A STUDY OF VIRTUAL REALITY CYBERSICKNESS AND CHANGES IN BINOCULAR VISUAL FUNCTION AND POSTURAL BALANCE

JAE-BEOM SON[1],JAE-MIN LEE[2],JEONG-LAE KIM[3],HYUN-SUNG LEEM[4]

[1]PhD, Eulji University, Department of Optometry, Republic of Korea

[2]PhD Cand,Eulji University, Department of Optometry, Republic of Korea; Master of Science, Southern California College of Optometry, Marshall B. Ketchum University, Department of Clinical Optometry, U.S.

[3]Prof, Eulji University, Department of Biomedical Engineering, Republic of Korea

[4]Prof, Eulji University, Department of Optometry, Republic of Korea (Corresponding author)

E-mail: [1]thswoqkfdl@gmail.com, [2]woals46qks@naver.com, [3]jlkim@eulji.ac.kr,[4]hsl@eulji.ac.kr

ABSTRACT

To analyze the causes of virtual reality (VR) cybersickness, which varies in severity from person to person after playing VR games using a head-mounted display (HMD) equipment, this study attempts to see how it affects binocular visual function and postural balance, and how it correlates with cybersickness. Before and after playing the VR game, the virtual reality sickness questionnaire (VRSQ) was used to objectively assess changes in cybersickness. Changes in binocular visual function were determined by measuring distance and near phoria, near point convergence (NPC), positive and negative fusional vergence at distance and near, and vergence facility. Finally, the stability index (SI) and fall risk index (FI) were confirmed using the TETRAX (balance ability test) to examine postural balance.Subjects were selected by controlling for variables such as age, corrected vision, and medical conditions that could affect the results. Significant changes in VRSQ, binocular visual function, and postural balance occurred after the VR game.

Keywords: *VIRTUAL REALITY(VR), HEAD-MOUNTED DISPLAY, CYBERSICKNESS, VIRTUAL REALITY(VR) MOTION SICKNESS, BINOCULAR VISUAL FUNCTION, BALANCE TEST (TETRAX)*

1. INTRODUCTION

Currently, VR is used in various fields such as mine simulation, aviation maintenance, surgery, etc., which are difficult to train in the real environment [1-3]. In addition, although you can go and experience the actual place, such as education [4], real estate [5], tourism [6], etc., you can experience the scene through VR even if you don't actually go there. Not only that, by implementing spaces that cannot be experienced in reality, such as games and movies, you can experience the other world as well as the actual real world through VR. Thus, with the development of new virtual reality (VR) devices and the increase of VR content, the VR industry is growing rapidly.Especially, the area where VR is most widely used today is gaming [7]. VR experiences in other fields are often aimed at education in areas that are difficult for ordinary people to experience in real life, so the number of users is not large. However, since games can easily access VR content by connecting a PC and head-mounted display (HMD) or a PC and smartphone, i.e., it has high accessibility, the number of VR game users is rapidly increasing. You can easily see roller coasters with VR devices and moving chairs in nearby large shopping malls, and VR cafes, where you can experience various VR games, have recently attracted attention as a dating course.

However, some VR users complain of symptoms of motion sickness, dizziness, nausea, and even vomiting in severe cases [8]. This is called VR sickness or cybersickness [9]. Before the introduction of HMD, cybersickness was an after-effect of experiencing implemented three-dimensional (3D) space through the use of 3D displays and 3D glasses, which were made of polarized or red-green glasses. But now it is one of the side effects people feel after experiencing VR through HMD. According to previous research on the causes of VR sickness, the sensory conflict

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theory and the postural instability theory are the most representative [10, 11]. Here, the sensory conflict theory is the theory that individual senses such as hearing, sight, and vestibular are not integrated into the brain, causing cybersickness. For example, the vestibular organ, which is responsible for body's sense of balance, is perceived as 'not moving' because the user is standing still while using VR. On the other hand, because the user is walking and moving briskly in VR, it is perceived as 'moving' in the visual stimulation (sense). In this way, this theory explains that cybersickness occurs because these individual senses collide with each other in the brain. Next, the postural instability theory suggests that cybersickness occurs because an unstable posture persists during VR use, unlike bodies that try to maintain postural stability every moment of life. In other words, in the artificial environment of VR, there is no need to control the body and posture according to the situation in the way that people have accumulated in life, so the unstable posture that is not suitable for the situation persists for a long time, and cybersickness occurs. Using the example of tightrope walking, in the real world you swing your body slightly from side to side to maintain balance, while in VR you stand still and walk the tightrope without this action, causing cybersickness due to an unstable posture inappropriate for the situation.

