이학석사 학위논문

Investigations on the visual and oculomotor effects of HMD use

두부장착형 디스플레이(HMD) 사용이 시각과 안구운동 조절에 끼치는 영향 연구

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이지현의 이학석사 학위논문을 인준함

2017년 07월

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Abstract

Head Mounted Display (HMD) is a virtual reality device worn on the head with a display covering the eyesight. The HMD has promising applications in various areas and it is leading towards a drastic makeover of the virtual reality industry. However, many users have reported discomfort associated with dizziness and diplopia yet the unidentified mechanisms of these side-effects remain the biggest hurdle to overcome. Since disruptions in sensory information processing occurs in virtual environments, investigating the neurological mechanism in HMD use may give fundamental guidelines for this potential threat.

The present study investigated the effects of the visual and oculomotor determinants such as vergence-accommodation linkage and interocular torsional disparity in HMD use. Thus, physiological symptoms such as the pulse rate and center of pressure (COP) were measured, and the Simulator Sickness Questionnaire (SSQ) data were collected to clarify the factors underlying side-effects. Empirical validation of the effect of each factor was conducted using the biomarkers.

By considering such neurological mechanisms in vision, the present results suggest a possible approach to reduce visual discomfort and side effects occurring via HMD.

Keyword: Head-Mounted Display(HMD), Virtual Reality, Neurological side-effects, Visual system, Vergence-Accommodation Conflict, Interocular Torsional Disparity, Listing's law

Student Number: 2015-22481

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Chapter 1. Introduction

Head-Mounted Display (HMD) is a display device used in virtual reality (VR) applications. The HMD is worn on the head with a display covering one or both eyes. The use of the HMD is leading towards a drastic makeover of the VR industry. However, the system is associated with various side effects caused by unknown mechanisms; these pose the biggest hurdle to be overcome.

The research objective of the present study was to specify the theoretical frameworks and neural substrates of ocular movements, which are considered the basis of the HMD-related side effects. Empirical validation of the effects of each visual and oculomotor determinant will be conducted by comparing biomarkers and questionnaires. In the relevant experiment, each condition will be fabricated after adding or correcting expected errors due to ocular determinants, and the results compared based on the conditions.

1.1. Importance of elucidating the underlying mechanisms of human sensory processing in VR

HMD experience can be thought as an interaction between the user and environment, and this relationship is artificially materialized to simulate the user's physical presence with replacing the visual input of the actual reality. There is a significant difference between viewing objects in the natural world and the virtual environment. The visual array changes into a digitalized system, inevitably causing unnatural lags and flickers. Since such discrepancy occurs in virtual environments, the disruptions in sensory information processing may be the main factor causing the discomforts in VR. Therefore understanding the mechanism of the human sensory system and investigating the mechanisms of neurological compensation in HMD use may give fundamental guidelines for providing a better experience.

Need of human centered approach on developing VR

Although most causes of suboptimal VR designs are due to technical limitations, the lack of understanding of the sensory system, perception system, interaction, design principles, and real users are also common factors (Jerald, 2015).

A good design starts with a good understanding of people and their needs, related to both psychology and technology. The mind and brain are complex entities that still occupy considerably scientific research. By this reason it is necessary to implement a human centered approach when designing VR-related devices or system. HCI is a discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them (Hewett et al., 1992). Also, Human Centered Design is a design philosophy that puts human needs, capabilities, and behavior in the first place, thus designing to accommodate those features (Norman, 2013). Many of the HCI and HCD methods highlight the importance of considering the lower level sensory perception.

For instance, Norman (2004) has reported three distinct levels of design: visceral, behavioral, and reflective. The visceral design can be defined as the subconscious reaction based on appearance. The visceral process occurs at the sensory level, which is beneath the attention level; thus, the behavior is strongly influenced without any conscious realization. This is the level where the initial reactions of interaction occur, and the bottom-up trigger to the higher level. Optimal visceral design is important because it dominates our physical features, in a universal manner, and it cannot be controlled by our mind or behavior.

Design paradigm is about phenomenological concerns and how technology takes occupies the user’s life. It is also about embodied interaction, involving our whole bodies and spirit making greater meaning within our interaction (Hartson et al., 2012). There are three different paradigms in design and development, namely Engineering, HIP, and Design-thinking. Among these paradigms, the HIP paradigm can be an approach focusing on the underlying mechanisms of processing human sensory information, and is based on elucidating how information is sensed, accessed, and transformed in the human mind. This paradigm puts a metaphor of mind and computer as symmetrically coupled information processors (Hartson et al., 2012).

Considering the neural substrates to emphasize the distinctiveness of VR

VR devices are often expressed as 'the immersive media.' The most distinguished characteristics and the greatest strength of VR devices would be the ability to maximize the transparency of the media itself. For this reason, when using the HMD, the user should be able to accomplish a task or be in a flow with a minimum of "unnecessary" interventions. Moreover, to achieve this goal, a system should efficiently react to reduce the likelihood of fatigue (Dünser et al., 2007). Design solutions meeting the needs of the visceral level, based on neural substrates, will be the key for clarifying and eliminating the interventions occurring from the lowest level of our interaction process.

According to Occam's razor principle, simpler theories are preferable to complex ones. To date, most development in VR has been technology driven. The associated research has been mainly focused on how to overcome hardware and software issues; moreover, development is limited to symptomatic treatments offering narrow-sighted solutions. The neurologic approach in the HMD design will help reveal the fundamental mechanisms related to human interaction and offer more generally applied problem-solving principles.

1.2. VR related side effects

Terminologies and aspects

Numerous symptoms have been associated with VR, such as dizziness, vertigo and blurred vision. Cybersickness is a widely used term that describes the discomfort linked to the use of computerized devices such as the HMD. Side effects occurring while using VR devices are also described as simulator sickness or Visually Induced Motion Sickness (VIMS).

It has been suggested that most of the terminologies of VR-related sickness are mainly derived from motion sickness. However, the significant difference between the terminologies of VR-related sickness and motion sickness depends on the reality of the external environment. All terminologies point to the discomfort associated with using human-made devices. However, while motion sickness is focused on explaining situations using vehicles with the purpose of performing actual movements, cybersickness and other terminologies are focused on explaining situations involving computerized displays and devices. Therefore, motion sickness can only be applied to situations involving actual vestibular input occurring from actual movements, while the other terms are broadly applied to situations involving artificially designed vestibular input (which is intended to match the artificially designed visual inputs), or even situations without involving any actual vestibular input.

For this reason, the conflict between visuo-vestibular inputs is one of the leading causes of cybersickness. The conflict includes vection, which corresponds to the feeling of movements induced by vision. The visual inputs and the related neural mechanisms are suggested to be important factors underlying discomfort in VR-related situations. Hence, investigating the effects of the visual and oculomotor determinants will be a good start point for elucidating the underlying mechanisms of human sensory processing in VR.

Use of physiological signals as a measure of discomfort

Given that most HMD-related side effects are subjective, it is difficult to observe and measure the exact underlying mechanisms. This may be a critical barrier for solving the VR-related side effects fundamentally. Thus, by matching the involving bio-signals with the symptoms, a way to classify and clarify the induced symptoms can be suggested. Biomarkers and physiological signals can be a relevant tool to evaluate the application of HCI methods.

Several studies have been conducted to relate the physiological signals to measure discomfort in VR situations. Kim et al. (2005) investigated the characteristic changes in the physiology of cybersickness. The total severity of cybersickness had a significant positive correlation with gastric tachyarrhythmia, eyeblink rate, heart period, and electrogastrogram (EGG) delta wave. Dennison et al. (2015) reported instances of stomach activity (EGG), blinking, and respiration signals. Many other signals such as pupil size and nystagmus were suggested as observable measures of VR-related side effects. Center of pressure (COP) and pulse rate were also considered effective measurement factors.

COP is defined as the point of application of the ground reaction force vector, and its positional change is used to estimate neurological and biomechanical mechanisms related to human postural control (Lafond et al., 2004). COP has been previously used to quantitate the degree of cybersickness or dizziness during VR experience (Lott et al., 2003; Hakkinen et al., 2002; Stoffregen et al., 2008).

The pulse is the mechanical pulse of blood flow through the capillaries caused by the heart contractions per minute. An increase in heart rate is widely used as an indicator for sympathetic activation and vagal withdrawal. It is also an indicator of the activation degree of the sympathetic and parasympathetic nervous system. The normal pulse rate is 60–100 beats per minute. The pulse can be used as an indirect indicator of the heartbeat and has been used as a quantitative indicator for cybersickness, because it increases when the sympathetic nervous system is stimulated. For example, Cowings et al. (1986) reported that heartbeat increases during motion sickness, and Kim et al. (2005) also reported that the degree of cybersickness is positively correlated with the cardiac cycle and the respiratory quotient.

Chapter 2. Neural substrates of ocular determinants in HMD use

Oculomotor discomfort has been consistently reported on using the HMD; however, no direct solution for monitoring or correcting the cause based on neurological principles, has been proposed to date. Theoretical frameworks and neural substrates of ocular movements, which are considered the basis of the HMD-related side effects, are needed to be specified.

2.1. Binocular depth perception

Binocular disparity is information used to obtain stereopsis by calculating the differences in information from two images. When viewing an object with both eyes, different images of the object fall on the retina of the right eye and the retina of the left eye because human eyes are separated by an interpupillary distance (IPD). An object within the visual field, which is a three-dimensional (3D) space, is fused at Panum's areas of both retinas, which are 2D planes. Subsequently, non-corresponding images of different shapes are formed, resulting in stereoscopic and distance perception. In particular, in a situation where perception is obtained at a short distance within 2 m, information of binocular disparity is primarily utilized. It may be said that the 3D display of the HMD also uses binocular disparity.

Human vision defines depth cues by using both relative and absolute disparity (Parker, 2007). Here, the absolute disparity is a depth cue utilized through changes in eye movements, and both vergence and accommodation are related to this. On the other hand, relative disparity is a cue that can be captured between the relationships of the object, which can be the size of an object, a shadow, brightness, and motion parallax.

There is a significant difference between viewing objects in the natural world and on an HMD display. When viewing objects in an HMD display, which is a computerized stereo display on a flat screen, the depths of objects are mainly described by the relative disparity. The left and right images are presented independently causing interocular separation. This difference causes various conflicts on the neural substrates and the mechanisms of the ocular determinants suited for viewing in the real world. This is considered a major factor of disturbance when using the HMD.

2.2. Vergence-accommodation conflict

Accommodation and vergence

Accommodation is a way to control the optical power of the eye and is necessary when focusing on an object in the visual field. The eye converges or diverges light by changing the shape of the lens through accommodation. A more convex lens would refract more light rays, giving a consequential increase in optical power.

The unit for the optical power is diopters, and it is reciprocal of the focal length of the lens. The optical power for converging lens is listed as + and for diverging lens as –. If the focal length is 20 cm, the optical power will be 1/0.2 m, which results in ±5 diopters.

Vergence is a disconjugate binocular eye movement when eyes move in opposite directions. Convergence is indicated when both eyes move nasally, while divergence is when both eyes move temporally. Accommodative convergence is the convergence of the eyes stimulated by accommodating or focusing on a near target.

