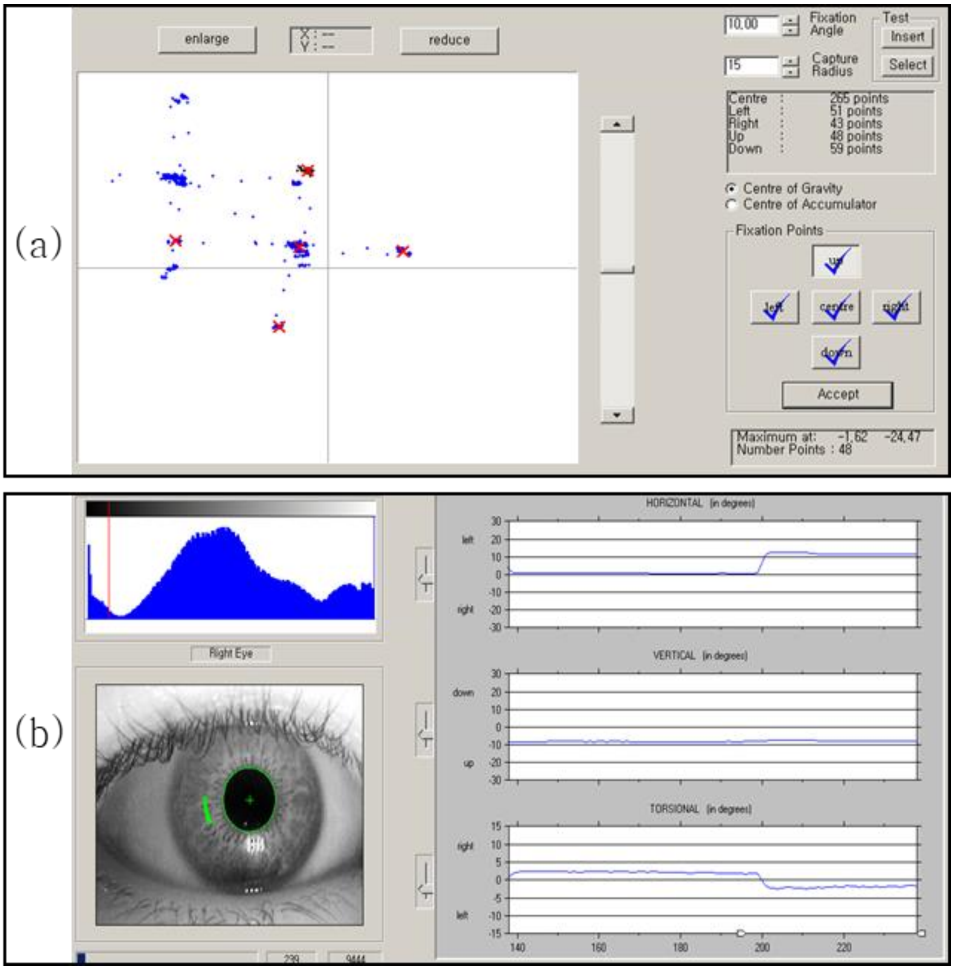

Figure 9. The process of measuring the eye movement: (a) Calibrating the right eye' s primary position. (b) Using the Chronos program, the information on the torsional amount moving in horizontal, vertical, and torsional direction.

3. Results

3.1 The Torsion Difference in the Monocular Eye Vision and the Binocular Eye Vision

Two way ANOVA was conducted on the left eye in both monocular and binocular eye conditions to see the interaction between the eye's torsional amount and the eye condition type: monocular and binocular. The results revealed that there is no interaction between the eye condition and the torsional amount, $F(3,112)=.743$, $p=.529$. The main effect on the eye condition type was also not significant, $F(1,112)=1.084$, $p=.3$; however, the main effect on the position was significant, $F(3,112)=12.659$, $p=.0$.

Table1. The result of the two-way ANOVA: the interaction between monocular and binocular vision and the torsional amount

Source	F	Sig.
Corrected Model	5.951	.000
Intercept	100.246	.000
Monobino	1.084	.300
Position	12.659	.000
Monobino * position	.743	.529
Error		
Total		

3.2 The Torsion Difference in the Version and Vergence Condition

Two way ANOVA was conducted on each left and the right eye to examine whether the presence of vergence and different center positions affect the torsion amount. The results on the left eye revealed that the interaction between presence of vergence and different center positions on torsion amount was not significant, $F(3,72)=.487$, $p=.693$. However, the two separate independent variables were significant: the position effect was significant, $F(3,72)=5.391$, $p=.002$ and the presence of vergence was also significant, $F(1,72)=4.888$, $p=0.030$.