In addition, it can be assumed that cybersickness and binocular vision are closely related to each other through the operating principle of HMDs. The VR implementation method using HMD is to install a thick plus convex lens between the eye and the display to see the display in front of the eye. At this point, the display must be positioned closer to the eye than the focal length of the convex lens, thereby inducing an erect and magnified virtual image so that the image feels farther away than the actual display being viewed. Also, there is one video playing on the display, but each display for each eye has a different 'disparity'. It is an implementation in a virtual space of the stereopsis that occurs when we look through a binocular vision in real life.When we keep both eyes on an object in space, because of the difference in the field of view between the right and left eyes, different images of the object are focused on each eye. At this point, by fusing the different images into one in the brain, the object is perceived three-dimensionally, causing us to feel perspective, this is stereovision [12]. HMD, the equipment that implements virtual reality, creates a virtual three-dimensional effect through binocular disparity by displaying one video on two displays at each different disparity. This is done using a 3D screen and a polaroid lens. Namely, it is a method of implementation that uses the disparity created in the right and left eyes by the polaroid lens.

Long-term use of the aforementioned 3D display leads to fatigue and discomfort [13-17], reportedly due to visual fatigue caused by an imbalance between accommodation and convergence in the process of combining two different images [16, 18, 19]. Accommodation here refers to the adjustment of focus to bring the object into focus by adjusting the thickness of the lens. When looking at a distant object, we are in a static refractive state in which accommodation does not usually interfere, but when looking at a near object, it does. Thus, accommodative convergence appears, and proximal convergence also occurs because we perceive the object to be close. As such, accommodation, convergence, and miosis normally occur simultaneously in near viewing, but VR causes an imbalance between these mechanisms. As described above, virtual reality with HMD makes the right and left eyes see each different image through the screen, and it creates stereovision through natural binocular disparity and implements it as if an object is in the same place as the real thing. The problem arises in this area. Because the user sees the object on the screen through a plus spherical VR lens mounted on the HMD, the near display is constantly viewed. This causes accommodation and convergence. However, we see the image generated by the erect and magnified virtual. Therefore, we feel that the object is far away, so convergence does not occur and only accommodation is maintained. Thus, HMD VR technology technically implements binocular disparity, but the focus adjustment has technical limitations that cannot follow actual reality. If accommodative convergence is not occurring because the focus is not being controlled, it has the potential to affect near positive fusional convergence.

As you can see, the way HMDs work is closely related to binocular vision. In fact, many studies have recently been conducted on VR cybersickness and changes in visual function in binocular vision. It has been reported that watching VR videos with HMD equipment for a long time can increase the distance of the near point convergence (NPC), affect the change in the degree of phoria, and the accommodation power did not change after watching VR videos [20, 21]. In contrast, Long et al. showed that accommodation power was increased after VR gaming, but visual acuity, refractive error, and pupil size did not change [22].

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Therefore, since nothing has been clearly shown regarding the visual functions related to cybersickness, it seems that further follow-up research and correlation analysis between the two is needed.

Although research on VR sickness and its solutions continues in various approaches, a clear cause and solution for VR sickness have not yet been discovered. Therefore, to analyze the causes of cybersickness, this study aims to analyze the relationship between postural balance, which is the most representative cause of cybersickness, binocular visual function, and cybersickness.

2. MATERIALS AND METHODS

2.1 Participants

If we think about the cause of cybersickness in the grand scheme of things, the above theories will be representative. However, if we look more closely, there is research on personal and technical factors [9, 23-26]. First of all, the personal factors are included: the higher the age group, the more likely they are to feel VR sickness, in addition, if the user is unhealthy, the more severely likely it is, and if the user is a woman, the more severely likely it is because they have a wider field of view than men, etc. (Technical factors are discussed separately below.)

The study attempts to recruit subjects by minimizing the above factors. Participants included both men and women between the ages of 20 and 39. The person with less than 1.0 corrected visual acuity was excluded from the subject. If the size of the image formed in the right and left eyes is different, it will be impossible to integrate the VR images separated by the two eyes into one, which may affect the test results. Therefore, even if the corrected visual acuity was 1.0 or better, subjects with aniseikonia with a difference of 2.00 D or more between the right and left eye power were excluded. In addition, glasses wearers were excluded to eliminate the influence of prism effects caused by glasses wearers during VR use, and only contact lens wearers or subjects with emmetropia or refractive surgery were selected. All study procedures were approved by the Institutional Review Board (IRB, approval number: EU21-91), and study participants gave informed consent after receiving an adequate explanation of the informed consent form.

