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Master's Thesis
Academic Year 2020

Comfortable Locomotion in Virtual Reality Space with fNIRS

Keio University
Graduate School of Media Design

Hiroo Yamamura

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Hiroo Yamamura

Master's Thesis Advisory Committee:

Professor Kai Kunze	(Main Research Supervisor)
Professor Akira Kato	(Sub Research Supervisor)

Master's Thesis Review Committee:

Professor Kai Kunze	(Chair)
Professor Akira Kato	(Co-Reviewer)
Professor Keiko Okawa	(Co-Reviewer)

Abstract of Master's Thesis of Academic Year 2020

Comfortable Locomotion in Virtual Reality Space with fNIRS

Category: Science / Engineering

Summary

Cybersickness is one of the main challenges when trying to accomplish comfortable VR locomotion. When users move in a VR space that is much larger than the real space, there is a mismatch between the visual information they get from the VR space and what their body experiences. This can cause serious physical disorders. Narrowing the field of view (FOV) is known as an effective way to mitigate cybersickness but it also reduces immersion in VR locomotion. It means reducing cybersickness is a trade-off for immersion and presence in VR locomotion. Besides, it noted that there is a great deal of individual variation in the degree of cybersickness. So that optimal measures that appropriate each user who have individual tolerance to cybersickness and current states of the users are needed. In this paper, we try to detect cybersickness based on the total hemoglobin (Hbt) concentration change measured via an fNIRS device and we try to mitigate cybersickness by dynamically changing FOV. In this experiment, participants experienced VR locomotion with dynamically FOV controlled by velocity changes and by Hbt value. We evaluated the degree of cybersickness and immersion by physiological data from fNIRS device and questionnaire. Our data suggests that fNIRS can detect subjective cybersickness and reduce that without interfering with immersion in VR by dynamically controlling the FOV with fNIRS.

Keywords:

virtual reality, fNIRS, FOV, cybersickness, locomotion

Keio University Graduate School of Media Design

Hiroo Yamamura

Contents

List of Figures

List of Tables

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Chapter 1
Introduction

1.1. Introduction

Various virtual reality(VR) contents are appearing with the increasing demand for remote work and the development of video technology. Especially, VR devices that integrated head-mounted display (HMD) came into widespread use. VR locomotion has an important role to play in the future development of VR content. VR locomotion is the technology that provides the sensation of moving in a virtual reality space that has a different structure and environment(Ragozin et al. 2020, Pai and Kunze 2017, Outram et al. 2018, Pai et al. 2018, Tregillus and Folmer 2016). This feature has the advantage of being able to experience VR in a much larger space compared to physical space. The joystick controller is widely used as an interaction to the VR space that has a much bigger space than physical space. It allows users to easily control however, it increases the cognitive intensity and causes cybersickness(Boletsis 2017). Cybersickness is similar to motion sickness, and it occurs the symptom like nausea and vertigo. These physical disorders can interfere with immersion in VR experience and need to be reduced. The serious problem that immersion in VR locomotion is also reduced occurs in proceeding to reduce cybersickness. In VR locomotion, the reproduction of detailed and accurate VR (manipulation techniques and image technologies) leads to a heightened sense of immersion in the VR experience but also highlights the differences from the physical space, and these differences can cause cybersickness. It means that the reduction of cybersickness incorporates a trade-off with respect to increasing immersion and presence.The measure that can alleviate cybersickness without interfering with immersion in the VR locomotion is needed.

1.2. Contribution

This study is an attempt to achieve a comfortable VR locomotion that can reduce the cybersickness while still ensuring immersion. Many kinds of methods are proposed to reduce cybersickness. However, these methods also reduce immersion. A measure that mitigates cybersickness without interfering with immersion in the VR locomotion is needed. There is a difference in the tolerance to cybersickness and that makes the problem more complex. The people who have a high tolerance to cybersickness don't need strong countermeasures to reduce it and the people who don't have the tolerance to cybersickness need more effective measures to mitigate it compare to the former. Furthermore, the tolerance to cybersickness varies depending on the current state of the users. So that optimal measures that appropriate each user who have individual tolerance to cybersickness and current state of the users is needed to achieve comfortable VR locomotion. Our contributions are measuring current state of the users and detect individual cybersickness. Besides, reducing cybersickness without lack of immersion by dynamically FOV change based on Hbt value.