The linkage between accommodation and vergence

For a clear, binocular vision, accommodation is needed to bring the object into focus and the vergence system is required to determine the direction of gaze in depth and locate the object on the fovea of each eye (Riddell et al., 1999). It is achieved and maintained by the cross-link between accommodation and vergence, which is embodied in the visual system. A response by one system will systematically drive a response in the other (Rushton et al., 1999), and focusing on a closer object requires progressively more accommodation and vergence.

Accommodation and vergence are tightly linked, and the balance of this link is usually preserved to maintain a clear binocular vision. This relationship can be expressed as the AC/A ratio, which is defined as the amount of convergence measured in prism diopters per unit (diopter) change in accommodation (Manas, 1955).

The stimulus AC/A ratio is the rate of accommodative convergence to the change in stimulus to accommodation (Goss, 1995). A general formula for the stimulus AC/A ratio is as follows:

$$\text{Stimulus AC/A ratio} = \frac{\text{Accommodative convergence (in } \Delta)}{\text{Change in stimulus to accommodation (in D)}}$$

Adverse effects caused by vergence-accommodation conflict

The increase in the mismatch between accommodation and vergence causes loss of accommodation and fusion function, which leads to blur or diplopia, and subsequently to visual fatigue. Furthermore, an abnormality of the AC/A ratio may also cause certain types of strabismus (Parks, 1975).

3D displays, including the HMD, result in conflicts between vergence and accommodation which may lead to difficulty in combining visual information of both eyes, or visual fatigue and discomfort (Hoffman et al., 2008). Moreover, it was also reported that long exposure to displays could cause discomfort and headache (Geng, 2013).

In the case of wearing the HMD, accommodation is adjusted so that the distance between the HMD screen and the lens may be maintained to a certain extent; however, the vergence angle varies with the distance to an object implemented on the screen. If this distance is set at 0.5 m, the vergence angle varies to fit 0.5 m. On the other hand, a conflict occurs because accommodation is identified as 2 m according to information from the image. Thus, a situation in which the visual information is at conflict occurs in the brain. If the signal of mismatch between accommodation and vergence is too strong or lasts for a long time, the brain sends the order to recalibrate the perception system in order to update the relationship between the information. In this process, dizziness and nausea may occur.

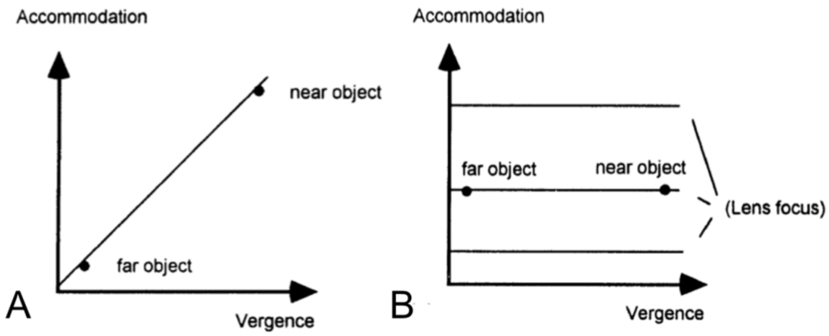


Figure 1. The relation between accommodation and vergence

(A) Diagram of the relation between accommodation and vergence stimuli in normal viewing. (B) Diagram of the relation between accommodation and vergence stimuli in virtual reality displays

(Rushton et al., 1999)

2.3. Interocular torsional disparity

Listing's law

The kinematics of eye rotation can be described with three degrees of freedom. Eye rotation occurs within three axes: X (parasagittal), Y (transverse), and Z (vertical) (Leigh and Zee, 2015).

Listing's law is a principle that governs 3D eye movements. It is an empirical law that quantitatively specifies the torsional angle for each direction (Fesharaki et al., 2008). Listing's law states that any eye position can be reached from the primary position by a rotation around a single axis. The plane formed by this axis is called Listing's plane (Helmholtz, 1867). The Listing's plane lies orthogonal to the gaze line when in primary position.

The primary position can be defined as a straight-ahead gaze position. However, it can be precisely defined in this situation as the position from which purely horizontal or purely vertical rotations of the eye are unassociated with any torsion (Leigh and Zee, 2015). Thus, Listing's plane is orthogonal to the gaze line when the gaze line is parallel to the sagittal plane.

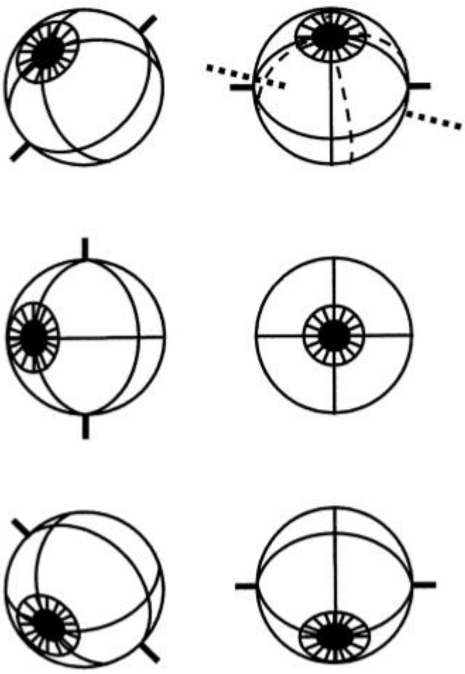


Figure 2. Orientations of the eye while obeying Listing's law.

Orientations of the eye when they rotate to secondary and tertiary positions while obeying Listing's law. In the tertiary position, the eyes appear to rotate around the visual axis (torsion). Each follows the Listing's law because it is attainable by rotating from the primary position (center image) around the axes (drawn as thick black solid lines) lying on the Listing's plane (the plane of the paper). The dashed line at the top does not comply with Listing's law because the rotation to this position from the primary position occurs around an axis that is tilted outside of the primary position (Wong et al., 2004; Leigh and Zee, 2015).

Interocular torsional disparity and the amount of torsion

During vergence, Listing's plane is temporally rotated relative to that observed when focusing on distant targets. Specifically, it is rotated through an angle that depends directly on the amount of vergence (Mok et al., 1992; Somani et al., 1997). For this reason, the object images could be oriented differently on the two retinas, and this difference in the torsional amount of each eye is called inter-ocular torsional disparity (IoTD).

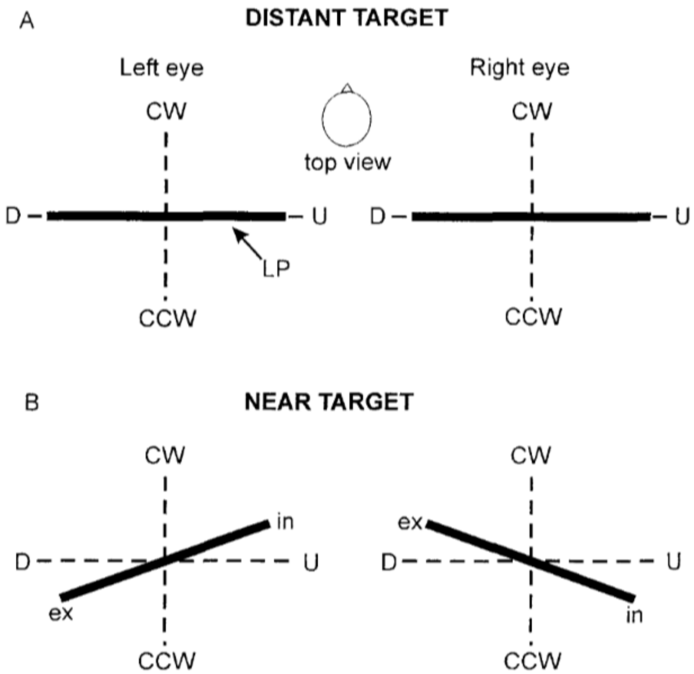


Figure 3. Orientation of Listing's planes of both eyes for gaze at distant targets(A) and near targets(B) (Somani et al., 1998).

Additionally, a difference in the torsional amount of each eye will be maximized when gazing to the oblique direction. In contrast, there will be no IoTD when gazing on the primary position (straight-ahead). Intorsion is a nasal rotation of the vertical meridian and extorsion is a temporal rotation of the vertical meridian.

We can estimate the extent of the difference by calculating the torsional amount based on Listing's law. This is mostly represented as quaternions, but for easier computation, we used the formula converted into Helmholtz equation in polar coordinates, which is a 2D coordinate system.

Expressed mathematically in Helmholtz coordinates, Listing's law can be measured as follows (Somani et al., 1997):

$$\text{Torsion (T)} = \frac{-HV}{2}$$

Where all angles are given in radians (not degrees), *T* indicates torsional, *H* horizontal (Z axis rotation), and *V* vertical (Y axis rotation). The positive direction is clockwise (*T*), left (*H*), and Y (*V*).

Adverse effects caused by interocular torsional disparity

The torsional amount becomes bigger when the object gets nearer. Given that an object is viewed at a distance of 0.5 m from the eye, the vergence angle becomes 7.3°; thus, the difference in torsional amount occurs by about 4°, which corresponds to approximately 70–80% of the vergence angle. A torsion of 4° is expected to make a significant difference in perceiving the object.

When wearing the HMD and looking at an object implemented at a 0.5-m distance, the brain supposes that the object is actually located 0.5 m ahead and compensates the retinal image based on the torsional amount so that the image may be perceived as vertically aligned. However, the retinal image is actually formed under the condition of a 2-m distance. Thus, when the torsional amount is applied as it is, excessive torsional amount occurs, This may lead to diplopia, which is one of the main cause of dizziness."

In particular, if the object is located close to the eyes, diplopia will continue and cause dizziness. This phenomenon is an important factor in cybersickness because the HMD requires objects to be within reach for interaction with immersive VR situation. Furthermore, the retinotopic array will change dynamically as the eye moves into oblique gaze positions. This leads to a change in the reference frame and consequently to a change in sensing self-verticality (Nakayama and Baliet, 1977).

2.4. Subjective visual vertical cues

Visual inputs are a major factor in maintaining self-verticality. A sense of objective vertical is known as the subjective visual vertical (SVV), which acts as a reference frame by arraying the upright stance and maintaining posture stability. In VR situations, using an independent visual background (IVB) method has been suggested as a solution for this matter.

Any image with a vertical form may act as a reference frame for self-verticality. It is consistently controlled and maintained at a lower level without involving attention. Verticality cue is mainly obtained through both visual and vestibular inputs. When these two sensory inputs provide different information on direction, a mismatch occurs leading to dizziness.

Chapter 3. Experimental Settings

The HMD system for the relevant experiment has three main objectives: (1) The eye tracking device should fit in the HMD and minimally interfere with the display; (2) the eye-tracking system should run real-time in synchronization with the HMD application; and (3) corrected displays should be developed by widely used VR game development platforms such as Unity.

3.1. Hardware Settings

Designing an eye tracking HMD implicating oculomotor determinants

To track the eye movement while wearing the HMD, we modified the original apparatus and developed an eye tracking HMD device. We suggested using a dichroic mirror as the design solution for the above-mentioned problems. Hasegawa et al. (2009) used a dichroic mirror to measure lens accommodation in the HMD. Visible ray from the HMD display passed through the dichroic mirror, while 50% of the infrared ray was reflected. By using the dichroic mirror, the infrared light source of the eye tracker targeted the camera and captured the pupil image reflected in the mirror.