2.2 Measurements and Procedures

2.2.1 Binocular visual function test

Refraction to confirm refractive error was performed with an automatic phoropter (HRT-7000, Huvitz, USA), and NPC to confirm convergence amplitude was checked with a fixation rod and ruler. Next, the degree of distance and near phoria was tested to confirm the presence or absence using a Howell phoria card (3m, 40cm) and 6△ BU (base-up prism). In this case, exophoria is indicated by a minus sign, and esophoria by a plus sign. Positive and negative fusional vergence at distance and near to confirm convergence and divergence reserve were examined using an automatic phoropter, chart projector, near chart, and prism bar. Finally, the vergence facility test was measured with 3△ BI (base-in prism) and 12△ BO (base-out prism) flippers to confirm how many vergence repetitions they could perform in a limited time. All tests were repeated after playing the VR game to see if there was any change.

2.2.2 Virtual reality sickness questionnaire (VRSQ)

The simulator sickness questionnaire (SSQ) [27] is the most commonly used questionnaire to measure the degree of cybersickness caused by 3D. However, since this study is concerned with virtual reality environments rather than 3D environments, the VRSQ [28] is used, which is a modified version of the SSQ tailored to VR cybersickness caused by virtual reality using an HMD rather than cybersickness caused by simple 3D. The symptoms in the questionnaire are divided into two categories: oculomotor dysfunction and disorientation. Oculomotor dysfunction consists of four items: general discomfort, fatigue, eyestrain, and difficulty focusing. Disorientation is made up of five items: headache, fullness of the head (i.e., feeling that your head is full), blurred vision, dizziness with eyes closed, and vertigo with a spinning sensation. Symptoms were rated on a 4-point scale from 0 to 3, with higher scores indicating more severe symptoms(Table 1). The VRSQ, like the binocular visual function test, was administered both before and after playing the VR game.

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Table 1: Computation Of VRSQ Score

	VRSQ Symptom	Score
Oculomotor*	General discomfort	0-3
	Fatigue	0-3
	Eyestrain	0-3
	Difficulty focusing	0-3
Disorientation†	Headache	0-3
	Fullness of head	0-3
	Blurred vision	0-3
	Dizzy (eyes closed)	0-3
	Vertigo	0-3

Oculomotor* = ([1] / 12) * 100: [1] = Oculomotor total score, Disorientation† = ([2] / 15) * 100: [2] = Disorientation total score,Total score = (Oculomotor* + Disorientation†) / 2

2.2.3 Balance ability test (TETRAX)

TETRAX (Sunlight Inc, Israel) can check weight distribution and postural balance by measuring weights through a total of four force plates, one for the front and back of the right and left foot. This is the Balance Diagnostic System used in this study to confirm stability index (SI) and fall risk index (FI). The SI checks the subject's overall postural stability by measuring the degree of postural sway. A higher score indicates less postural stability. The FI is measured by analyzing the area, length, velocity, etc. of body sway in a static posture using four ground reaction force sensors. It is an index of fall risk, which is the risk of injury caused by sudden changes in body position, such as falling or slipping. In other words, the higher the FI, the higher the risk of being injured by slipping or falling from a height. Based on the score, it is divided into a total of three levels: low-risk level (0-35), medium-risk level (36-57), and high-risk level (58-100). These two tests were also repeated before and after playing the VR game.

TETRAX is measured in a total of eight postures: NO (natural standing posture with eyes open), NC (with eyes closed), PO (posture with both arms spread at 45 degrees with eyes open), PC (with eyes closed), HR (posture with head tilted to the right with eyes closed), HL (to the left), HB (to the back), and HF (to the front). Each posture was tested for 32 seconds per posture.

2.2.4 HMD device and content

The technical factors mentioned above that cause cybersickness include the following: the delay time of the screen, the mismatch between the user's field of view and the viewing angle of the HMD equipment, and the complex background, etc. Therefore, in order to minimize these effects of cybersickness caused by the device, the VIVE PRO2 full kit released by HTC Corporation in June 2021 was used as the VR HMD device because of its high resolution and ability to align the focus with the eye as accurately as possible. It has a high-resolution image quality of 5K, 2448 x 2448 pixels per eye (4896 x 2448 pixels combined), and an adjustable inter-pupillary distance (IPD) from 57 to 70 mm. In addition, to minimize the effects of cybersickness caused by lagging and viewing angle, it supports a wide viewing angle of up to 120 degrees (horizontal) compared to other devices, and the refresh rate, which expresses the smoothness of the screen, can use up to 120 Hz. Not only that, two base stations (HTC VIVE Base Station 2.0) were used to accurately track the subject's movement and location, and two controllers (HTC VIVE Controller, 2018) were used together to enable manipulation, such as moving around or moving objects within the virtual world.