1.3. Thesis Overview

- The purpose of this chapter is to introduce VR locomotion and briefly address the cybersickness that needs to be solved. Also, we described the goals to achieve comfortable VR locomotion.

- Chapter 2 gives a deeper cybersickness and immersion in VR overview. We review current attempts about the measurement of the cybersickness and reduction cybersickness.

- Chapter 3 explains in detail our approach and reasons for using VR locomotion with fNIRS. We present the novelty of this study in light of previous research here.

- Chapter 4 presents our experiment in detail and describes the results and analysis in each experiment.

- Chapter 5 gives the discussion of our findings in light of all the experimental results and analysis.
- Finally, Chapter 6 summarizes this study and presents future works to develop a more comfortable VR locomotion.

Chapter 2
Related Works

2.1. Definition of Physical Symptoms Caused from VR Experience

To begin with, the definition of VR is "the use of computer-generated virtual environments and the associated hardware to provide the user with the illusion of physical presence within that environment"(Jayaram et al. 1997). And the virtual reality environment (VRE) often causes physical discomfort to users. These are called simulator sickness, VR sickness and cybersickness. These words are sometimes used in the same meaning, but there are differences in detail. In this section, we classify these words' definitions based on the conditions of occurrence, factor and symptoms to give a definition for each word.

2.1.1 Simulator Sickness

Simulator sickness was originally the name for the symptoms caused by experiencing simulated vehicles such as cars and airplanes. Head tracking is not used when experiencing these simulations. In other words, simulator sickness was a term that existed before the spread of recent VR devices integrated head-mounted display (HMD)(Dużmańska et al. 2018). The symptoms of simulator sickness are similar to disorders evoked by motion sickness(Dużmańska et al. 2018). However, there seems to be no common cause for these occurrences. Motion sickness is reported to require vestibular stimulation(Casali 1985), such as low-frequency vibration. The occurrence of simulator sickness has also been reported in simulations that doesn't involve physical motion. In addition to physical disorders, simulator sickness gives negative effect such as loss of motivation and decrease in evaluation validity.

2.1.2 Cybersickness

The term "Cybersickness" came into use after the widespread use of VR content using HMD. It is used as a term to address new sources of sickness that did not occur in traditional simulated VR, such as the delay between the actual head motion and the generated view(Dużmańska et al. 2018). The difference between these definitions is that simulator sickness happens when users experience driving simulator and flight simulator, it means that simulator sickness is a subset of motion sickness experienced from travel through a virtual reality environment. On the other hand, cybersickness happens when users experienced virtual space in a more inclusive sense(McCauley and Sharkey 1992). The adverse effect of cybersickness on the user is similar to that of simulator sickness. In this paper, we use cybersickness as more general terms in order to more comprehensively understand the cause of its occurrence and negative effect. As mentioned in section 2.1.1, cybersickness has a wide range of negative effects on users and solutions are desired.

2.1.3 The Factors May Be Associated with Cybersickness

The root cause of cybersickness is not known, but several related factors have been reported. 40 factors have been associated with simulator sickness and these factors can be roughly classified into three groups: subject, simulator and task. There are a total of 11 factors belonging to the subject group, including gender, age ,and personal characteristics. For example, females may be more susceptible to sickness(Kolasinski 1995).

There is a total of 13 factors belonging to the task group, including duration, method of movement, rate of linear or rotational acceleration ,and sitting vs standing(Kolasinski 1995). It's reported that sitting should be less conducive to sickness(Riccio and Stoffregen 1991). For the method of movement in VR, various methods have been proposed, such as motion tracking, teleport, etc. Teleport has been found to significantly reduce SSQ scores compared to motion tracking(Weißker et al. 2018). More details can be found in 2.3.1.