The HMD device used in this study was Samsung Gear VR second generation model (SM-R323) with Galaxy S7 (SM-G930KZDEKTO), with a 345-g weight and measuring 207.8 × 122.5 × 98.6 mm. The system was attached to a 2,650 × 1,440 pixel AMOLED display with a 60-Hz refresh rate. The field of view (FOV) was 101 degrees with a lens diameter of 43 mm.

The eye tracker was the Arrington Viewpoint PC-60 with a temporal resolution of 60 Hz and pupil width resolution of < .03 mm). We used a dichroic mirror (25.2 × 35.6 mm; Edmund Optics DICHROIC SHRTPASS 700NM) to prevent the eye tracker from obstructing the FOV. The dichroic mirror was attached to the front of the HMD lenses at a tilted angle, and the eye tracker was inserted on the upper side of the HMD. Using this design, the pupil image was successfully captured without blocking the FOV. Furthermore, considering the inter-individual differences in eye size and location, we used a solid and flexible adhesive to make a customized fit for each individual.

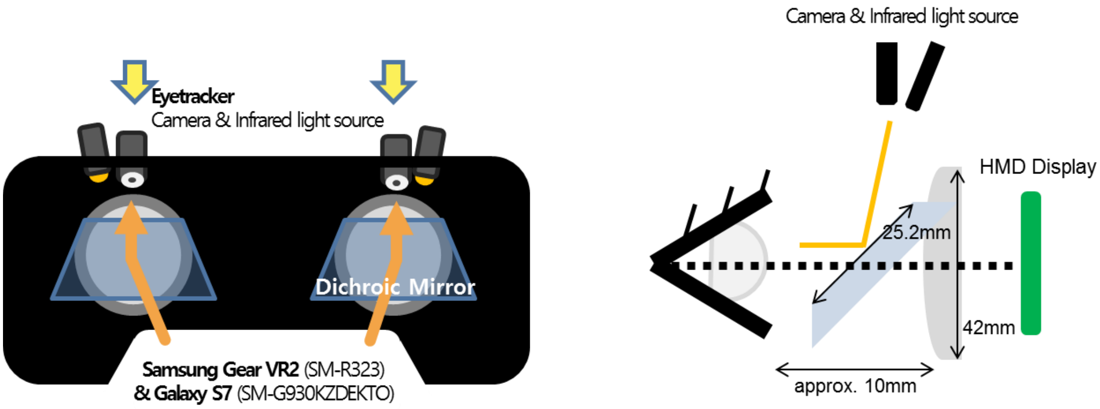


Figure 4. An eye-trackable head-mounted display (HMD)

Additionally, the weight of the HMD significantly increased because of the installation of the eye tracker. As a solution to compensate for the pressure, a 500-g weight was additionally attached to the back to apportion the pressure and maintain posture balance.

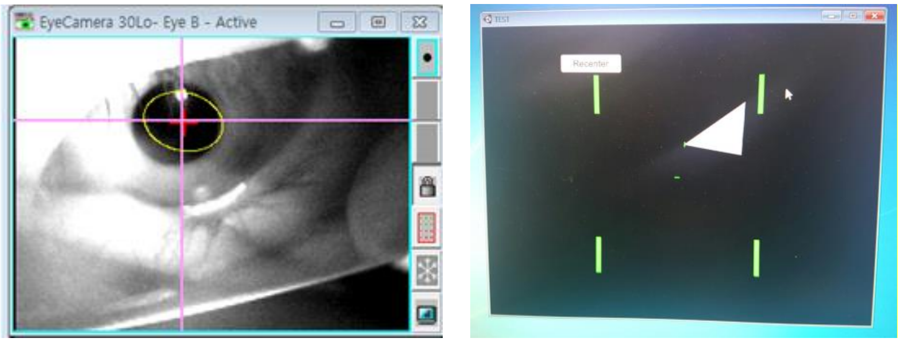


Figure 5. Sample image of the eye-tracking system

(Left) A sample image of pupil monitoring using Arrington PC-60 (Right eye); pupil image reflected on the dichroic mirror is captured by the eye-tracking device while wearing the head-mounted display (HMD). (Right) A sample image of head positron tracking; tracks based on the gyroscope and accelerometer data were collected from Galaxy S7 and calculated based on the Euler coordinates.

3.2. Software settings

The system was made available by Unity Game Engine and MATLAB. The primary control unit of the system was a PC running MATLAB. The collected biomarkers were aggregated at the serial port and sent to the PC.

Designing an IoTD-compensating warping display

A solution to compensate the effects occurring from the IoTD difference, warping the display of the objects located in the oblique position of the peripheral area could be suggested. This is expected to have more significant effects in the reachable space (closer than 0.5 m) within which the arm can still actively reach any object. In this range, binocular disparity functioned dominantly to provide more certain information on visually guided motor commands. We need more delicate depth cues to control our hand positions accurately.

Setting a different camera on each eye can be a design solution to compensate for the different amount of torsion by using Unity Game Engine. The distance of the left and right camera needs to be set at 64 mm, considering the hardware specifications of Samsung Gear VR.

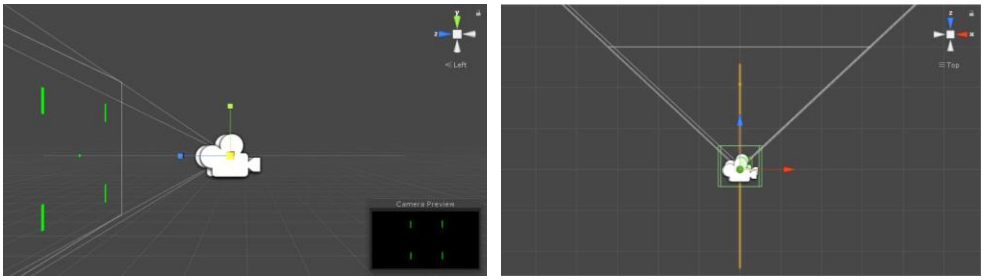


Figure 6. Captured image of display development using Unity Game Engine.

Calculating the torsional amounts for IoTD-corrected conditions

The method for determining the binocular torsional amounts according to the actual experiment conditions could be explained by focusing on the bar located at θ = 45° among the four bars presented on the screen under the IoTD-V experiment condition of a 0.5-m distance between the eyes and the screen. The distance from the fixation point of the screen to the bar was 165√2mm, and the IPD was set at 64 mm. The formulas for finding the H and V of the right eye were as follows:

$$H_{RIGHT} = -\tan^{-1}\frac{R\cos(\theta) - IPD/2}{500}$$

$$V_{RIGHT} = -\tan^{-1}\frac{R\sin(\theta)}{\sqrt{500^2 + (R\cos(\theta) - \frac{IPD}{2})^2}}$$

The calculation of T with H and V resulted in a torsional amount of –2.2976°. Likewise, the calculation of T for the left eye resulted in a torsional amount of –3.2028°. Thus, an IoTD of 2.2976° + 3.2028° = 0.9052° was generated.

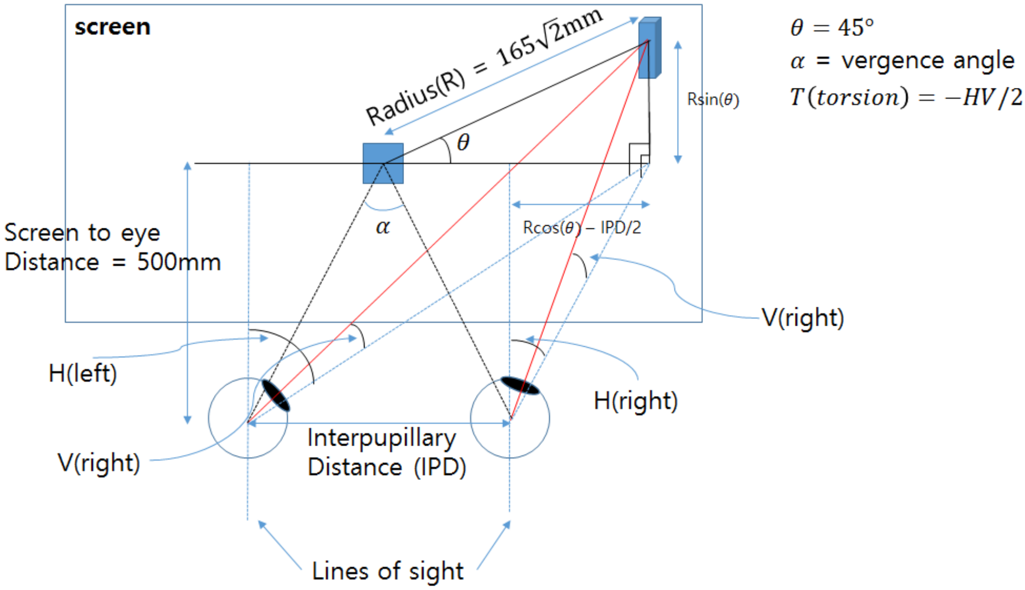


Figure 7. The required parameters to find the torsional amount in a specific experiment

In the case of a difference of 0.9052° in the falling angle of an image on the retina between both eyes, diplopia will occur. To resolve this problem, an additional torsion amount can be presented to each eye. The additional amount was calculated so that it might be proportionate to the amount of H for each eye. After the observation of actual ocular movement, it has been reported that the torsion value added or subtracted additionally to resolve IoTD is not fully reflected, but only approximately 91% is reflected (Somani et al., 1997). Therefore, the torsional amount equivalent to a correction value multiplied by 0.91 was added or subtracted for the eyes.

$$T^*_{RIGHT} = T_{RIGHT} - T_{DISP} \frac{H_{RIGHT}}{H_{RIGHT} + H_{LEFT}} * 0.91$$

$$T^*_{LEFT} = T_{LEFT} + T_{DISP} \frac{H_{LEFT}}{H_{RIGHT} + H_{LEFT}} * 0.91$$

If the bar stands upright, and a participant moves the pupils to the location of the bar and fixes the lines of sight, the angle of an image falling on the retina will be tilted by T^*_{RIGHT} at the right eye and T^*_{LEFT} at the left eye. Therefore, the bar should be turned by the same amount to a direction opposite to the pupil rotation, so that the bar may be perceived as vertical. Here, the calculated torsion correction corresponded to 2.6356°. In the actual experiment, about 75% of the torsion amount, corresponding to 1.9767°, was calculated and applied, suggesting that the application of the torsion amount calculated caused dizziness or diplopia.

Table 1. The amount of torsion applied on the IoTD condition.

Bar location	45°		135°		225°		315°	
Eye	Left	Right	Left	Right	Left	Right	Left	Right
Applied (75%)	2.0368°	1.9767°	-1.9767°	-2.0368°	1.9767°	2.0368°	-2.0368°	-1.9767°
Actual (100%)	2.7158°	2.6356°	-2.6356°	-2.7158°	2.6356°	2.7158°	-2.7158°	-2.6356°

Designing an error-controlled display condition for the experiment

The aim of this study was to investigate and verify the effects of the oculomotor determinants. Therefore, we designed an error-controlled display condition to compare the effects for the experiment. Each condition was subjected to the correction of vergence-accommodation mismatch error, IoTD error, and the misleading subjective visual verticals. The results were compared based on the conditions.