Table2. The result of the two-way ANOVA: the interaction between the presence or absence of vergence and the torsional amount on the left eye.

Source	F	Sig.
Corrected Model	3.217	.005
Intercept	269.980	.000
Vergence	4.888	.030
Position	5.391	.002
Vergence * position	.487	.693
Error		
Total		

The results on the right eye did not show any significance in the interaction between presence of vergence and different center positions on listing's plane $F(3,72)=.671$, $p=.673$. The vergence effect also was not significant $F(1,72)=1.748$, $p=.190$, but the position effect was significant $F(1,72)=9.674$, $p=.000$

Table3. The result of the two-way ANOVA: the interaction between the presence or absence of vergence and the torsional amount on the right eye.

Source	F	Sig.
Corrected Model	4.683	.000
Intercept	84.078	.000
Vergence	1.748	.190
Position	9.674	.000
Vergence * position	.671	.573
Error		
Total		

The descriptive statistics looking at the left and the right eye's torsional amount whether vergence is present or not present shows that when there is vergence, the left eye and the right eye's average torsional amount is each $Mean_{left}=-15.251$ and $Mean_{right}=5.309$. In the version condition, the left eye and the right eye's average torsional amount is each $Mean_{left}=-$

11.634 and $Mean_{right}$=3.971.

Table4. Descriptive statistics on the left and the right eye's torsional movement in vergence and version condition

	N	Minimum	Maximum	Mean	Std. Deviation
VergOleft	40	-30.06	1.90	-15.251	9.352
VergOright	40	-6.60	17.88	5.309	5.126
VergXleft	40	-27.43	3.29	-11.634	5.967
VergXright	40	-12.78	14.46	3.971	5.277
Valid N (listwise)	40				

3.3 Primary Position

An independent-sample t-test was conducted to compare torsional movement in the left and the right eye's horizontal axis in movements. There was not a significant difference between the left (M=5.52, SD=9.15) and the right eye's horizontal axis in movements (M=8.09, SD=4.97); t(22)=-8.6, p=.40) (table 5 and 6).

Table5. The result of the t-test between the left and the right eye's horizontal axis in movements

		Levene's Test for Equality of Variances		t-test for Equality of Means		
		F	Sig.	t	df	Sig. (2-tailed)
IV Side	Equal variances assumed	2.771	.110	-.856	22	.401
	Equal variances not assumed			-.856	16.976	.404

Table6. Descriptive statistics on the left and right eye's horizontal axis in movements

	DV	N	Mean	Std. Deviation	Std. Error Mean
IV Side	Left X	12	5.5196	9.15124	2.64174
	Right X	12	8.0947	4.97317	1.43563

Another independent-sample t-test was conducted to compare torsional movement in the left and the right eye's vertical axis in movements. There was also not a significant difference between the left (M=-4.25, SD=3.51) and the right eye's vertical axis in movements (M=-4.46, SD=3.40); t(22)=.154, p=.88) (table 7 and 8).

Table7. The result of the t−test between the left and the right eye's vertical axis in movements

		Levene' s Test for Equality of Variances		t−test for Equality of Means		
		F	Sig.	t	df	Sig. (2−tailed)
IV Side	Equal variances assumed	.005	.946	.154	22	.879
	Equal variances not assumed			.154	21.980	.879

Table8. Descriptive statistics on the left and right eye's vertical axis in movements

	DV	N	Mean	Std. Deviation	Std. Error Mean
IV Side	Left X	12	−4.2454	3.50670	1.01230
	Right X	12	−4.4630	3.40258	.98224

In addition, 4 different independent−sample t−tests were conducted to compare each eye' s horizontal and vertical axis in movements with the ideal primary position, which is when the movements of eyes become 0. All 4 t−tests shows that horizontal and vertical directional movements were significantly different in this experiment when compared with what is known as Listing' s law' s primary position (table 9).