The game of choice for this study is Half-Life: Alyx, a VR FPS (first-person shooter) game released by Valve Corporation on the Steam VR platform in March 2020. To attract the interest of the subjects, games that have a good response among users were selected, and among them, the game that can maximize cybersickness due to its high realism was chosen. The total time of the VR game, excluding the time needed to explain the operation method and the game, was 30 minutes to allow enough time to induce cybersickness.

2.2.5 Statistical analysis

Statistical analysis was performed using SPSS Statistics 26.00 (SPSS Inc, Chicago, IL, USA). Normality of results was tested using the Sapiro-Wilks test, and the paired t-test was used to compare TETRAX balance test results (SI and FI) in 8 postures (NO, NC, PO, PC, HR, HL, HB, and HF), VRSQ scores, and binocular visual function test results (NPC, degree of phoria at distance and near, positive and negative fusional vergence at distance and near, and vergence facility) before and after playing the VR game. Correlations between binocular visual function, VRSQ, and TETRAX were checked by Pearson Correlation Coefficient (PCC), and when the significance level was less

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than 0.05, the results were considered significant differences.

3. RESULTS

3.1 Subject Characteristics

As shown in Table 2, there were 32 subjects, 12 males and 20 females, and the mean for refractive error of the subjects was OD -2.78 ± 2.61 D and OS -2.58 ± 2.42 D.

Table 2: Characteristic Of Subjects

	Mean ± SD		
	Male (n=12)	Female (n=20)	Total (n=32)
Mean age	28.25 ± 4.50	22.95 ± 2.44	24.94 ± 4.20
Refractive errors (S.E‡) (Diopter, Mean ± SD)			
OD§	-1.75±2.67	-3.40±2.44	-2.78±2.61
OS‖	-1.88±2.65	-3.00±2.23	-2.58±2.42

S.E‡ = Spherical equivalent,OD§ = Oculus dexter,OS‖ = Oculus sinister

3.2 Binocular Visual Function

As shown in Table 3, the NPC ($p < 0.001$) was significantly farther away after playing the VR game than before playing the VR game, and the degree of distance ($p = 0.016$) and near ($p < 0.001$) phoria also significantly increased in the exophoria direction. In addition, the negative ($p = 0.039$) and positive ($p = 0.001$) fusional vergence at distance, the negative ($p = 0.008$) and positive ($p < 0.001$) fusional vergence at near, and the vergence facility ($p = 0.015$) were all statistically significantly decreased.

Table 3: Changes In Binocular Visual Function Before And After Playing The VR Game

	Mean ± SD		t	p
	Before	After		
NPC (cm)	5.45 ± 1.59	7.58 ± 2.06	-10.929	**< 0.001*****
Distance phoria (△)	-1.47 ± 2.23	-1.75 ± 2.41	2.560	**0.016***
Near phoria(△)	-4.50 ± 4.43	-6.34 ± 4.76	7.886	**< 0.001*****
Distance BI vergence¶ (△)	11.09 ± 2.44	10.75 ± 2.44	2.156	**0.039***
Distance BO vergence# (△)	22.66 ± 5.66	20.50 ± 5.73	3.501	**0.001****
Near BI vergence** (△)	20.88 ± 4.26	19.91 ± 4.53	2.821	**0.008****
Near BO vergence†(△)	25.16 ± 8.10	19.44 ± 6.92	8.869	**< 0.001*****
Vergence facility (cpm)	14.19 ± 2.58	13.41 ± 3.07	2.573	**0.015***

Distance BI vergence¶ = Distance negative fusional vergence,Distance BO vergence# = Distance positive fusional vergence,Near BI vergence** = Near negative fusional vergence, Near BO vergence† = Near positive fusional vergence
*p< 0.05, **p< 0.01, ***p< 0.001

3.3 VRSQ

As shown in Table 4, scores for total oculomotor ($p < 0.001$), general discomfort ($p < 0.001$), fatigue ($p < 0.001$), eyestrain ($p < 0.001$), and difficulty focusing ($p < 0.001$) increased significantly after playing the VR game. Similarly, scores for total disorientation ($p < 0.001$), headache ($p < 0.001$), fullness of the head ($p < 0.001$), blurred vision ($p = 0.004$), dizziness with eyes closed ($p < 0.001$), and vertigo with spinning sensation ($p < 0.001$) increased significantly. Finally, the total VRSQ score ($p < 0.001$) also increased significantly. All this indicates that the participants experienced symptoms of cybersickness after playing the VR game.