For this study, the target bars were located at the oblique positions to maximize the effects of the influence of the IoTD (except the H/V meridian-near and-natural condition). A different amount of torsion was applied on both the left and right cameras for the IoTD-V and IoTD-T conditions. None of the correction was applied for the other conditions, thus showing the same image with the IPD distance, only giving the binocular depth cues. A pilot-study was conducted to determine the torsional amount. By comparing the comfort between the amount compensating the IoTD to 100%, 75%, and 50%, the experimental conditions were designed to apply 75% of the total torsional amount. The specific design and aspects are described in Table 2 of Chapter 4.

Chapter 4. Methods

4.1. Participants

A total of 25 participants (14 men and 11 women; mean age 26 years; age range 20–32 years) were recruited, with all having normal or corrected-to-normal visual acuity and stereoscopic vision. Optical corrections were restricted to contact lenses since eyeglasses cannot fit into the eye-trackable HMD. None of the participants suffered from any known neurological disorder or claustrophobia. We did not test younger or older participants because of the possibility of accommodative range difference. It has been reported that presbyopia may cause reduced accommodative range, and the visual systems in children tend to have more plasticity than in adults (Rushton et al., 1999).

4.2. Dependent measures

In this study, the discomfort of the display was analyzed in two aspects, the objective signs and the subjective ratings on symptoms. Any objective evidence of discomfort, which could be recognized by others, was a sign, and included vomiting or increase of the pupil size. In this study, the pulse rate and COP data were used as a biomarker to measure the objective signs.

However, symptoms could only be felt by the user; thus, they are subjective and could only be revealed when a participant communicate them. Stomachache, dizziness, fatigue are examples of such symptoms. The Simulator Sickness Questionnaire (SSQ) was used in this experiment to rate the subjective symptoms.

Objective signs to measure the balance control and disorientation

The COP sway area was measured to observe the balance control and disorientation, and was referred to as the degree of cybersickness or dizziness.

The equations used for the calculation of COP using a force platform with an X- and Y- axis were as follows:

$$COP_X = \frac{X}{2}\frac{(TR + BR) - (TL + BL)}{TR + BR + TL + BL}$$

$$COP_Y = \frac{Y}{2}\frac{(TR + TL) - (BR + BL)}{TR + BR + TL + BL}$$

Where *X* indicates the width length of the Wii Balance Board and was 433 mm, and *Y* indicates the height length of the board and was 238 mm. *TR*, *BR*, *TL*, and *BL* are the force unit (*N*)-transformed values of pressure sensors located at the base sides of the four corners (top right, bottom right, top left, and bottom left, respectively) of the Wii Balance Board. There are traditional methods for COP analysis to examine changes in a participant's body balance (Schubert, Kirchner, Schmidtbleicher and Haas, 2012). The present study analyzed the sway area formed by the pathways of COP among them (Park et al., 2005). The sway area was calculated as the area of an ellipse comprising 95% of the area formed by COP pathways, and the standard deviation of COP distances was also calculated for supplement. Among COPs measured for 5 minutes, a period of implementation for each experiment condition, COPs for the 2nd–4th intervals excluding the first and last minute were analyzed. The COP values were used for analysis after subjecting them to standardization.

Objective signs to evaluate the extent of activation of the autonomic nervous system

The response of the sympathetic and parasympathetic nervous systems was indicated by a high pulse rate. To measure the pulse, a clip-on type pulse oximeter (model name: CMS50E) placed on a fingertip, was used. Its operating principle was to calculate the pulse rate from oxygen saturation found by using the ratio of pulse components obtained from the absorbance at two different wavelengths of light.

The present experiment extracted and analyzed only pulses falling under the interval of target and alternatives disappearing phase within each condition. Each phase was designed in such a way that it appeared 107 times per condition, and thus 107 pulse means were found and their average was calculated as the mean pulse rate of the relevant condition.

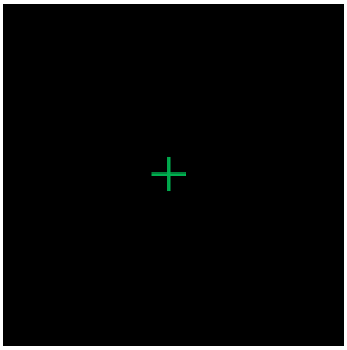


Figure 8. Sample image of the phase used in pulse data collection

(Target and Alternatives disappearing phase)

Subjective symptoms ratings

Subjective symptoms ratings were measured using the SSQ, the most widely used method to measure the VR-related sickness (Appendix 1). The SSQ suggested by Kennedy et al. (1993) consists of 16 questions, and each subscale was measured on the none-to-severe 4-point Likert scale.

Sickness symptoms were measured before and after the sessions using the SSQ. During the sessions, SSQ were taken by verbal ratings at 3-min intervals.

4.3. Task and stimuli

In the relevant experiment, each display was fabricated after correcting errors expected to occur due to such a mechanism of ocular movement. Each condition was subjected to the correction of vergence-accommodation mismatch, IoTD error, and misleading SVV. The results were compared based on the conditions.

The stimuli were designed in a single plane used by Unity Game Engine. The background was a black, empty screen of a 1:1 aspect ratio, scaled as a 0.66 × 0.66 m field on the 2-m distance condition. The object distance between the plane and the participant (camera location of Unity) was maintained at 2 m or 0.5 m differed by each condition. The target stimulus presented on display was designed as a green 2D vertical bar-type, with the size of 4 × 30 cm.

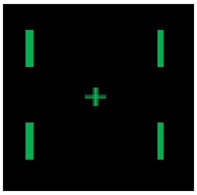
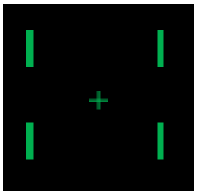
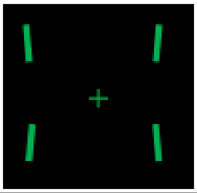
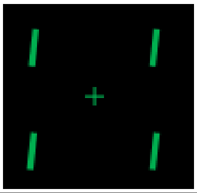
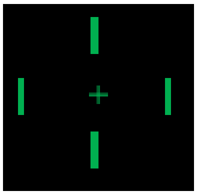
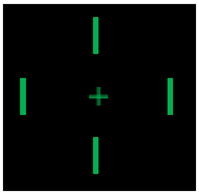
For the 0.5-m state, we downsized the stimulus to 1/4 to enable the stimulus to form a same image size on the retina. The stimulus was designed as simply as possible, to clarify the effects of interest and eliminate other factors.

At the beginning of each trial, a fixation target was presented at the center of the screen. The alternatives, also formed as same green vertical bars, were then presented at the four orthogonal edges of the screen in the direction of 45, 135, 225, and 315 degrees. Participants were required to saccade to this point and steadily fix their gaze on the target till it disappeared. The target was chosen pseudorandomly on each trial among four of the alternatives.

Six different conditions were displayed in random order. Each condition consisted of five repetitive events. The event flow of the developed system consisted of the following sequence: Trial Start, Alternatives Appearance, Blinking Cue on Target, Target and Alternatives Staying phase, and Target and Alternatives disappearing phase. The bar was made as a vertical shape for the use as an anchoring point to estimate the upright stance. Non-corrected bars at H/V meridians condition (top right) were added after the pilot test to compare with the Non-corrected bars at natural state condition to evaluate the influence of the reverse IoTD.

Table 2. Naming and design aspects of each Experiment Conditions

Design aspects subjected to the correction of vergence-accommodation mismatch error, interocular torsional disparity (IoTD) error, and misleading subjective visual verticals.

Condition naming	Non-corrected Natural	Non-corrected Near
Display Image		
Distance	Natural state (2m)	Near state(0.5m)
Bar type	Non-corrected Bars	Non-corrected Bars
Condition naming	**IoTD-V**	**IoTD-T**
Display Image		
Distance	Near state(0.5m)	Near state(0.5m)
Bar type	IOTD corrected in Vertical alignment	IOTD corrected in 6.5 ˚Tilted alignment
Condition naming	**H/V meridian-Near**	**H/V meridian-Natural**
Display Image		
Distance	Near state(0.5m)	Natural state (2m)
Bar type	Non-corrected Bars at H/V meridians	Non-corrected Bars at H/V meridians

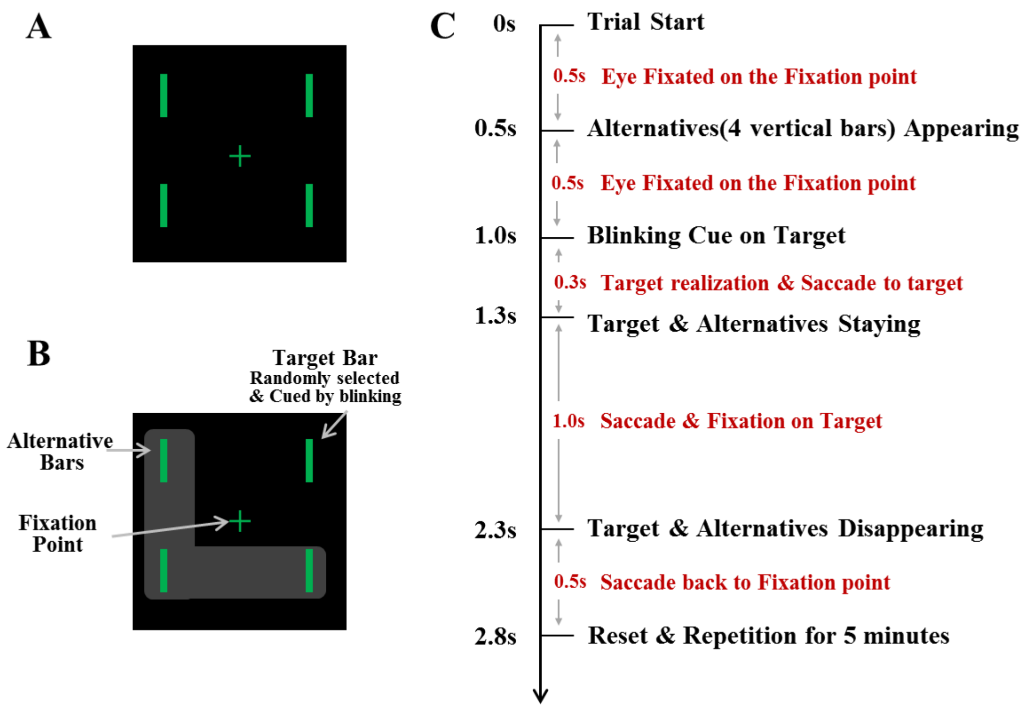


Figure 9. Description of the task design

(A) Spatial arrangement of Visual arrays. (B) Description of display components. (C) Letters in black describes the Phase information and red describes the task information.