There are a total of 16 factors belonging to the simulator group, including FOV, calibration, position-tracking error, frame rate(Kolasinski 1995). Restricting the field of view has been found to reduce cybersickness severity (Dużmańska et al. 2018). Details are given in 2.3.3. Unlike the factors from subject characteristics, the simulator factors is easy to deal with and is being researched. VR developers are always required to consider these sickness factors in their development. From the above, it can be seen that the factors of cybersickness are various. Furthermore, since cybersickness is actually caused by a combination of several of these factors, it is very difficult to identify the cause of cybersickness.

2.1.4 Theory Explaining These Symptoms

The Sensory Conflict Theory is widely used to explain motion sickness, simulator sickness ,and cybersickness. This theory proposes that the signals from visual, vestibular ,and non-vestibular proprioceptors are different from the sensations the user actually receives and what is predicted from the user's past experience, which causes conflicts and thus these symptoms are occurred. According to this theory, the only cause of the syndrome is the difference between the sensations users receive based on their recent experiences and the actual sensations they receive. In other words, if users continuously receive the same stimulus, their recent experience are overridden and the difference between the sensation and the actual sensation they receive decreases. It means users adapt to the VR environment and symptoms are reduced. This is based on the observation that long-term VR experience alleviated sickness(Reason and Brand 1975, Dużmańska et al. 2018).

The Postural instability theory is another one that explains these symptoms. This theory proposes that the symptoms of motion, simulator ,and cybersickness may be experienced when users have been exposed to long-lasting VR postural instability. It means that users get sickness in situations in which they don't have a way (or have not learned yet) that are effective for the maintenance of postural stability. This theory criticizes the sensory conflict theory, which states that only stimulus changes in the perceptual system can cause these sicknesses. It's argued that these changes are not independent of the interaction between the users and the environment, but are determined by changes in the control of the action. Furthermore, they argue that it is immeasurable whether the sensations predicted by past experience are different from those actually received(Riccio and

Stoffregen 1991, Dużmańska et al. 2018).

Table 2.1 The Difference of Syndrome

	Simulator Sickness	Cybersickness
Effect	Same as cybersickness	Same as simulator sickness
Contents	VR simulator (e.g.flight simulator)	All VR contents
Since when	Before VR with HMD	After VR with HMD

2.2. Measurement of Cybersickness

2.2.1 Self-Report Measures

The simulator sickness questionnaire (SSQ) is widely used as a method for evaluating cybersickness(Kennedy et al. 1993). In this questionnaire, subjects respond to 16 items on a 4-point scale for various symptoms caused by cybersickness, such as nausea and dizziness. The advantages of the questionnaire are that the analysis is easy because the answers are stylized and the degree of cybersickness can be quantified. On the other hand, if the answers were given after the experiment was completed, the participants could not recall the sensation of the moment they felt the cybersickness, thus being not able to get the accurate answer and if subjects answer during the experiment, they need to be interrupted the experiment each time, thus reducing the immersion.

2.2.2 Physiological Signals

Some studies have attempted to assess cybersickness using physiological signals. Currently, no physiological indicators that can accurately assess cybersickness have been established, but some physiological signals seem to have possibility. An increase in arousal leads to changes in respiratory rate and causes a decrease in the concentration of carbon dioxide in the cerebral bloodstream, which in turn causes a decrease in the concentration of carbon dioxide. Those changes may cause symptoms of VR sickness (Bruck and Watters 2011). It was suggested that gastric tachycardia, blinking, heart rate ,and EEG delta waves were positively correlated with SSQ scores (Kim et al. 2005). Physiological signal assessments may be able to assess sobriety in real-time without interfering with the subject's immersion. When symptoms were mild, respiratory variability and ventilation were reduced and when severe sickness occurred, markedly larger respirations and increased respiratory variability were observed(Nakagawa 2008).

2.3. Reduction of Cybersickness

Video technology is advancing every day to bring the information users to receive from VR environments closer to that of the physical space. Maintaining the high rendering rate, minimizing latency can eliminate the mismatch of information that the user received. And it connects to the reduction of cybersickness(Yao et al. 2014). Besides, not only advanced video technology but also various approaches are proposed to reduce cybersickness. In this section, we introduce each approach to mitigate cybersickness and describe advantages and disadvantages.