Table9. Combined t−test results: Each left and right eye's horizontal and vertical axis in movements are compared with the ideal primary position (torsion=0)

		Levene' s Test for Equality of Variances		t−test for Equality of Means		
		F	Sig.	t	df	Sig. (2−tailed)
Left eye x axis	Equal variances assumed	19.850	.000	2.089	22	.048
Left eye y axis		20.511	.000	-4.194	22	.000
Right eye x axis		35.057	.000	5.638	22	.000
Right eye y axis		28.226	.000	-4.544	22	.000

4. Discussion

This study was conducted to have a deeper understanding of the eye's 3−dimensioanl movements as a new way to address feelings of discomfort while using HMDs. Listing's law defines eye movements in 3 different contexts, which are the monocular, binocular version, and binocular vergence conditions; therefore, this experiment was conducted to examine the eye's different torsional movement to have a better understanding of eye movements in these contexts. In addition, primary position, which is the reference position to any eye movements while the head is fixed is examined. Observing where a person's primary position lies will bring fundamental understanding of the eye movements because it can be used as a reference position to calculate the eye's torsional movement. Examining these conditions will provide information on each eye's different rotational movements which will ultimately be used as a suggestion to provide more realistically rendered images to HMD users.

4.1 The Torsion Difference between the Monocular Eye Vision and the Binocular Eye Vision

The first hypothesis is that an eye's torsional movement will not be the same between the monocular and binocular condition. In this experiment, only the left side of the eye was examined in the monocular condition; therefore, only the left side of the eye movement in the binocular condition was used to match the comparing variables. The focus of the eye in the binocular condition was manipulated to have it set at a distance of 2m by using the +2 diopter lens as oppose to the eye in the monocular condition test where the artificial set up of experiment was not necessary. This set up created a situation for binocular vision to perceive images where the vergence distance is created 2m beyond the TV screen while the accommodation distance is fixed at the TV screen that is 40 cm away from the eye. When the eye's rotational movement in the monocular and the binocular condition in the left eye was compared, there was no significant difference in torsional movement.

This result can imply that the eyes' torsional movement between monocular 2m and binocular 2m conditions work under similar mechanism when viewing far distances. The tilt of Listing's plane in the left eye of both monocular and binocular conditions tilt in the same direction, with the plane tilt difference being not significant (figure 10). This suggests that when there are not enough depth cues presented to each eye to perceive the world in 3-dimension, the eye's movements treat perceived world as if it is on 2-dimension and rotate the eye movement in similar manner. This finding can be suggested in the current issue with HMD to present rendered images differently depending on the distance of the focused objects.

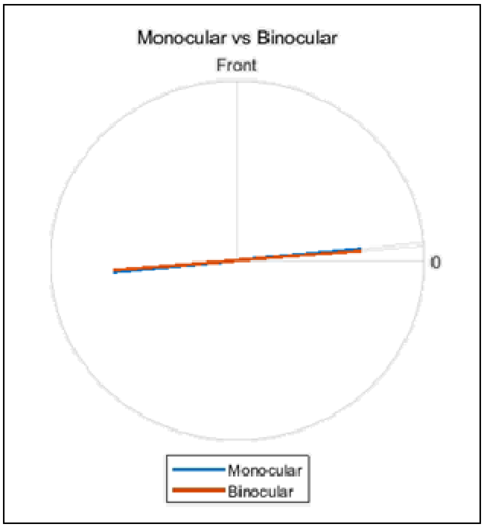

Figure 10. Listing's plane comparison between monocular and binocular condition. The blue line represents the Listing's plane of the left eye of the monocular condition and the red line represents the Listing's plane

of the left eye of the binocular condition. The two overlapped Listing's planes suggest there are no significant changes in the torsion amount in both conditions.

There were a number of limitations present in this experimental design. Since this experiment only examined the left eye for the monocular condition test, comparisons to the right eye in both conditions were not made. The left eye was selected for this experiment since the eye tracker recorded better data and landmarks within the left eye for the majority of participants. Due to the nature of the experiment, keeping the eyes open for a long duration of time was necessary to obtain more reliable data. Therefore, this experiment did not measure the movement in the right eye for the monocular condition test because patients may experience eye strain and fatigue which can produce unreliable data.