4.4. Experimental Setup

The experiment was held in a dark room to eliminate the effect of dark adaptation of the eyes. A COP measuring board (Wii board) was inside the room, and a table was set in front of the board for participants to hold on when feeling dizziness. A chair was set next to the COP measuring board to rest in during every 3-minute break. A monitor was displayed, synchronically showing the same display on the HMD. The HMD device we used was cord free, but a cord was attached to the computer to transfer the eye tracking data. Outside the darkroom, the main computer was set for eye monitoring and operating the experiment.

4.5. Experimental procedure

Prior to the experiment, all participants were briefly informed about the procedure. SSQ was rated both before and after the experiment. Moreover, individual adjustment was made for the angle of the dichroic mirror to stably capture the participants’ pupil during the experiment.

During the experiment, COP data, pulse rate data, and SSQ responses were collected. During the experimental phase, all participants wore the HMD and stood on the COP measurement board with the pulse oximetry device attached on the second finger of the right hand.

Participants were instructed to look at the target bar with the blinking cue in one of the four corners of screen display. Six display conditions were presented in a randomized order. After each condition, participants took a 3-minute break and verbally rated the severity of their symptoms by SSQ. The total experiment time was approximately 90 minutes.

4.6. Hypotheses and analysis

The objective of this study was to determine the relationship between the conditioned display and the measured level of cybersickness. The experimental conditions were designed to see a significant difference between each of the error-controlling conditions. Three hypotheses in this study were established as follows:

H1: A vergence-accommodation conflict error controlled display would produce lower levels of sickness and discomfort

The influence of the vergence-accommodation conflict by comparing the effects of non-corrected bars at *Natural state* (2-m distance) condition, and non-corrected bars at *Near state* (0.5-m distance) condition was observed.

The distance of the target locations differed as 2 m and 0.5 m in each condition, thus the vergence angles also differed by 0.2 and 7.3 degrees in each condition. In addition, accommodation persisted in the 2-m state in both conditions. At the near state condition, as the eye focused on the target located at a 0.5-m distance, the vergence angle changed while the accommodation remained the same. The breakage between the link of vergence and accommodation resulted in a conflict, which was assumed to cause discomfort.

H2: An IoTD error-controlled display would produce lower levels of sickness and discomfort

The influence could be mainly observed by comparison of conditions designed as *Non-corrected* bars at near state, and the condition of *IoTD corrected* bars at the near state. When moving the gaze to the object located in oblique positions, the occurrence of the IoTD creates a conflict. We expected less diplopia in the IoTD error-controlling conditions than in the non-controlled conditions. Natural and Near state conditions with non-corrected bars at the H/V meridians were free from the IoTD error since the bars were in the cardinal position, whereas the rotation axis was located in Listing’s plane.

H3: A SVV misleading error treated display would produce lower levels of sickness and discomfort

The effect of the SVV misleading error could be notably observed by contrasting IoTD corrected *tilted* bars at *Near state* condition against the other conditions. Specifically, it could be seen by comparing the difference between IoTD corrected tilted bars at *Near state* condition (perceived to be 6.5° tilted) and the IoTD corrected vertical bars at *Near state* condition (perceived to be vertical).

The conditions free from any of the SVV misleading errors are both the Natural and Near state conditions with non-corrected bars at H/V meridians. The IoTD corrected vertical bars at *Near state* condition were considered to have the most minimized amount of error. In the first place, it was designed to have no verticality error at all. However, since we used 75% of the amount of torsional treatment, the verticality error remained. However, as it is a relatively small amount (estimated about 0.65°), the error in this condition was considered insignificant than in the other conditions.

Any other condition resulted in misleading verticality cues. Non-corrected bars at *Natural state* (2-m distance) condition and non-corrected bars at *Near state* condition (0.5-m distance) will have the SVV misleading errors because it would be received as tilted influenced by the torsion of the eye. The IoTD corrected *tilted* bars at *Near state* condition will have the most significant amount of error since it is designed to be perceived as 6.5° tilted.

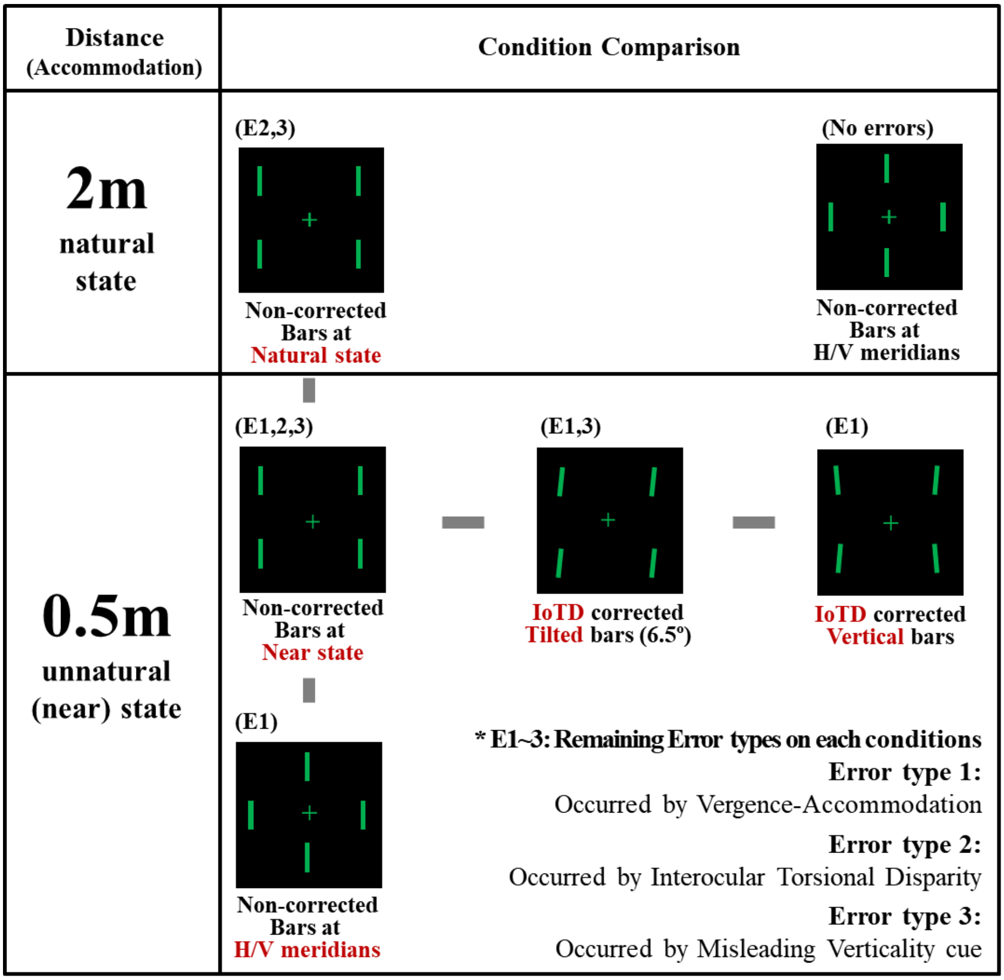


Figure 10. Description of the condition comparison

Comparison of each conditions observes the influence of error occurred by vergence-accommodation mismatch, IoTD, and misleading verticality cue.

A within-subject experiment has been conducted to investigate the effects of the displays controlling errors occurring from oculomotor determinants. A repeated measures one-way analysis of variance (ANOVA) was performed on the results for each dependent measure. Hereafter, a pairwise t-test was used to compare the effects of treated display conditions.

Chapter 5. Results

5.1. COP sway area

The COP data of 19 participants were subjected to repeated measures one-way ANOVA. The analysis showed significant differences in areas according to the experimental conditions. The mean COP sway area obtained with the six conditions is shown in Figure 13 (C3 to C8 refers to each condition in serial order; Non-corrected Natural as C3 to H/V meridian-Natural as C8).

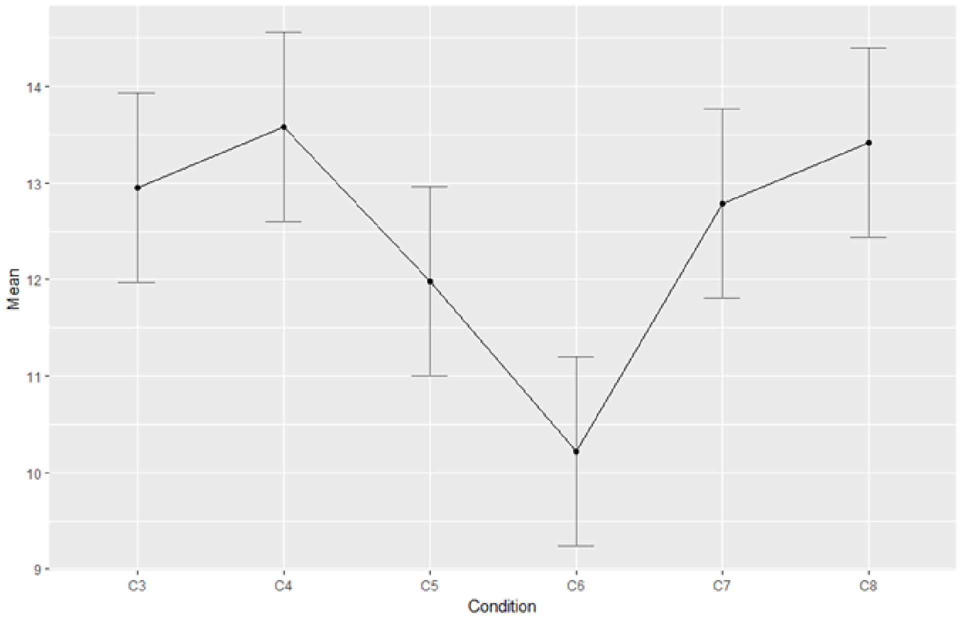


Figure 11. Mean center of pressure (COP) sway area (mm)

Table 3. Repeated measures one-way analysis of variance table of center of pressure (COP) sway area

Effect	Num DF	Den DF	F-value	p-value	P<.05	ges
Intercept	1	18	765.15569	< .0001	*	0.9342
Condition	5	90	3.18462	0.0108	*	0.1053

A post-hoc test (pairwise t-test) was carried out to determine the conditions among which there were differences. As a result of the test, IoTD corrected tilted condition showed significant differences from Non-corrected Near condition ($p = 0.035$) and H/V meridian-Natural condition ($p = 0.035$). IoTD corrected tilted bars at Near state condition showed differences, though not statistically significant, from conditions Non-corrected Natural condition and H/V meridian-Near condition. However, given the great individual differences, the participants were divided into two groups, and repeated measures two-way ANOVA was carried out. The k-means clustering technique was applied to the COP area data for dividing the groups.