2.3.1 Teleportation

Teleportation is a popular method to move in VR space. There are two types of teleportation: "Direct teleportation", where the user can go directly to the interest points ,and "Jumping", where the user can teleport only within the range of their view. Direct teleportation can cause disorientation if the user teleports long distances especially beyond vista space(Montello 1993). While jumping reduces the range of movement, users teleport to the point that they perceived. This solves the problem of spatial awareness. For this reason, jumping is currently the mainstream method of teleportation using HMD(Weißker et al. 2018).

Also, teleportation is a well-known technique for reducing cybersickness(Berger and Wolf 2018). Since the screen changes instantly, teleportation reduces the sensation of moving and can suppress cybersickness. A study comparing SSQ scores for steering(the user continuously perceives the scene along the path to the destination) and jumping reported significantly lower scores for jumping. However, in the same experiment, steering tended to be preferred for the task of allowing users to freely explore the VR space(Weißker et al. 2018). In addition, changing the screen instantly reduce reality, so that it's not suitable for VR locomotion.

2.3.2 Motion Tracking

Motion tracking is also a popular method to move in VR space. In particular, HTC VIVE and Oculus track the movements of the controller and headset to reproduce the user's movements in VR space. There are two types of VR locomotion that uses motion tracking system: walk-in-place and armswing. Walk-in-place requires the user to physically walk in VR space. The head shaking caused by the walk determines the speed at which the user moves in the VR space. The faster the user moves (and the faster the head moves), the speed of moving will increase. This method intend to create a sense of reality by bringing manipulation techniques closer to the way people actually move. In the case of armswing, the user's arm swing is detected and its swing speed is reflected in the VR locomotion speed(Ragozin et al. 2020). This method also aims to reproduce the actual move as locomotion (Pai and Kunze 2017). One of the advantages of armswing is that it consumes less energy than walk-in-place because there is no need to move the legs. In the case of walk-in-place, sometimes shaking head movement will be misinterpreted as walking and it occurs cue conflict. Both methods improve reality because movement in VR space is reproduced by actual movement. On the other hand, there are still issues that difficult to manipulate such as the difference in structure between VR space and physical space, situations where actual physical movement is not possible and user characteristics.

2.3.3 Control FOV

The controlling field of view (FOV) is a cybersickness reduction method that focuses on the simulator factor. It is known that there is a relationship between FOV and cybersickness as mentioned in 2.1.3. Decreasing FOV can reduce cybersickness(Lin et al. 2002). Control FOV is easy to adapt for many users and can easily reduce cybersickness but it's noted that narrowing FOV reduces the sense of presence(Seay et al. 2001). It has been found that both the sense of immersion and the severity of cybersickness increase as the FOV becomes wider(Lin et al. 2002). There is an attempt to reduce cybersickness while minimizing the loss of immersion by dynamically manipulating the FOV. Cybersickness was reduced without loss of immersion by controlling the FOV when the participant's moving speed and angular velocity became above a certain level. The FOV control speed is also discussed and it is reported that even if the FOV contraction speed is faster during shaking head compared to when they aren't doing that, it does not cause discomfort(Fernandes and Feiner 2016). Dynamic FOV control can solve issues such as differences in each spatial structure and physical characteristics of the user and can maintain the sense of immersion. In this research, we adopted dynamic FOV control as a method to reduce cybersickness.

Chapter 3
Approach

3.1. Comfortable Locomotion

With the spread of VR content, more and more people will be exposed to VR environments(VRE). VR locomotion that provides the sense of moving in the VRE that has different structures than the physical space is needed to be achieved. Cybersickness is the big problem to achieve comfortable VR locomotion. The adverse physical disorders induced by cybersickness severely affect the comfortableness and immersion in VR locomotion. Many kinds of method to mitigate the cybersickness are proposed, but most of them are also mitigate the immersion in VR locomotion. It means cybersickness incorporates a trade-off with respect to immersion in VR. There is an individual difference of tolerance to cybersickness. And the tolerance for cybersickness varies depending on the current state of the users. So the new VR locomotion methods that optimized for current state of the users and users who have different tolerance for cybersickness is needed. The requirements in achieving a comfortable VR locomotion are as follows.