Because Listing's law explains eye movement that is confined to one eye movement, measuring only the left eye for torsional control limits the understanding of the eye's mechanisms used for monocular and binocular vision. Whether both eyes work symmetrically or asymmetrically has not been studied in Listing's law. In a future study, both eyes should be measured in monocular condition to have a thorough analysis on the difference between monocular and binocular eye movements for far distance conditions. Another limitation of this study is the focal distance. Although +2m diopter lenses were used to control vergence distance, it was inevitable to have vergence angle at 0 degrees in a 2m condition. The vergence angle must be 0 degrees for the eyes to be focused at an object at a distance of infinity. However, as this experiment was placed in a laboratory and the accommodation is always set at the distance of 40cm, creating a condition where there is no vergence was impossible. Therefore, in this experiment, the maximum distance of 2 meters was used in this experiment which ultimately resulted in a vergence angle of 1.72 degrees. For a future study, presenting two identical images to each eye can help create a situation where the eyes do not converge but gaze at an infinity distance. This will be a better controlled experiment to measure eye's torsional movement during monocular and binocular conditions.

4.2 The Torsion Difference in the Version and Vergence Condition

The second hypothesis is that the eyes torsional amount will be different between the eyes when they are looking at the infinity distance (version) compared to when they are converging at the near object (vergence). This condition is an extension from the first experiment that was conducted to examine the effect of vergence on eye's torsion, which is comparing half angle and binocular extension rule according to Listing's law. As the experiment compares the eye movement that starts, not from the eye's primary position, but from the eccentric position, the fixation point was set at four different locations: left, right, up, and center. The interaction between the torsional amounts on two different conditions did not show any significance; however, the presence of vergence on the left eye was significant while the right was not significant. This can be interpreted that both the left and the right eye move asymmetrically when vergence occurs.

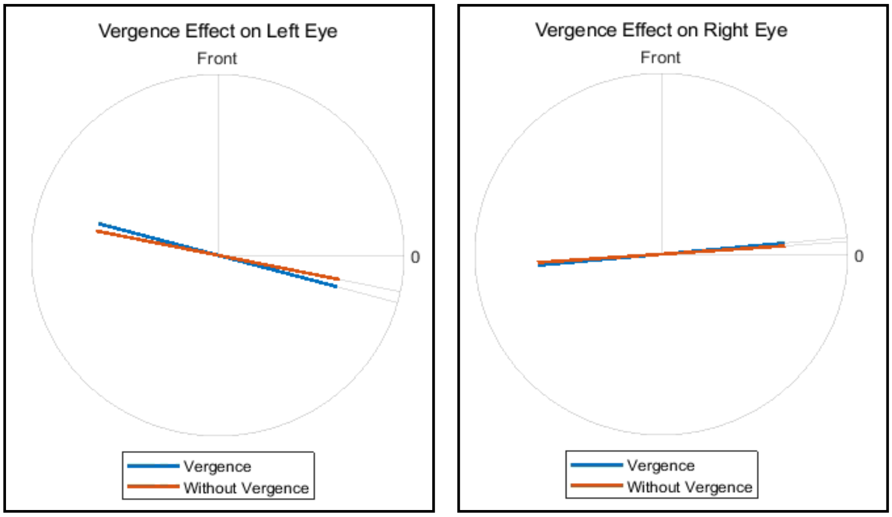

Figure 11. Listing's plane to see the effect of vergence in both the left and the right eye. In each figure, the blue line represents the vergence eye condition and the red line represents the without vergence (version) condition. The left figure shows the different alignment of Listing's plane which implies the presence of vergence has a significant impact on the left eye. The right figure shows the overlap of Listing's plane which implies the presence of vergence does not have a significant impact on the right eye.

It is likely that there is another factor—other than the binocular extension law that affects the torsion control. As only the left eye's torsional amount was significantly different in two conditions, vergence and version, this can be explained with people's ocular dominance. There is a tendency to prefer visual input processed from one eye over the other (Khan et al., 2001). When fixating on to a destined target, one eye initially fixates on to the target before the other eye follows to fixate on to the same target. The muscles of the left and the right eye work cooperatively to fuse images clearly in the most efficient way. There is a certain amount of torsional movement that is required to fixate on to an object, especially when there is a vergence angle. In our experiment, the vergence angle was set to be 8.58 degrees. If both eyes do not move in respect to the vergence angle, diplopia occurs and this will cause significant visual discomfort. Therefore, if one eye does not make enough torsional movement, the other eye compensates the amount of torsion that the other eye has not taken to gain clear vision.