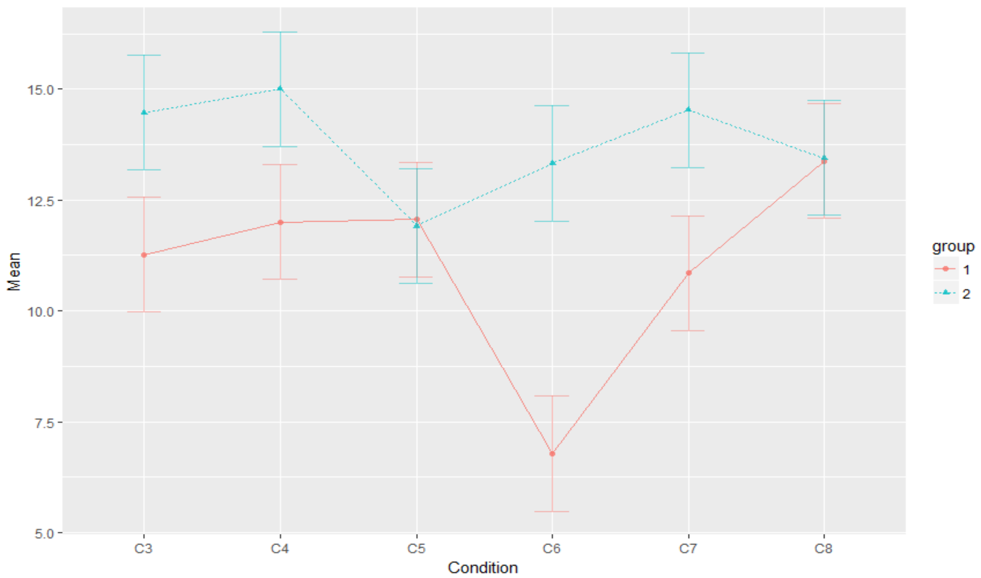


Figure 12. Mean center of pressure (COP) sway area divided into two groups (mm)

Table 4. Repeated measures two-way analysis of variance results of the center of pressure (COP) sway area

Effect	num DF	den DF	F-value	p-value	P<.05	ges
Intercept	1	17	1456.28	0.0000	*	0.9522
group	1	17	17.2585	0.0007	*	0.1910
condition	5	85	3.6549	0.0048	*	0.1416
group:condition	5	85	3.6549	0.0048	*	0.1417

Based on the COP area, the participants were divided into small COP area (Group 1) and large COP area (Group 2) groups. As a result of analysis under IoTD-T condition, it was found that the mean COP area of Group 1 was significantly lower than that of Group 2 (p = 0.0003). Furthermore, while Group 2 showed no significant difference under condition IoTD-T condition, compared with other conditions, the mean COP area of Group 1 under condition IoTD-T condition was significantly small, compared with conditions Non-corrected Near condition, IoTD-V condition, and H/V meridian-Natural condition.

Table 5. Pairwise t-test table of Group 1 center of pressure (COP) sway area

Comparison Group with IoTD-T	Non-corrected Natural	Non-corrected Near	IoTD-V	H/V meridian-Near	H/V meridian-Natural
p-value	0.0703	**0.0147**	**0.0130**	0.1480	**0.0004**

5.2. Pulse rate

The pulse data of 21 participants were subjected to repeated measures one-way ANOVA. Conditions were found to be marginally significant on pulse rate ($p = 0.0768$). The mean pulse rate obtained with the six conditions is shown in Figure 15(run3 to 8 refers to each condition in serial order; Non-corrected Natural as run3 to H/V meridian-Natural as run8).

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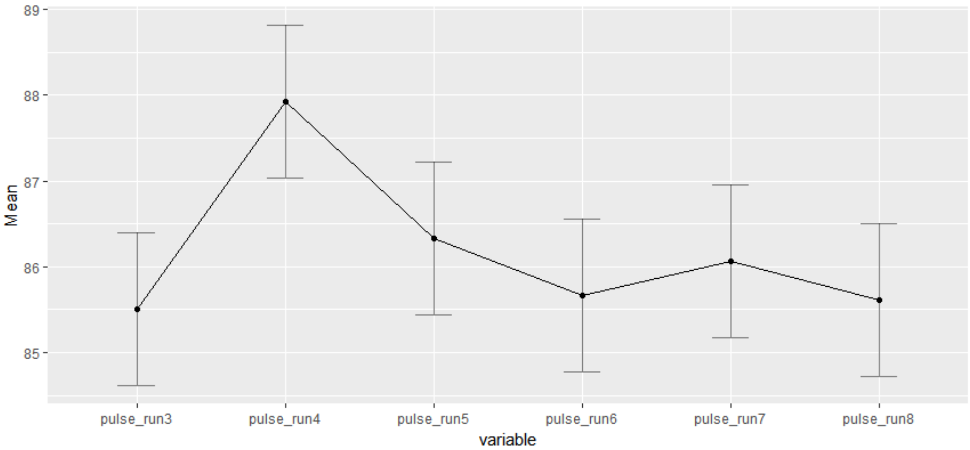

Figure 13. Mean pulse rate (bps)

Table 6. Means and standard deviations of the pulse rate

Conditions	n	M	SD
Non-corrected Natural	22	85.315	7.206
Non-corrected Near	22	87.441	8.810
IoTD-V	21	86.326	8.674
IoTD-T	21	85.666	9.133
H/V meridian-Near	21	86.065	8.402
H/V meridian-Natural	21	85.607	8.437
Total	21	86.075	8.320

Table 7. Repeated measures one-way analysis of variance results of the pulse rate

Effect	Num DF	Den DF	F-value	p-value	P<.05	ges
Intercept	**1**	**20**	**2413.506**	**< .0001**	*	**0.99**
Variable	5	100	2.059211	0.0768		0.01

Table 8. pairwise t-test table of the pulse rate

	Non-corrected Natural	Non-corrected Near	IoTD-V	IoTD-T	H/V meridian-Near
Non-corrected Near	**0.01**				
IoTD-V	0.65	0.10			
IoTD-T	0.95	**0.03**	0.62		
H/V meridian-Near	0.74	**0.03**	0.88	0.80	
H/V meridian-Natural	0.95	**0.03**	0.55	0.95	0.66

As a result of analyzing the mean pulse rate, the table of pairwise t-test results showed that the mean pulse rate under Non-corrected Natural condition was significantly lower than that under Non-corrected Near condition. Moreover, the mean pulse rate under Non-corrected Near condition(M=87.441, SD=8.81). was significantly lower than that under IoTD-T condition(M=85.666, SD=9.133)., H/V meridian-Near condition(M=86.065, SD=8.402)., and H/V meridian-Natural condition(M=85.607, SD=8.437). The rest shows that the participants' pulse rate was faster under Non-corrected Near condition, where the vergence-accommodation linkage was disturbed than under Non-corrected Natural condition where the vergence-accommodation linkage was maintained.

The participants exhibited a higher mean pulse rate under Non-corrected Near condition than IoTD-T condition, where the verticality cue was misleading, but IoTD was corrected. In addition, the mean pulse rate was higher under Non-corrected Near condition, where IoTD was not corrected with providing a misleading verticality cue, than under H/V meridian-Near condition, where no correction of IoTD was needed and a right verticality cue was provided.

5.3. Simulator Sickness Questionnaire

The SSQ data of 24 participants were subjected to repeated measures one-way ANOVA. The null hypothesis of no significant differences in each conditions was retained for all the symptom groups of SSQ score. The analysis failed to show significant differences in areas according to the symptom groups (p =0.7048, 0.5635, 0.5647, 0.2863).

Table 9. Means and standard deviations of each symptom groups (Nausea, Oculomotor, Disorientation, Total Severity) of SSQ score

	Nausea		Oculomotor		Disorientation		Total Severity	
Conditions	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Non-corrected Natural	1.42	0.84	1.80	0.99	1.38	0.82	1.51	0.87
Non-corrected Near	1.27	0.64	1.76	0.92	1.27	0.61	1.41	0.76
IoTD-V	1.38	0.79	1.92	1.00	1.29	0.60	1.51	0.84
IoTD-T	1.38	0.74	1.91	1.00	1.33	0.70	1.53	0.86
H/V meridian-Near	1.37	0.81	1.88	0.98	1.28	0.64	1.47	0.83
H/V meridian-Natural	1.32	0.70	1.64	0.91	1.16	0.54	1.37	0.75

Table 10. Repeated measures one-way analysis of variance results of each symptom groups of SSQ score

Effect	SS	df	MS	F	p-Value	P<.05
Nausea	0.3488	5	0.0698	0.5936	0.7048	
Oculomotor	1.4065	5	0.2813	0.7831	0.5635	
Disorientation	0.6152	5	0.1230	0.7814	0.5647	
Total Severity	1.6426	5	0.3285	1.2468	0.2863	

Participants reported the highest mean score of total severity on IoTD-Tilted condition (M=1.53, SD=0.45). Non-corrected Natural condition was ranked the highest mean score of the Nausea symptom group (M=1.42, SD=0.84), IoTD-Vertical of the Oculomotor symptom group (M=1.92, SD=1.00), and Non-corrected Natural condition of the Disorientation symptom group(M=1.38, SD= 0.82). The H/V meridian-Natural condition, which is designed to have none of the errors ocuured by the ocular determinants, ranked the lowest mean score among the Oculomotor related symptom group(M=1.64, SD=0.91). This condition also ranked the lowest in the Disorientation symptom group (M=1.16, SD=0.54). Non-corrected Near condition ranked the lowest in the Nausea symptom group (M=1.27, SD=0.64).

Table11. Means and standard deviations of the SSQ score of total experiment conditions, pre and post measurement

		Experiment (Total)		**Pre**		**Post**	
Symptoms	**n**	**M**	**SD**	**M**	**SD**	**M**	**SD**
General Discomfort	24	2.31	0.99	1.21	0.41	1.96	1.08
Fatigue	24	2.32	0.8	1.79	0.78	2.17	0.96
Headache	24	1.49	0.76	1.08	0.28	1.33	0.48
Eyestrain	24	2.34	0.89	1.50	0.59	2.21	0.98
Difficulty focusing	24	1.4	0.9	1.08	0.28	1.17	0.38
Increased Salivation	24	1.12	0.84	1.08	0.28	1.00	0.00
Sweating	24	1.13	0.28	1.13	0.34	1.04	0.20
Nausea	24	1.27	0.47	1.04	0.20	1.17	0.48
Difficulty concentration	24	1.51	0.82	1.25	0.53	1.21	0.41
Fullness of head	24	1.35	0.54	1.29	0.55	1.25	0.44
Blurred Vision	24	1.35	0.64	1.08	0.28	1.13	0.34
Dizzy with eyes open	24	1.43	0.63	1.04	0.20	1.17	0.38
Dizzy with eyes closed	24	1.14	0.2	1.08	0.28	1.13	0.34
Vertigo	24	1.18	0.28	1.13	0.45	1.08	0.28
Stomach awareness	24	1.08	0.4	1.13	0.34	1.08	0.41
Burping	24	1.08	0.2	1.08	0.28	1.08	0.28
Total		**1.47**	**0.79**	**1.19**	**0.45**	**1.32**	**0.66**

There was a slight increase with the SSQ score after the exposure (M=1.32, SD=0.66) compared to the SSQ score of pre-measurement (M=1.19, SD=0.45). Moreover, the SSQ scores during the experiment were significantly higher than that of the post measurement, measured when the entire experiment was over. Obviously, the total exposure time of HMD is the longest in the post condition. This may indicate that the short term side effects and discomforts of HMD use are more significantly detectable than the long term side effects.