Table 4: Changes In VRSQ Score Before And After Playing The VR Game

	Mean ± SD		t	p
	Before	After		
General discomfort	0.09 ± 0.39	1.09 ± 0.86	-6.715	**< 0.001*****
Fatigue	0.44 ± 0.62	1.50 ± 0.80	-7.155	**< 0.001*****
Eyestrain	0.19 ± 0.47	1.31 ± 0.97	-6.313	**< 0.001*****
Difficulty focusing	0.31 ± 0.54	1.50 ± 0.88	-8.609	**< 0.001*****
Headache	0.09 ± 0.30	0.75 ± 0.88	-4.289	**< 0.001*****
Fullness of head	0.03 ± 0.18	1.38 ± 1.07	-7.132	**< 0.001*****
Blured vision	0.13 ± 0.34	0.56 ± 0.80	-3.091	**0.004****
Dizzy (eyes closed)	0.03 ± 0.18	1.28 ± 1.09	-6.562	**< 0.001*****
Vertigo	0.13 ± 0.34	1.50 ± 1.05	-6.891	**< 0.001*****
Oculomotor	8.59 ± 12.43	44.79 ± 22.17	-9.894	**< 0.001*****

Disorientation	2.71 ± 5.83	36.25 ± 26.07	-7.616	**< 0.001*****
Total Score	5.65 ± 7.93	40.52 ± 22.90	-9.170	**< 0.001*****

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

3.4 TETRAX

3.4.1 SI

As shown in Table 5, the SI showed a significant increase in all postures after playing the VR game (all, $p < 0.01$).

Table 5: Changes In The SI In 8 Postures Before And After Playing The VR Game

	Mean ± SD		t	p
	Before	After		
NO	15.61 ± 4.83	23.88 ± 14.29	-3.631	**0.001****
NC	18.20 ± 7.59	22.86 ± 8.05	-3.716	**0.001****
PO	13.52 ± 4.89	17.90 ± 7.05	-3.695	**0.001****
PC	18.31 ± 6.87	21.55 ± 9.24	-3.207	**0.003****
HR	17.89 ± 7.01	22.19 ± 9.05	-3.401	**0.002****
HL	19.24 ± 6.79	23.12 ± 8.23	-3.209	**0.003****
HB	22.30 ± 9.92	28.86 ± 12.75	-4.146	**< 0.001*****
HF	20.09 ± 7.26	25.98 ± 9.57	-4.799	**< 0.001*****

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

3.4.2 FI

As shown in Table 6, the FI was statistically significantly increased after playing the VR game ($p < 0.001$).

Table 6: Changes In The FI Before And After Playing The VR Game

	Mean ± SD		t	p
	Before	After		
FI	26.00 ± 20.59	55.63 ± 25.50	-8.847	**< 0.001*****

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

3.5 Correlation Analysis

3.5.1 Correlation of binocular visual function with change in VRSQ scores

This study analyzed the correlation between binocular visual function before playing the VR game and the degree of change from before in VRSQ scores after playing the VR game. As shown in Table 7, Figure 1, and Figure 2, the changes in the oculomotor dysfunction score had a significant negative correlation with distance positive fusional vergence before playing the VR game ($p = 0.034$). Changes in the disorientation score had a significant negative correlation with distance positive fusional vergence ($p = 0.004$) and near positive fusional vergence ($p = 0.017$) before playing the VR game. In addition, when calculated as the total score of the VRSQ, it showed a significant negative correlation with distance positive fusional vergence ($p = 0.007$) and near positive fusional vergence ($p = 0.024$) before playing the VR game. This means that the smaller the positive fusional vergence at distance and near before playing the VR game, the greater the degree of change in VRSQ scores. In other words, the more VR cybersickness is experienced.

Table 7: Correlation Between Binocular Visual Function Before Playing The VR Game And The Degree Of Change From Before In VRSQ Scores After Playing The VR Game

Before VR game	Before – After comparison					
	Oculomotor		Disorientation		Total	
	r	p	r	p	r	p
NPC (cm)	-0.082	0.657	-0.043	0.814	-0.064	0.727
Distance phoria (△)	0.036	0.845	0.029	0.875	0.034	0.853
Near phoria (△)	0.016	0.930	0.032	0.861	0.026	0.886
Distance BI vergence (△)	-0.192	0.293	-0.312	0.083	-0.273	0.131
Distance BO vergence(△)	**-0.375**	**0.034***	**-0.494**	**0.004****	**-0.466**	**0.007****
Near BI vergence(△)	-0.118	0.521	-0.058	0.751	-0.090	0.622

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Near BO vergence (△)	-0.325	0.069	**-0.418**	**0.017***	**-0.399**	**0.024***
Vergence facility (cpm)	0.005	0.980	-0.027	0.882	-0.014	0.941