In this experiment, as the left eye's torsion amount was significantly different in the situation with vergence than without vergence, it can be implied that the dominant eye, which in this case was the right eye, used its minimum torsion to fixate on to the target while the less dominant eye, the left eye, followed the right eye in order to fixate. This can explain why the right eye's torsional movement in version and vergence had no significant result while the left eye's torsional movement was significant in two different conditions.

Future studies can measure the subject's dominant eye prior to the experiment to see the interaction between the eye dominance and the torsional amount in the two different conditions. This will be a great contribution to the pre-existing experiments on dominant eye effects in normal vision which can help expand the knowledge to understanding the eye movements in VR.

4.3 Primary Position

The third hypothesis is that a person's primary position will not be placed at where the head is fixed when looking at an object at infinite distance. This experiment measures the saccadic movement that was made within the range of 26 degrees down to 6 degrees up in a vertical range and 9 degrees left to 9 degrees right in a horizontal range as explained in figure 8.

From Listing's law, the primary position is defined as a plane that is orthogonal to the line of sight when the eye initiates movement from primary position. From this definition, the primary position can be visualized 3−dimensionally by calculating the unique values of x, y, and z axis that satisfy the rotation of eyes, in this case where the torsion amount during horizontal and vertical movement becomes 0 (figure 10). This ideal shape of Listing's plane can be used as a reference position of primary position, which can later be used to compare with newly defined primary position from collected data set.

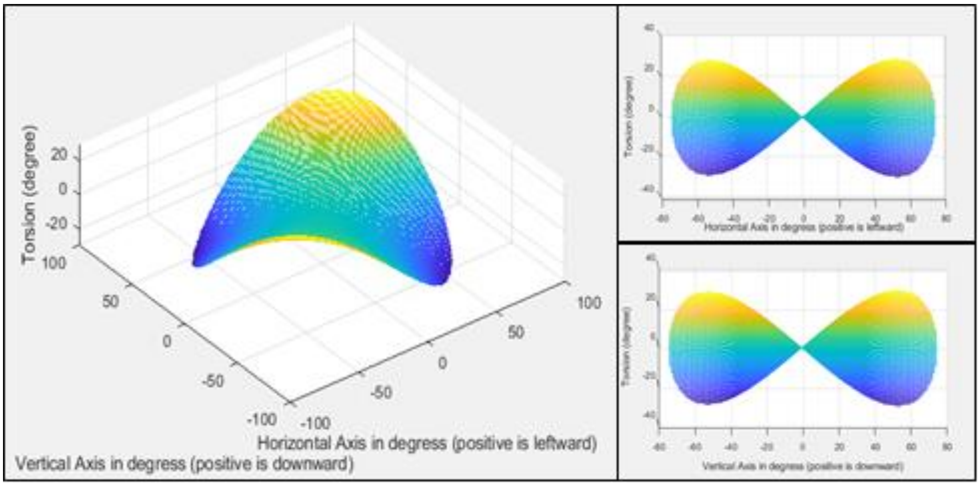

Figure 12. Ideal Listing's plane. The ideal Listing's plane is orthogonal to the line of sight and is located where the horizontal and vertical eye movement makes 0 torsional amount.

Data points between the range of −50 degrees to 50 degrees in each horizontal and vertical axis were selected to find one representative points which has the lowest error when compared with the measured data sets. The first step is trimming down the millions of points to a hundred points using a method called simulated annealing. This method is used when there are countless of local minima in a data set to find one global minimum. The simulated annealing method was run for one second to find the global minimum and this process was repeated hundred times to have 100 different local minima. From this 100 points that were selected, one point was chosen as global minimum as it had the least amount of error compared with the collected data set (figure 13).