- Detecting individual cybersickness in real-time.
- Reducing cybersickness without lack of immersion.
- That the two methods mentioned earlier do not interfere with the comfort of the VR locomotion.

3.2. Detection by Physiological Signals

There are some methods to detect cybersickness. We tried to detect that by physiological signals. The reasons why use physiological signals are to detect cybersickness in real-time, to address any factors that induce the cybersickness, to produce proper reduction methods for each user who has individual tolerance for cybersickness. The reduction of cybersickness has possible to reduce immersion, so that it should be used only when users feel cybersickness. Therefore, detection in real-time is needed. There are many kinds of factor that induces cybersickness, such as screen resolution, game bugs, lightning ,etc. The factors that causes or exacerbates cybersickness are not only on the VR content side but also in the user's physical condition and the surrounding environment. Therefore, it is difficult to completely eliminate cybersickness by focusing only on factors related to VR content. As with motion sickness, it is known that there are individual differences in tolerance to cybersickness as well. When cybersickness reduction suitable for people with low tolerance to cybersickness is used for both, it can be a factor that inhibits immersion for people with high tolerance. And of course, vice versa can happen. Besides, even if the same user, the tolerance varies depends on the time and current state of the users.

Therefore, similar reduction of cybersickness methods shouldn't be used for both sides of people. By detecting individual physiological signals, can address the people with different tolerance to cybersickness and current state of the users.

3.2.1 Cybersickness-Related Physiological Signals

Some kinds of physiological signals seem to detect cybersickness. So far, there is no robust detection mechanism for it (Dużmańska et al. 2018). Increased arousal is a state of activation that leads to changes in respiratory rate and low carbon dioxide levels (Bruck and Watters 2011). And that evoke feelings of lightheadedness, dizziness and concentration problems which are a symptom of cybersickness(Bresseleers et al. 2010, Bruck and Watters 2011).

Also, it's reported that the total severity of cybersickness had a significant positive correlation with eye blink rate, heart period, and electroencephalogram (EEG) delta wave etc. (Kim et al. 2005). It's known that when participants feel low sickness, their respiratory variability and tidal volume are decreased (Nakagawa 2008).

These physiological signals have a correlation with severity of cybersickness and the possibility of detecting that. However, detection methods have some disadvantages. In this research, we focus on not only the detection of cybersickness but also comfortable VR locomotion. Therefore measurement that is difficult to set up, such as respiration sensor based on chest motion and large scale brain-sensing is not suitable. In addition, it needs to be easy to integrate on the HMD and be able to detect data as accurately as possible under different environments. Smaller respiratory instruments, while less physically demanding on the users, do not detect better data than near-infrared spectroscopy in situations where respiratory or temperature changes occur, due to the use of optical pulse wave methods(Holper et al. 2016).

3.2.2 fNIRS

In this study, we attempt to detect with near-infrared spectroscopy (fNIRS) device(Figure3.1,3.2). fNIRS is a method for estimating changes in cerebral blood flow near the frontal area of the user's brain based on changes in hemoglobin concentration using near-infrared light. The real-time detection with fNIRS has a high tolerance to movement artifacts(Peck et al. 2013). It is expected that users move frequently in some VR games. Since these movements can affect physiological signals and cause false detection of cybersickness, we thought that the resistance of fNIRS sensors to movement artifact would be ideal for detection.

Additionally, the fNIRS device is set up and integrated with HMD easily(Solovey et al. 2009, Strangman et al. 2002). Non-invasive and not expensive are important for introducing to VR. Compared to other brain-sensing such as Electroencephalogram(EEG), functional magnetic resonance imaging(fMRI) ,and Magnetoencephalography(MEG), fNIRS has these advantages that allow users to more naturally interaction with VR space(Solovey et al. 2009).

Ideally, we should analyze the mechanism of cybersickness by clarifying the relationship between cybersickness and cerebral blood flow using fNIRS and detect cybersickness in advance.