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

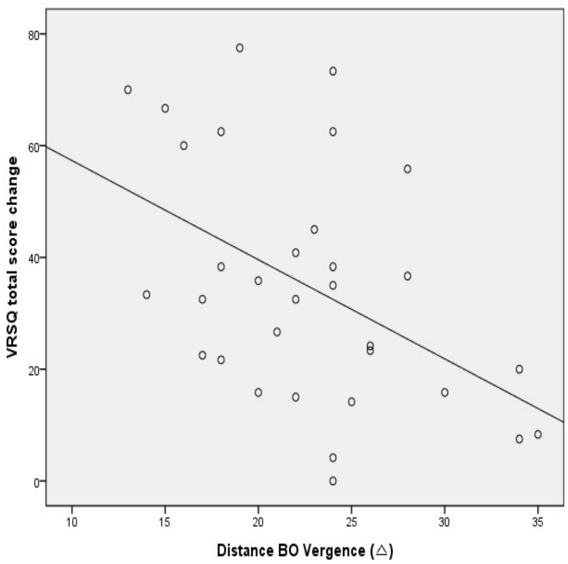

Figure 1: Negative Correlation Between Distance BO Vergence And VRSQ Total Score Change

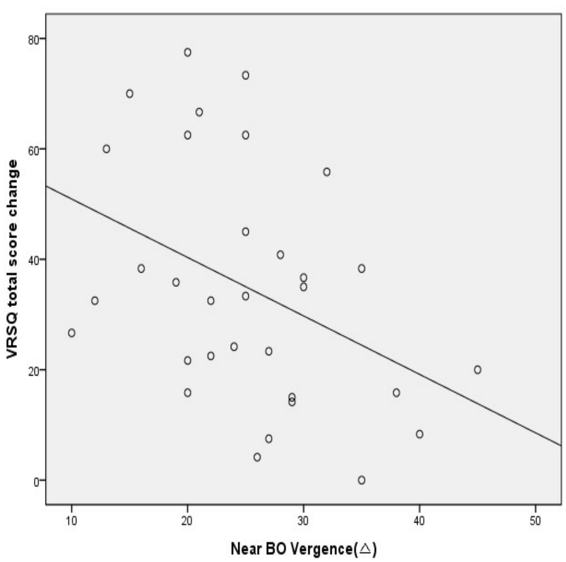

Figure 2: Negative Correlation Between Near BO Vergence And VRSQ Total Score Change

3.5.2 Correlation of VRSQ scores with change in TETRAX

When this study analyzed the correlation between the VRSQ scores before playing the VR game and the degree of change from before in TETRAX after playing the VR game, the correlation was significant only for the SI change. As shown in Table 8 and Figure 3, there was a significant positive correlation between the oculomotor dysfunction score, disorientation score, and total VRSQ score before playing the VR game, and the SI change in the PO posture (all, $p < 0.05$). This means that the higher the score on the VRSQ before playing the VR game, the greater the degree of change in postural stability in the PO position, similar to the position in which users play the VR game. In other words, the worse the postural stability in the PO position. These results explain the impact of the user's health on VR cybersickness among the personal factors mentioned above.

Table 8: Correlation Between The VRSQ Scores Before Playing The VR Game And The Degree Of Change From Before In The TETRAX After Playing The VR Game

Before – After comparison	Before VR game					
	Oculomotor		Disorientation		Total	
	r	*p*	*r*	*p*	*r*	*p*
FI	0.338	0.059	0.026	0.890	0.274	0.129
NO (SI)	0.234	0.198	0.179	0.326	0.249	0.169
NC (SI)	0.242	0.182	0.086	0.639	0.221	0.224
PO (SI)	**0.362**	**0.042***	**0.386**	**0.029***	**0.426**	**0.015***
PC (SI)	0.093	0.611	0.208	0.254	0.150	0.414
HR (SI)	0.103	0.574	-0.013	0.942	0.076	0.680
HL (SI)	0.256	0.158	0.224	0.217	0.283	0.117
HB (SI)	0.112	0.542	0.244	0.178	0.177	0.331
HF (SI)	0.126	0.491	0.205	0.260	0.175	0.339

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

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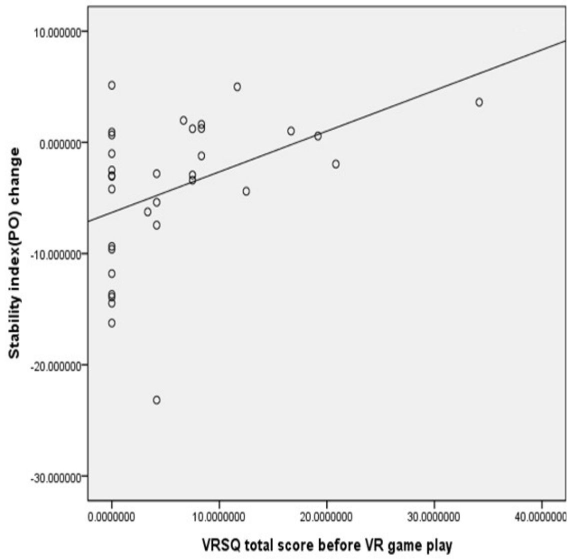