Focusing on the symptoms, the mean score is shown to be the highest in General Discomfort, Fatigue and Eyestrain, which are the symptoms of the Oculomotor group. On the contrary, it is shown to be the lowest in Burping, Stomach awareness and Increased Salvation and these are the symptoms of the Nausea group.

Table 12. Means and standard deviations of the SSQ score of each condition

Condition		**Non-corrected Natural**		**Non-corrected Near**	
Symptoms	**n**	**M**	**SD**	**M**	**SD**
General Discomfort	24	2.38	0.90	2.17	0.85
Fatigue	24	2.33	0.85	2.21	0.76
Headache	24	1.33	0.62	1.38	0.75
Eyestrain	24	2.21	0.96	2.33	0.90
Difficulty focusing	24	1.42	0.81	1.42	0.70
Increased Salivation	24	1.13	0.33	1.04	0.20
Sweating	24	1.25	0.66	1.13	0.33
Nausea	24	1.46	0.96	1.17	0.37
Difficulty concentration	24	1.58	0.86	1.38	0.70
Fullness of head	24	1.38	0.63	1.25	0.52
Blurred Vision	24	1.33	0.75	1.42	0.57
Dizzy with eyes open	24	1.54	0.91	1.42	0.81
Dizzy with eyes closed	24	1.29	0.54	1.13	0.33
Vertigo	24	1.42	0.76	1.13	0.33
Stomach awareness	24	1.08	0.40	1.00	0.00
Burping	24	1.08	0.28	1.00	0.00
Total		**1.51**	**0.87**	**1.41**	**0.76**

Condition		IoTD-Vertical		IoTD-Tilted	
Symptoms	**n**	**M**	**SD**	**M**	**SD**
General Discomfort	24	2.38	0.99	2.38	0.86
Fatigue	24	2.46	0.71	2.46	0.82
Headache	24	1.63	0.95	1.67	0.99
Eyestrain	24	2.63	0.70	2.50	1.00
Difficulty focusing	24	1.42	0.57	1.38	0.63
Increased Salivation	24	1.04	0.20	1.04	0.20
Sweating	24	1.17	0.47	1.13	0.33
Nausea	24	1.33	0.62	1.25	0.60
Difficulty concentration	24	1.54	0.87	1.58	0.70
Fullness of head	24	1.38	0.56	1.58	0.95
Blurred Vision	24	1.38	0.70	1.42	0.64
Dizzy with eyes open	24	1.42	0.57	1.42	0.70
Dizzy with eyes closed	24	1.21	0.41	1.13	0.33
Vertigo	24	1.04	0.20	1.25	0.52
Stomach awareness	24	1.08	0.40	1.13	0.44
Burping	24	1.13	0.33	1.13	0.33
Total		**1.51**	**0.84**	**1.53**	**0.86**

Condition		H/V meridian-Near		H/V meridian-Natural	
Symptoms	**n**	**M**	**SD**	**M**	**SD**
General Discomfort	24	2.38	0.99	2.21	0.96
Fatigue	24	2.33	0.80	2.13	0.83
Headache	24	1.50	0.76	1.42	0.81
Eyestrain	24	2.29	0.89	2.08	0.95
Difficulty focusing	24	1.63	0.90	1.08	0.28
Increased Salivation	24	1.29	0.84	1.17	0.47
Sweating	24	1.08	0.28	1.04	0.20
Nausea	24	1.17	0.47	1.25	0.60
Difficulty concentration	24	1.54	0.82	1.42	0.57
Fullness of head	24	1.29	0.54	1.25	0.52
Blurred Vision	24	1.46	0.64	1.13	0.44
Dizzy with eyes open	24	1.38	0.63	1.42	0.76
Dizzy with eyes closed	24	1.04	0.20	1.04	0.20
Vertigo	24	1.08	0.28	1.17	0.37
Stomach awareness	24	1.08	0.40	1.08	0.40
Burping	24	1.04	0.20	1.08	0.28
Total		**1.47**	**0.83**	**1.37**	**0.75**

Participants ranked the highest mean score in Eyestrain of the IoTD-V condition (M=2.63, SD=0.70), and the lowest in Burping of the Non-corrected Near condition (M=1.00, SD=0.00).

IoTD-tilted condition (M=1.53, SD=0.86) was ranked as the highest mean score among six different conditions. Non-corrected Natural condition and IoTD-Vertical condition was followed. H/V meridian-Natural (Horizontal & meridian bars at natural distance) condition was ranked as the lowest score among all six conditions(M=1.37, SD=0.75). This was expected since the condition has none of the error occurred by the ocular determinants. However, Non-corrected Near condition ranked the second lowest mean score among the conditions (M=1.41, SD=0.76). This is surprising because in the relevant experiment, Non-corrected Near condition is designed to maintain all the errors occurred by accommodation-vergence linkage, IoTD, and misleading self-verticality cue. In comparism between H/V meridian-Near state and Natural state, H/V meridian-Near state(M=1.47, SD=0.83)-the accommodation-vergence mismatch condition- had the higher mean score than the H/V meridian-Natrual state(M=1.37, SD=0.75), without the accommodation-vergence mismatch. However, the accommodation-vergence mismatch condition showed a lower mean score in comparism between Non-corrected Natural(M=1.51, SD=0.87) and Non-corrected Near (M=1.41, SD=0.76) condition.

Chapter 6. Discussion

6.1. Vergence-accommodation linkage

To examine the contribution of the relevant mechanism, differences in the measurements of indicators for cybersickness between the Non-corrected Natural condition and Non-corrected Near condition should be observed. Moreover, differences between H/V meridian-Near condition and H/V meridian-Natural condition are also a method for examining the degree of contribution by this mechanism.

The mean pulse rate under Non-corrected Natural condition being lower than that under Non-corrected Near condition is evidentiary to increased cybersickness if the AC/A ratio is disturbed. However, in the case of the participants mean score for the item of SSQ-Oculomotor, it was found that the participants reported higher degrees of fatigue under H/V meridian-Near condition than under H/V meridian-Natural condition, though not significant ($p = 0.05$). To be consistent with the results of the above observation, eye fatigue should be lower under condition H/V meridian-Natural condition, where the AC/A ratio was maintained, than under condition H/V meridian-Near condition, where the AC/A ratio was disturbed. Moreover, the score for the item of SSQ-Oculomotor was significantly higher under the IoTD-V condition than under Non-corrected Natural condition. Since Non-corrected Natural condition assumed that IoTD error would not occur as well as the vergence-accommodation linkage would not be broken, and a wrong verticality cue will not be provided, the comparison was similar to that between H/V meridian-Near condition and H/V meridian-Natural condition. Therefore, it may be said that this evidence is different from the expectation that cybersickness symptoms will decrease in a situation where vergence-accommodation linkage is expected to be disrupted.

This can have two different interpretations. First, it is conceivable that the optical power cannot fully change with the characteristics of physical stimuli due to individual physical characteristics. Thus, although the device is set to present the HMD screen at a distance of 2 m, if the thickness of the optical power is altered so as to view a nearer object. It may be assumed that the disruption degree of vergence-accommodation linkage will be rather less when viewing an object located at a distance nearer than 2 m. In particular, a distance of 50 cm, usually called ‘reachable space,’ is the distance between the eye and an electronic device such as a computer or a notebook computer used by modern people. If people are accustomed to viewing objects at this distance, it is possible that the accommodating power fail to reach required levels when viewing distant objects. This may be the probable interpretation in the case of short-sighted people (Gwiazda et al., 2005).

The second possible interpretation is that the accommodation distance changes at the moment of wearing the HMD. Indeed, this is called psychological “awareness of distance” (Ogle and Martens, 1957). Despite the device setting that makes the bar appear as if it is 2 m away, upon wearing the HMD, prior knowledge about the length of the HMD can make one think that the screen is located nearer than 2 m, thereby shortening the distance of accommodation. As a result, to maintain a value of AC/A ratio close to 1, accommodative convergence is also adjusted to a situation of viewing an object at a distance shorter than 2 m; thus, it may be supposed that the object located nearer than 2 m causes less cybersickness. In addition, while wearing the HMD, the tightening of a Velcro worn around the head or the weight of the HMD continues to provide proximity cues, that is, cues that make one think that an experiment stimulus in sight is in fact provided by the HMD close to the eye, thereby creating the possibility of causing changes in accommodation.

It might be thought that cybersickness will increase simply in proportion to the degree of the breakage of vergence-accommodation linkage; however, given experimental results showing that the characteristics of the linkage vary with individual user's physical characteristics and various environment variables in a situation where the HMD is used, it is deemed that more consideration will need be given to an individual user's vergence-accommodation linkage. Listing's plane may be settled closer on the 0.5-m distance due to the proximal cues

6.2. Interocular torsional disparity

To examine the contribution of the relevant mechanism, it should be observed whether there are differences in the measurement values of indicators for cybersickness between Non-corrected Near condition and IoTD-T condition. In the case of pulse rate, its mean was higher under Non-corrected Near condition than under IoTD-T condition. The value of COP sway area was also found to be significantly lower under IoTD-T condition than under Non-corrected Near condition. These results can be evidence supporting the argument that cybersickness is significantly reduced by the correction of IoTD.

As for the lack of significant difference in the other measuring indicators between Non-corrected Near and IoTD-T conditions, it may be presumed that few adverse effects due to lack of correction appear because the eyes carry out an additional correction to resolve the situation of non-IoTD correction.

According to the Predictive Coding theory, long-termed errors, which are assumed to be processed in the cerebellum, are expected to require system calibration while short-term changes, mainly processed in the frontal lobe do not require recalibrating the system. Therefore, it can be expected that the effects of the lack of IoTD correction will appear in the HMD experience if the experience lasts for a longer time, not for within 5 minutes as in the experimental conditions.

6.3. Visual and vestibular verticality cues

To examine precisely the contribution of the relevant mechanism, differences in values of indicators between IoTD-V condition and IoTD-T condition should be observed. A significant difference between IoTD-V and IoTD-V conditions was only found in the indicator of sway area, and the other indicators showed no significant difference between the two conditions. In the case of the sway area, the interpretation might be that the importance of the visual and vestibular verticality cue decreased because the sway area was significantly narrower under IoTD-T condition than under IoTD-V condition. To think about the limitations of IoTD-V condition, however, when the participant looks at the fixation point of the screen, the bars fail to provide proper cues, but appear to be tilted toward the outside because the bars presented at oblique positions are under the state of the continuous application of IoTD correction. However, when the gaze shifts towards the target bar, the bar appears to be vertical as a result of the IoTD correction following Listing's law. Thus, because the properties of verticality cues are perceived differently when the gaze is in the center and when it is oblique, it becomes difficult to predict on which information to be referred as the SVV cue. By this result, the errors will be accumulated, which may lead to the lack of a significant difference between the IoTD-V and IoTD-T conditions in the values of measuring indicators, or even that IoTD-V condition is construed as causing more sickness.

However, there is a tendency shown in the SSQ score of SVV error remaining conditions (IoTD-T, Non-corrected Natural condition) ranking the higher mean score compared to the error compensated conditions(IoTD-V, H/V meridian-Near and Natural) on the Disorientation related symptom groups. This shows the possibility of the visual and vestibular verticality cue as a considerable factor causing cybersickness.