Figure 3.1 HOT-1000 Sensor

Figure 3.2 HOT-1000

3.3. Reduction of Cybersickness

3.3.1 Reduction Methods of Cybersickness

There are some ways to reduce cybersickness. Teleportation is widely used as a moving interaction. Teleportation switches the screen in front of the user's in an instant when a button is entered. The advantages are that it is easy to operate and it is difficult to evoke sickness because it moves in an instant. However, switching the screen instantly can't give the sensation of movement and reality. This is a critical issue to achieving VR locomotion.

Motion tracking is another famous method to mitigate cybersickness. Motion tracking produces the sensation of movement by tracking their motion with joystick controllers and HMD. The advantages of motion tracking are to produce a sense of reality by input interaction similar to walk movement. It reduces the difference between visual information and sense received by the vestibular systems. Therefore it can mitigate cybersickness. On the other hand, if the VR space has a different structure from physical space, motion tracking is not suitable. One of the features of VR space is the ability to create an environment that is different from the physical space, for example, a much larger than physical space. Users move through the physical space based on the information obtained from VR space. However, if an obstacle in the physical space is not shown in the VR space, there is a risk that the users will run into that obstacle. To eliminate this danger, the VR space and the physical space need to have exactly the same structure, which is very difficult. Another disadvantage is that users with physical disabilities cannot use motion tracking because it uses the body for input interaction.

3.3.2 Controlling FOV

Controlling field of view(FOV) has the possibility to reduce cybersickness. It restricts the FOV that reduces the information received eye and mitigate the cybersickness (Lin et al. 2002, DiZio and Lackner 1997). The advantages of controlling FOV are that it is easy to set up and there are no problems due to differences in spatial structure (e.g.: collisions with obstacles) because the users don't have to physically move. However, it is known that too much restricting of FOV reduces user's sense of presence(Seay et al. 2001, Cummings and Bailenson 2016). It is important that controlling FOV that doesn't interfere with the user's immersion and sense of presence. In this study, we try to control FOV by cerebral blood flow data from fNIRS and set the optimal FOV that does not interfere with immersion for each user.

Chapter 4
Research and Development

4.1. Cybersickness Detection

We attempted to build a new cybersickness detection system using fNIRS. After the initial test was conducted, a cybersickness detection experiment with an increased number of subjects was conducted in order to have accuracy. The purpose of this experiment was as follows.

- To confirm the physiological signals that are correlated with subjective cybersickness.
- To evaluate the validity of the real-time cybersickness detection by physiological signals.
- To set the cybersickness sign based on the collected data.

4.1.1 Initial Detection Test

In the initial test, how the Hbt value changes response to the cybersickness is investigated. First, subject experienced three different sessions. The session consists of normal, cybersickness, and non-sick move. Each session was lasting 5 minutes, for a total of 15 minutes. The subject uses the HTC VIVE VR headset integrated fNIRS device(HOT 1000) produced by Hitachi(Figure 4.1). The application is developed on the unity and virtual reality environment (VRE) is generated from unity free assets(Nature Starter Kit2). The fNIRS device collects total hemoglobin (Hbt) value and pulse rate data. In the normal session, the subject wears an HMD integrated with an fNIRS device (Figure 4.1) and remains stable. After experiencing the normal session for 5 minutes, the cybersickness session begins. In this session, physiological signals are measured when the subject is feeling subjective sickness. The subject moved randomly in the VR space in an uncontrollable state for 5 minutes. when the cybersickness session is over or the subject feels unbearable sickness, the non-sick move session starts. In this session, the subject moves around in the VR space to the extent that does not feel sickness. If the subject is about to feel sick, slow down until the risk of sickness is gone. After all the sessions were completed, interviews were conducted to investigate the symptoms of cybersickness.

Second, the duration of each session was shortened and the change in Hbt values were measured. The acceleration while subject was moving was also measured. Each session consist of normal (60 sec), cybersickness (140 sec) and non-sick-move (100 sec). Subject is instructed verbally tell when they feel sickness.