Figure 3: Positive Correlation Between SI Change In PO Posture And VRSQ Total Score

4. DISCUSSION

This study aimed to confirm the change in binocular visual function, balance ability (via TETRAX), and VR cybersickness level (via VRSQ) before and after playing the VR game, and the correlation between them.

This study showed significant changes in binocular visual function after playing the VR game. Alhassan et al. reported no change in distance and near phoria [29]. In contrast, Elias et al. showed an increase in distance and near phoria in the exophoria direction after playing the VR game [30], which is consistent with the results of this study. In addition, Alhassan et al. reported a decrease in both positive and negative fusional vergence at near after playing the VR game [29]. Similarly, in this study, both positive and negative fusional vergence were reduced at near. However, in this study, positive and negative fusional vergence were also significantly reduced at distance, whereas Alhassan et al. reported no significant change [29]. Finally, Alhassan et al. [29] and Munsamy et al. [31] reported an increase in vergence facility after playing the VR game, but it was significantly reduced in this study(Table 3).As mentioned above, the results of this study differ in some ways from previous studies, which we believe may be due to differences in the content and equipment used, also the individual binocular visual function status of the subjects, etc.

After experiencing VR content with an HMD, various changes in binocular visual function are thought to be caused by the structure of the VR lens inside the HMD. The lenses used in the optical lens portion of many VR devices today are primarily biconvex or plane convex Fresnel lenses of approximately +40.00D or more. Among these, plane convex lenses are currently the most commonly used. When these lenses have a power of + 40.00 D and above, the thickness is too thick for the HMD. Therefore, a Fresnel lens shape is used to reduce the thickness. When we look at the point away from the optical center, we are affected by the prism. Even though the thickness may look thin, the higher the power of the lens, the greater the effect. Lamoreux et al. showed that if visual acuity decreases, stereoscopic vision is reduced, and the risk of falling increases [32]. In this study, we tried to minimize this effect by using a device that can adjust the PD before the game starts, so that each individual's PD can be tailored.However, even if the pupillary distance (PD) of the eye is accurately aligned with the optical center of the optical lens mounted on the HMD by adjusting the IPD in the HMD, when the user looks at the near object in the VR video, he/she will perceive that there is near even though he/she is actually viewing the display at the same distance. This triggers proximal convergence, causing the user to be influenced by the BO prism created by the plus lens. Eventually, this causes exophoria and fusional convergence is used more than necessary. In this case, accommodation is not provided by the +40.00D optical lens mounted on the HMD, so accommodative convergence does not occur, and fusional convergence is overused as much as the lack of accommodative convergence. In other words, if people do not have enough near positive fusion reserve (i.e., convergence reserve), they will experience asthenopia due to the effect of the prism when using an HMD to experience VR, and this will lead to symptoms of cybersickness. In this study, the lower the positive fusional vergence at distance and near, the higher the VRSQ scores, which is consistent with the above explanation (Table 7, Figure 1, and Figure 2). Although further research is needed, it is suggested that testing positive fusional vergence at distance and near in advance can be used as an index to predict the degree to which the user will experience VR cybersickness before purchasing an HMD to experience VR games. In addition, Cho et al. [33] showed that vision therapy such as extraocular muscle reinforcement training (EMRT), binocular fusion stimulus training (BFT), fusional vergence training (FVT), eye tracking reinforcement training (ETRT), etc. alleviated the symptoms of VR cybersickness, and Preciado et al. [34] also reported that vision training can reduce VR cybersickness. Although more research is required, it is possible that improving visual function through training can reduce VR cybersickness.

It is also considered that the cause is the mismatch between accommodation and convergence, which is not the effect of the prism. As described earlier, there is no large change in accommodation because the user is looking at the display at the same distance, whereas convergence and divergence are repeated as the object in VR is repeatedly moved closer and farther away. This is in contrast to the usual mechanism by which convergence, accommodation, and miosis occur sequentially when we look near. Choi et al. [35] showed that visual fatigue is caused by a mismatch between accommodation and convergence, and Park et al. [36] also reported that binocular fusion is disrupted by a mismatch between accommodation and convergence. It seems that further research is needed to determine whether the changes in binocular visual function are due to a mismatch between accommodation and convergence or to the VR lenses mounted on the HMD.