6.4. Other influential factors causing discomfort

There may be some influence of the HMD lens artifacts. This experiment particularly involves saccades to longer distance involving the periphery side of the FOV. The low quality of the lens may lead to distortion of the image, especially in the peripheral area. Furthermore, since there is no way to personalize simultaneously both the accommodation state and the IPD state, even the most sophisticated methods cannot completely eliminate the errors. Further research and comparisons are needed with the advances in VR technology.

6.5 Conclusion

In the present experiment we have investigated that the visual and oculomotor determinants may effect on the discomforts during HMD use. It is verified that the condition with none of the mismatches ocuured by the ocular determinants suggested in this paper ranked the lowest SSQ mean score among the Oculomotor related symptom group.

The present experiment suggested that vergence-accommodation linkage and IoTD can be considered as a cause inducing discomforts. Especially IoTD is considered as a significant factor, as the value of COP sway area in the IoTD treated condition was found to be significantly lower than the untreated conditions. The torsional difference of each eye may cause diplopia, and also give misleading verticality cues causing disorientation and dizziness. Hence, warping the different amount of torsion on display in the oblique position of the peripheral area could be suggested the methods to reduce the side effects of using the HMD, and may be a solution for reducing eye fatigue and diplopia.

However, further research and comparisons are needed to verify if the HMD designed in this paper can be suggested as a better alternative to the traditional HMD displays.

More valuable insights are expected if the evaluation would be conducted by simultaneously measuring the physiological signals and assessing the effectiveness and usability. Iconic memory task or other cognitive tests are suggested in future research.

References

Campbell, F. W. (1957). The depth of field of the human eye. Journal of Modern Optics, 4(4), 157-164.

Card, S. K., Newell, A., & Moran, T. P. (1983). The psychology of human-computer interaction.

Cowings, P. S., Suter, S., Toscano, W. B., Kamiya, J., & Naifeh, K. (1986). General autonomic components of motion sickness. Psychophysiology, 23(5), 542-551.

Dennison, M. S., Wisti, A. Z., & D'Zmura, M. (2016). Use of physiological signals to predict cybersickness. Displays, 44, 42-52.

Dünser, A., Grasset, R., Seichter, H., & Billinghurst, M. (2007). Applying HCI principles to AR systems design.

Fesharaki, M., Karagiannis, P., Tweed, D., Sharpe, J. A., & Wong, A. M. (2008). Adaptive neural mechanism for Listing's law revealed in patients with skew deviation caused by brainstem or cerebellar lesion. Investigative ophthalmology & visual science, 49(1), 204-214.

Geng, J. (2013). Three-dimensional display technologies. Advances in optics and photonics, 5(4), 456-535.

Goss, D. A. (1995). Ocular accommodation, convergence, and fixation disparity: a manual of clinical analysis. Elsevier Health Sciences.

Gwiazda, J., Thorn, F., & Held, R. (2005). Accommodation, accommodative convergence, and response AC/A ratios before and at the onset of myopia in children. Optometry & Vision Science, 82(4), 273-278.

Hakkinen, J., Vuori, T., & Paakka, M. (2002, October). Postural stability and sickness symptoms after HMD use. In IEEE International Conference on Systems, Man and Cybernetics (Vol. 1, pp. 147-152).

Hartson, R., & Pyla, P. S. (2012). The UX Book: Process and guidelines for ensuring a quality user experience. Elsevier.

Hasegawa, S., Omori, M., Watanabe, T., Fujikake, K., & Miyao, M. (2009). Lens accommodation to the stereoscopic vision on HMD. Virtual and Mixed Reality, 439-444.

Hewett, T. T., Baecker, R., Card, S., Carey, T., Gasen, J., Mantei, M., ... & Verplank, W. (1992). ACM SIGCHI curricula for human-computer interaction. ACM.

Hoffman, D. M., Girshick, A. R., Akeley, K., & Banks, M. S. (2008). Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. Journal of vision, 8(3), 33-33.

Howard, I. P., & Rogers, B. J. (1995). Binocular vision and stereopsis. Oxford University Press, USA.

Jerald, J. (2015). The VR book: Human-centered design for virtual reality. Morgan & Claypool.

Kapoula, Z., Bernotas, M., & Haslwanter, T. (1999). Listing's plane rotation with convergence: role of disparity, accommodation, and depth perception. Experimental brain research, 126(2), 175-186.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The international journal of aviation psychology, 3(3), 203-220.

Kim, Y. Y., Kim, H. J., Kim, E. N., Ko, H. D., & Kim, H. T. (2005). Characteristic changes in the physiological components of cybersickness. Psychophysiology, 42(5), 616-625.

Kirchner, M., Schubert, P., Schmidtbleicher, D., & Haas, C. T. (2012). Evaluation of the temporal structure of postural sway fluctuations based on a comprehensive set of analysis tools. Physica A: Statistical Mechanics and its Applications, 391(20), 4692-4703.

Lafond, D., Corriveau, H., Hébert, R., & Prince, F. (2004). Intrasession reliability of center of pressure measures of postural steadiness in healthy elderly people. Archives of physical medicine and rehabilitation, 85(6), 896-901.

Leigh, R. J., & Zee, D. S. (2015). The neurology of eye movements (Vol. 90). Oxford University Press, USA.

Manas, L. (1955). THE INCONSTANCY OF THE ACA RATIO*. Optometry & Vision Science, 32(6), 304-315.

Mok, D., Ro, A., Cadera, W., Crawford, J. D., & Vilis, T. (1992). Rotation of

Listing's plane during vergence. Vision research, 32(11), 2055-2064.

Nakayama, K., & Balliet, R. (1977). Listing's law, eye position sense, and perception of the vertical. Vision research, 17(3), 453-457.

Nalivaiko, E., Davis, S. L., Blackmore, K. L., Vakulin, A., & Nesbitt, K. V. (2015). Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time. Physiology & behavior, 151, 583-590.

Norman, D. A., & Shallice, T. (1980). Attention to action: Willed and automatic control of behavior (No. CHIP-99). CALIFORNIA UNIV SAN DIEGO LA JOLLA CENTER FOR HUMAN INFORMATION PROCESSING.

Norman, D. A. (2004). Emotional design: Why we love (or hate) everyday things. Basic Civitas Books.

Norman, D. (2013). The design of everyday things: Revised and expanded edition. Basic Books (AZ).

Ogle, K. N., & Martens, T. G. (1957). On the accommodative convergence and the proximal convergence. AMA archives of ophthalmology, 57(5), 702-715.

Park, D. S., & Lee, G. (2014). Validity and reliability of balance assessment software using the Nintendo Wii balance board: usability and validation. Journal of neuroengineering and rehabilitation, 11(1), 99.

Parker, A. J. (2007). Binocular depth perception and the cerebral cortex. Nature Reviews Neuroscience, 8(5), 379-391.

Parks, M. M. (1975). Ocular motility and strabismus. HarperCollins Publishers.

Riddell, P. M., Bullinaria, J. A., & Rushton, S. K. (1999). Modelling Adaptation in the Human Oculomotor System. In Connectionist Models in Cognitive Neuroscience (pp. 206-217). Springer London.

Roberts, T. L., Anderson, H. A., & Stuebing, K. K. (2015). Accommodative Gain in Relation to Perceived Target Clarity. Optometry and vision science: official publication of the American Academy of Optometry, 92(11), 1092-1102.

Rushton, S. K., & Riddell, P. M. (1999). Developing visual systems and exposure to virtual reality and stereo displays: some concerns and speculations about the demands on accommodation and vergence. Applied Ergonomics, 30(1), 69-78.

Somani, R. A., Desouza, J. F., Tweed, D., & Vilis, T. (1998). Visual test of Listing's law during vergence. Vision research, 38(6), 911-923.

Stoffregen, T. A., Faugloire, E., Yoshida, K., Flanagan, M. B., & Merhi, O. (2008). Motion sickness and postural sway in console video games. Human Factors, 50(2), 322-331.

Van Run, L. J., & Van den Berg, A. V. (1993). Binocular eye orientation during fixations: Listing's law extended to include eye vergence. Vision research, 33(5), 691-708.

Von Helmholtz, H. (1867). Handbuch der physiologischen Optik (Vol. 9). Voss.

Wong, A. M. (2004). Listing's law: clinical significance and implications for neural control. Survey of ophthalmology, 49(6), 563-575.

Appendix

Appendix 1. SSQ Questionnaire

	1 none	2 mild	3 moderate	4 Severe
General Discomfort				
Fatigue				
Headache				
Eyestrain				
Difficulty focusing				
Increased salivation				
Sweating				
Nausea				
Difficulty concentration				
Fullness of head				
Blurred Vision				
Dizziness with eyes open				
Dizziness with eyes closed				
Vertigo				
Stomach awareness				
Burping				

Appendix 2. Computation of SSQ Scores

Symptom \ Group	Disorientation	Oculomotor	Nausea
General Discomfort		1	1
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing	1	1	
Increased salivation			1
Sweating	1		1
Nausea			1
Difficulty concentration		1	1
Fullness of head	1		
Blurred Vision	1	1	
Dizziness with eyes open	1		
Dizziness with eyes closed	1		
Vertigo	1		
Stomach awareness			1
Burping			1

Abstract

최근 두부 장착형 디스플레이(HMD)등의 가상현실 구현 기술이 괄목할 만한 성장세에 있으나 어지럼증, 복시 등의 부작용 또한 빈발하여 문제가 되고 있다. 이에 보다 근본적인 대책 마련을 위해 그 부작용을 신경학적 기전에 입각하여 접근하고, 특히 그 원인일 가능성으로 제시되는 양안편차, 입체시 지각 등의 안구운동요소들을 추려내어 그 영향 정도를 실험적 연구로 검증하고자 하였다.

본 연구는 가상현실에서 발생하는 주요 부작용들이 시지각 과정에 관여되는 신경기전의 변화와 관련되어 발생할 것으로 정의하고, 그 차이를 관찰할 수 있는 디스플레이를 리스팅 법칙과 조절/폭주 비 등의 신경학적 원리에 기반하여 구성하였다. HMD 착용상태에서 단속성 안구운동(saccade)이 발생하는 과제를 설계하였으며, 검증을 위해 COP(Center of Pressure), 맥박 등의 생체신호를 수집하고, 어지러움 측정에 가장 널리 사용되는 SSQ(Simulator Sickness Questionnaire)설문을 활용해 증상과 징후를 통합적으로 파악하고자 했다. 실험 분석결과 COP 면적이 유의미하게 감소하였음을 확인하였으며, 맥박과 SSQ 등 다른 항목들에서도 일관된 경향성을 보였다.

본 연구의 의의는 HMD 착용시 예상되는 부작용을 신경학적 기전에 근거하여 통합적으로 파악하고, 동일한 형태를 가진 자극이라도 화면 내 배치된 양상에 따라 눈에 다르게 지각된다는 사실을 실험적으로 검증하였다는 점이다. 해당 연구결과를 발전시켜 이용자가 편안함을 느끼는 HMD 디스플레이 배치 방안을 제안할 수 있을 것이다.

주요어 :
두부장착형디스플레이(HMD), 가상현실, 신경학적 부작용, 시지각, 양안편차, 원근조절, 리스팅 법칙