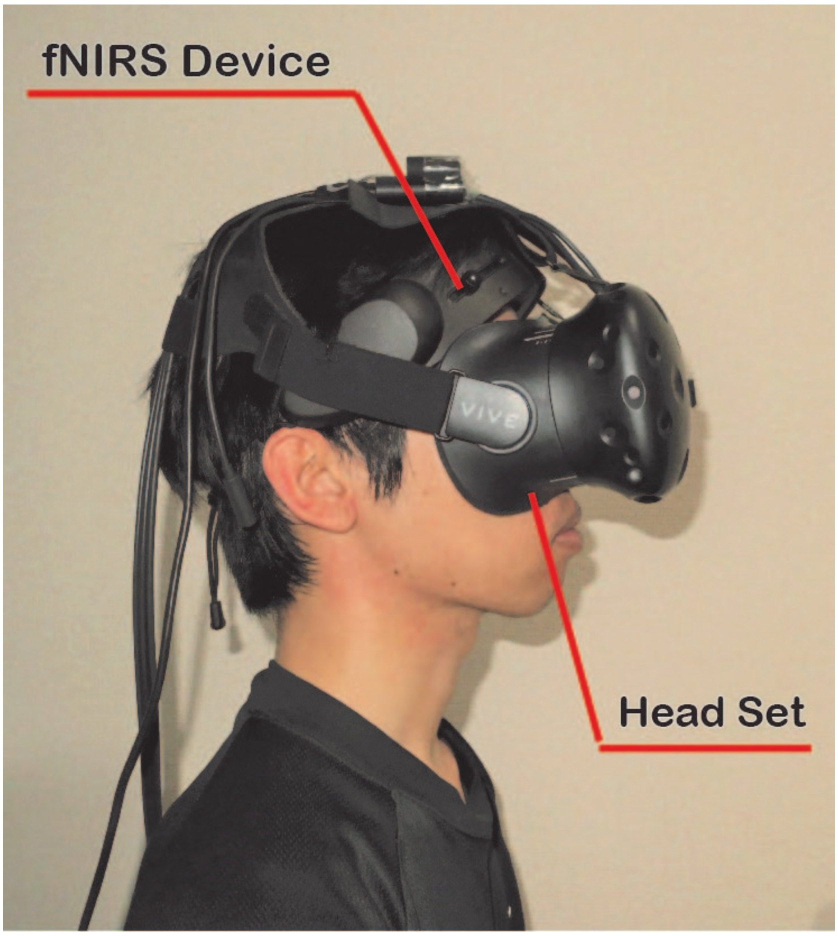


Figure 4.1 VIVE Head-set integrated with fNIRS device

4.1.2 Initial Test Insight

Figure 4.2 is the Hbt value transition graph. After the normal session, an increase in Hbt level was observed, and a sudden drop was observed around 480 seconds, which may be due to the subject's depressed posture and significant blood flow changes. After the cybersickness session was over, we moved on to the non-sick move session. The subject repeatedly moved a very short distance. As a result, it was confirmed that the Hbt value gradually went down.