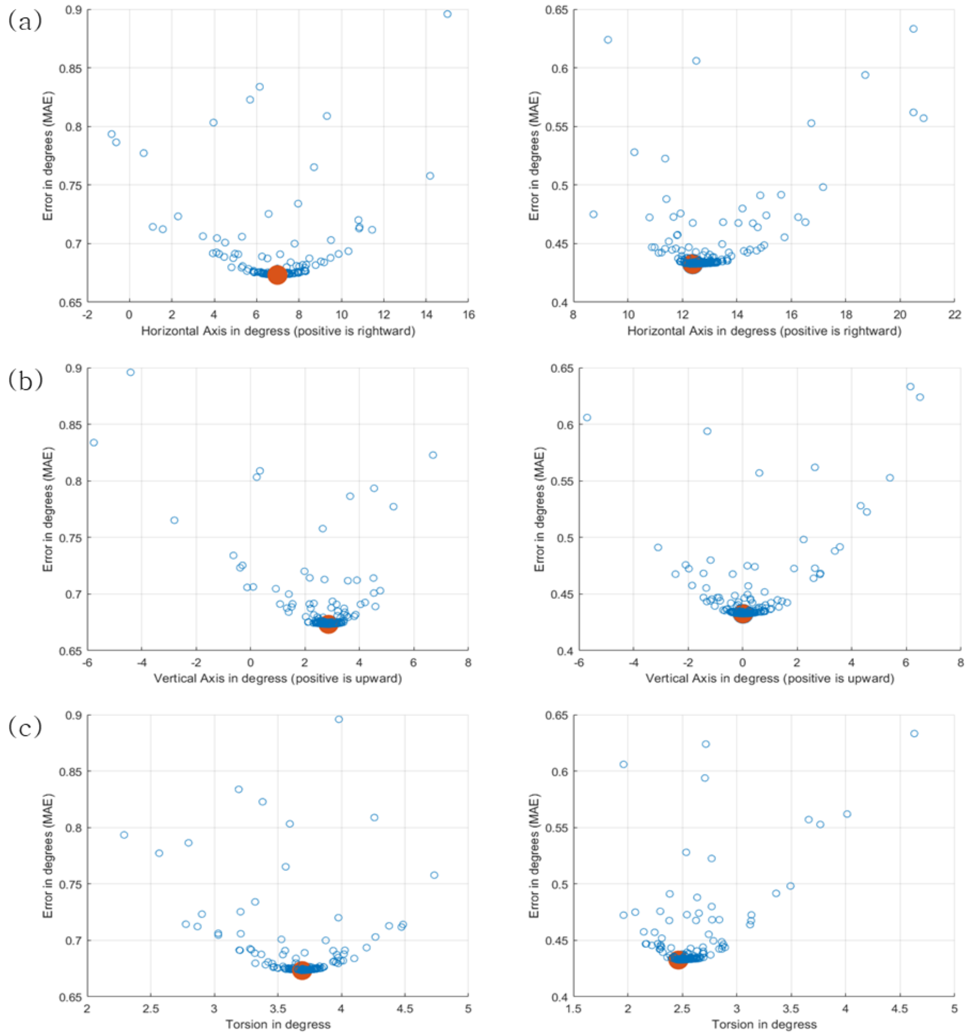

Figure 13. Simulated annealing method. The 100 points were selected using simulated annealing method and is presented in blue dots on graphs. The one point that has the least error amount was chosen to be the global minimum and is located one top of the upside down parabola in a red dot. Each graphs show selected 100 points and the global minimum in three different angles in respect to the error amount in degrees. The left eye's global minimum point is at (a) horizontal:

6.9829, (b) vertical: 2.8587, and (c)torsion: 3.6916 with the error amount 0.6732 degrees (graphs on the left side). The right eye's global minimum point is at (a) horizontal: 12.3786, (b) vertical: 0.0123, and (c) torsional: 2.4642 with the error amount 0.4325 degrees (graphs on the right side).