In this study, not only did positive fusional vergence decrease but so did negative fusional vergence in both distance and near. Alhassan et al. [29] found a significant decrease in near negative fusional vergence, which is consistent with the results of this study, and no statistically significant change in distance negative fusional vergence, which is contrary to the findings of this study. This is believed to be due to the prism effect caused by the lenses in the VR when the user looks to the right or left while playing the VR game. Since this study used an FPS game, it is expected that the eyes would have been constantly moving faster and wider under tension to detect and eliminate fast-moving and suddenly appearing aliens. When looking to the right, the right eye is affected by the BI prism, and the left eye is affected by the BO prism, causing it to look further to the right than the original fixation point. Conversely, when looking to the left, the right eye is affected by the BO prism, and the left eye is affected by the BI prism, causing it to look further to the left than the original fixation point. Since this affects the extraocular muscle, it is assumed that these results are due to the increased strain on the extraocular muscle.

SI is statistically significantly increased in all postures after playing the VR game, and FI also increased from low to medium-risk grade. This means that it is necessary to reduce the degree of cybersickness by taking sufficient rest immediately after playing VR games, because the decrease in balance ability that occurs after playing VR games with HMD leads to a decrease in postural stability and sense of equilibrium, and increases the likelihood of falling.

This study found a significant increase in VR cybersickness via the VRSQ after playing the VR game, and a significant positive correlation between VRSQ scores before playing the VR game and PO posture. (Table 4, Table 8, and Figure 3). This suggests that the higher the VRSQ score before playing the VR game, the worse the postural stability in a PO posture similar to the posture during gameplay. This implies a higher likelihood of experiencing cybersickness symptoms. However, it is believed that the relationship between postural stability and VR cybersickness requires further research.

As advances in VR content and equipment make it possible to experience a world that increasingly resembles reality, research is being conducted in various fields to reduce VR cybersickness after experiencing VR content to address the problem of cybersickness. However, because the onset and severity of cybersickness varies from person to person, there is no perfect solution yet that can reliably help solve all the problems that arise differently for each user. Previous studies have focused on the relationship between cybersickness and binocular visual function by addressing only the visual aspect of simple 'VR viewing'. However, our body's senses are not independent, but have a very close relationship with each other, for example, the vestibular senses, which are responsible for the balance of our body, and the visual senses have a very close relationship. This is easy to deduce, given that the most widely accepted theory of the cause of cybersickness is that it's caused by a conflict between the vestibular and visual senses. Similarly, the results of this study also showed that the occurrence of cybersickness induced changes in binocular visual function, postural stability, and fall risk. Like this, we believe it is necessary to conduct further complex research by interweaving multiple factors. Therefore, unlike previous studies, this study did not focus on a single field, but rather followed the concept of interdisciplinary research, and this study tried to identify and analyze the causes of cybersickness by confirming the correlation and adding other factors related to vision based on sensory conflict theory. To this end, this study added postural stability and fall risk to the study of binocular visual function changes and correlations using the TETRAX, which is used for postural balance testing, and confirmed the correlation with them. Although the diversity of factors was lacking, it was a novel attempt to combine two or more factors to analyze cybersickness. We believe that further research combining various factors is needed to identify the causes of cybersickness and find solutions in the future, and we hope that this study will serve as a cornerstone and help the process of interdisciplinary research to find solutions to VR cybersickness caused by HMDs. In addition, although further research is needed for reliability, this study confirmed the result that ‘the lower the amount of positive fusional vergence before playing the VR game, the higher the degree of cybersickness experienced’. Thus, there is a possibility that it can predict the degree of cybersickness by measuring positive fusional vergence before using HMD VR devices, so we believe that this is considered a very significant possibility in terms of ‘developing a quantification tool to measure cybersickness’.

5. CONCLUSION

In conclusion, the results of this study showed that playing VR games with an HMD affected binocular visual function and postural balance. After playing the VR game, the NPC became more distant, the degree of distance and near phoria increased in the exophoria direction, the positive and negative fusional vergence at distance and near decreased, and the vergence facility also decreased. In addition, the lower the positive fusional vergence at distance and near before playing the VR game, the more the VR cybersickness was experienced. This suggests that it may be possible to predict VR cybersickness by testing for the positive fusional vergence at distance and near before experiencing the HMD device. Also, after playing VR games, due to the decreased balance ability, the postural stability and sense of balance are decreased, and the risk of falling is increased, so it seems that it is necessary to fully recover from cybersickness through sufficient rest to reduce the risk of injury immediately after playing VR games.

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