The global minimum point is used as a reference position for all data sets to be transformed. The torsional movement value which were calculated using the reference position were compared with the optimal surface of Listing's plane (figure 14)

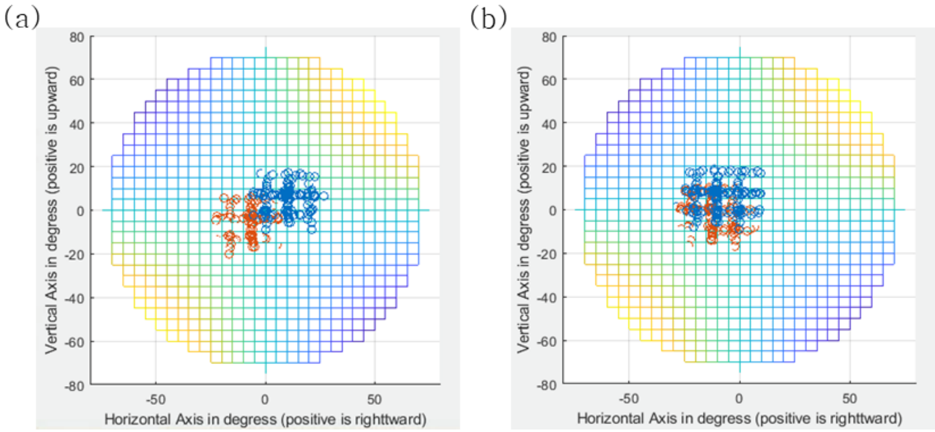

Figure 14. Global best fit on both eyes. One participant's data was chosen for these graphs. The transformed data according to the global minimum were compared with the optimal surface of Listing's plane. (a) The blue dots represent the raw output from chronos where the primary position is set to be at (0,0) and the brown dots represent transformed data sets, using the global minimum point as a reference

position in left eye and (b) right eye.

The transformed data sets for both left and the right eye are plotted to be compared to the optimal listing's plane. The result suggests that both the left and the right eye's primary position are each 4.2 and 4.5 degrees downwardly shifted. Also each eye's primary position is shifted to the right by 5.5 and 8.09 degrees from the center position (figure 15).

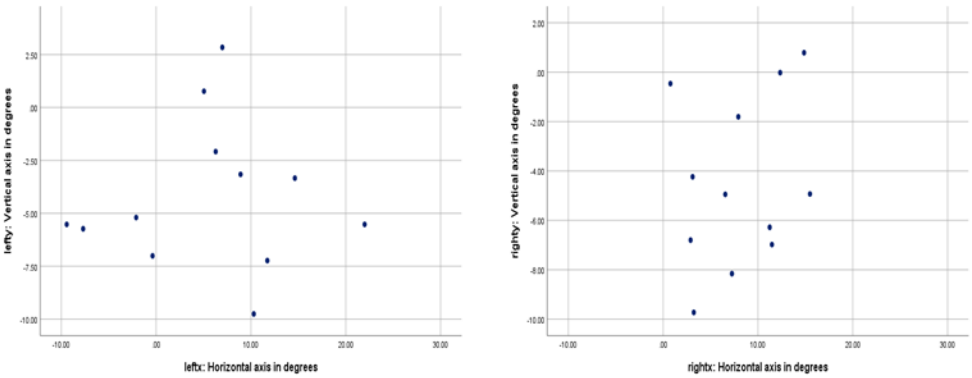

Figure 15. Eye's primary position. The horizontal axis in degrees show the movement of eyes in direction of left or right and the vertical axis in degrees show the movement of eyes in direction of up or down. In these graphs, both the left and the right eye are shifted toward right (5.5 and 8.09 degrees) and downward (4.2 and 4.5 degrees) from the optimal primary position (0,0).

The result suggests that people's primary position do not depend where the torsion becomes 0, but instead depends on where the downward and the rightward torsion exists. The eye muscles govern eye movements in a flexible way, influencing how vision changes throughout a person's lifetime. The studies from strabismus patients put weight on the flexibility of the eye's movement, where misaligned eyes were aligned back to normal by using a patch to cover each eye for a duration of time (Sharma and Reinecke, 2003). From these, it is foreseeable that primary position can be affected by outside factors. One of the major changes in the 21st century is the development of technology. Real time interactive devices such as mobile phones, desktops, and game consoles have emerged to take a huge part in peoples' lives. One thing that these devices have in common is that they require near distance and downwardly shifted eye movements. The repeatetive way of moving eyes can habituate the eye's movements, which in the end potentially changes the primary position where the eyes feel most comfortable.

The limitation of this study is that there is a possibility that an uncontrolled error could exist in the process of data analysis. The algorithm to calculate eye's torsional movement from eye tracking images were invented specifically for the purpose of this experiment. The torsional movement calculated within this experiment has an overall lower resolution compared to scleral search coils, which are lens inserted within the eyes that record movement. However, optical eye tracker technology is far less invasive than scleral search coils, allowing for more experiments with more participants. For future studies, more delicate algorithm to measure eye's torsional movement should be developed in further extent to be the reliable tool on its own to accurately provide information on the eye's movement. Furthermore, it will be interesting see what factors affect people's primary position. As primary position is a reference position for eye movements when the head is fixed, incorporating this information within HMDs can provide displays that are set to where the individual feels most comfortable by shifting images downward. This will be one of many novel ways to provide personalized HMDs which will ultimately be the solution to resolve feelings of discomfort while experiencing VR.

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안구 비틀림 제어에 관한 양안간 안구 위치와 양안 정보

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4차 산업혁명의 시대를 맞이하며 기술학적 측면이 발전함에 따라 안구움직임에 관한 연구의 중요성이 강조되고 있다. 그 중 특히 가상현실에서 발생하는 시각적 왜곡으로 인한 불편감을 해소하기 위해 3차원상에서의 안구움직임을 이해하는 것이 중요한 이슈로 떠오르고 있다. 본 연구는 3차원상에서 발생하는 눈 움직임에 대해 과학적으로 고찰하고 이에 대한 근본적인 이해를 돕고자 한다. 안구는 움직임을 담당하는 6개의 근육을 움직이며, x축, y축, 그리고 z축 총 세 방향으로 무수한 수의 방향으로 안구회전을 가능하게 한다. 이러한 3차원 공간에서의 안구움직임은 리스팅 법칙으로 설명할 수 있다. 본 연구는 기존 알려진 리스팅 법칙이 원거리, 근거리, 그리고 제일 안위 (primary position)에서 얼마나 리스팅 법칙과 부합되어 작동하는지를 살펴보고자 한다.

실험은 총 세 개의 조건으로 1) 한 눈과 양 눈에서의 눈 비틀림 정도 (torsional amount), 2) 눈의 이향운동의 유.무에 따라 변

화하는 눈 비틀림 정도, 마지막으로 3)제일안위의 위치를 살펴보는 것으로 진행된다. 그 결과, 1)한 눈과 양 눈에서의 눈 비틀림 정도는 비슷한 양상을 보였고, 2) 오른쪽, 왼쪽 눈을 따로 놓고 이향운동의 영향을 살펴본 결과, 왼눈에서는 유의미한 효과를, 오른눈에서는 유의미 하지 않은 효과를 볼 수 있었으며, 3) 제일안위의 위치는 오른쪽 눈, 왼쪽 눈에서 모두 눈 안쪽으로 그리고 더 낮은 위치에 존재한다는 것을 알 수 있다. 본 연구를 통해 눈의 3차원상에서의 안구움직임에 대한 폭 넓은 이해를 할 수 있었으며, 이는 더 나아가 가상현실에서 발생하는 불편감을 근본적으로 해소할 수 있는 디딤돌이 될 것이다.

주요어: 3차원 안구 움직임, 눈 비틀림, 리스팅 법칙, 제일안위, 가상현실, 사용자 경험

학번: 2016-20094

Appendix.

5-Item Dry Eye Questionnarie

1. Questions about **EYE DISCOMFORT:**

a. During a typical day in the past month, **how often** did your eyes feel discomfort?

0	Never
1	Rarely
2	Sometimes
3	Frequently
4	Constantly

b. When your eyes felt discomfort, **how intense was this feeling of discomfort** at the end of the day, within two hours of going to bed?

Never have it	Not at All Intense				Very Intense
0	1	2	3	4	5

2. Questions about **EYE DRYNESS:**

a. During a typical day in the past month, **how often** did your eyes feel dry?

0	Never
1	Rarely

2 Sometimes

3 Frequently

4 Constantly

b. When your eyes felt dry, **how intense was this feeling of dryness** at the end of the day, within two hours of going to bed?

Never <u>have it</u>	Not at All <u>Intense</u>				Very <u>Intense</u>
0	1	2	3	4	5

3. Question about **WATERY EYES:**

During a typical day in the past month, **how often** did your eyes look or feel excessively watery?

0 Never

1 Rarely

2 Sometimes

3 Frequently

4 Constantly

Score: 1a + 1b + 2a + 2b + 3 = Total

____+____+____+___+___= ____