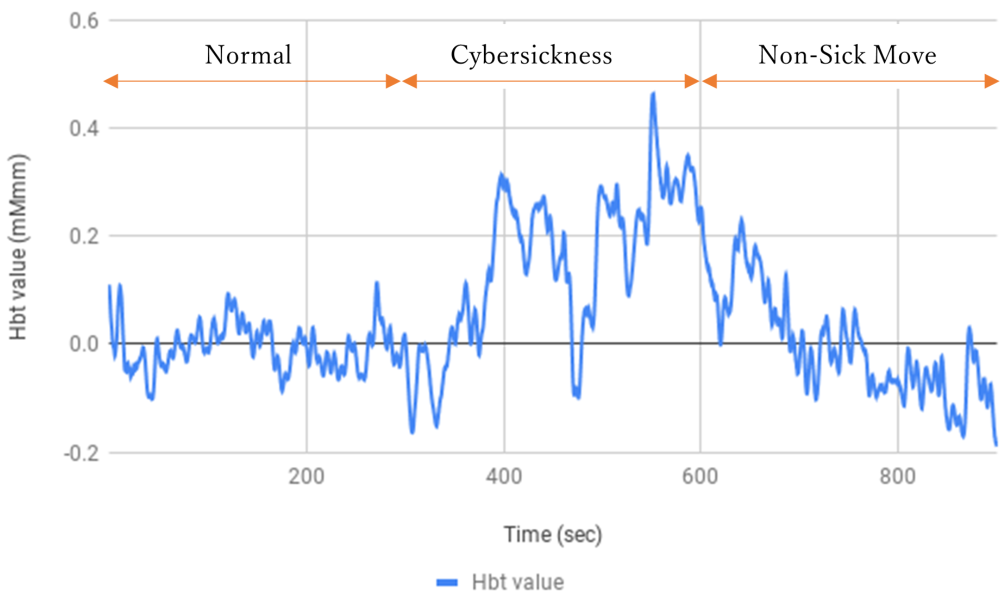


Figure 4.2 Hbt value transition

Figure 4.3 is the pulse rate transition graph. Again, this pulse rate graph showed an increase after the normal session. This was an expected result since there is a correlation between heart rate and cybersickness. By the time the non-sick move session started, the pulse rate had returned to the same level as the normal session. In the interview survey, nausea, sweating, and dizziness were identified as symptoms of cybersickness. In particular, nausea and sweating were reported as the most severe symptoms. In addition, it was reported that the time taken to get cybersickness again became shorter once cybersickness. Slowing down the speed of movement improves the symptoms to some extent, but if subject moves at the original speed again, the sickness may return within a few seconds. It was also reported that the mild symptoms of sickness (dizziness) continued for about 10 minutes after the experiment was over. Based on the above results, Hbt value and pulse rate may be correlated with cybersickness. However, we obtained the insight that the pulse may not be suitable for real-time detection because it does not change much.

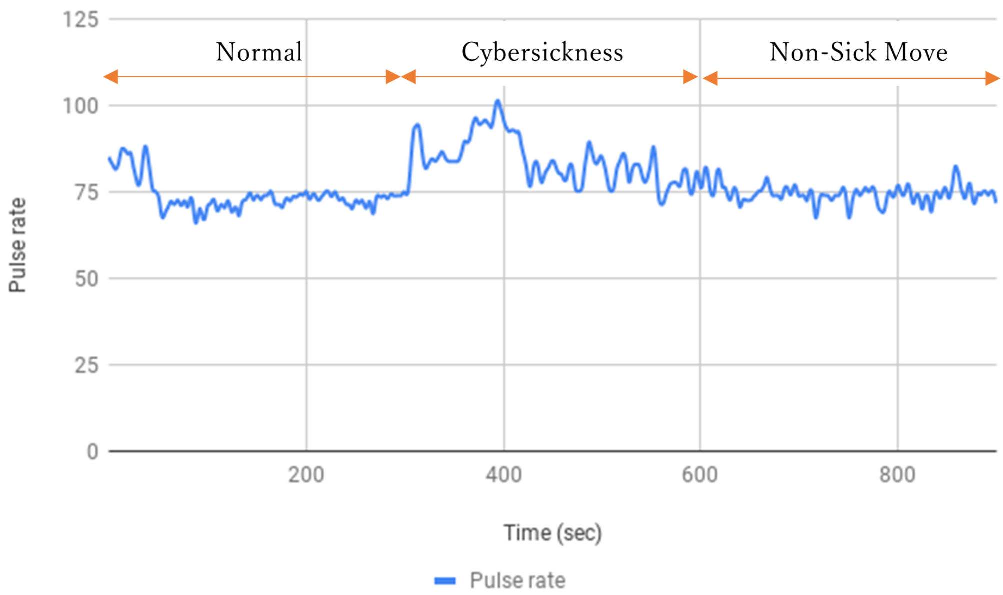


Figure 4.3 Pulse rate transition

Figure 4.4 is the Hbt transition with acceleration graph. The yellow area represents the time when subject get sickness. This graph shows the subject feel sickness about 20 seconds after starting to move. Hbt value shows the significantly change immediately after the start of the experiment. This change is caused by subject's large head movement. The Hbt value increased after subject get sickness as well as figure 4.2. As results of these experiments, we get the insight that cybersickness could be detected from Hbt value.

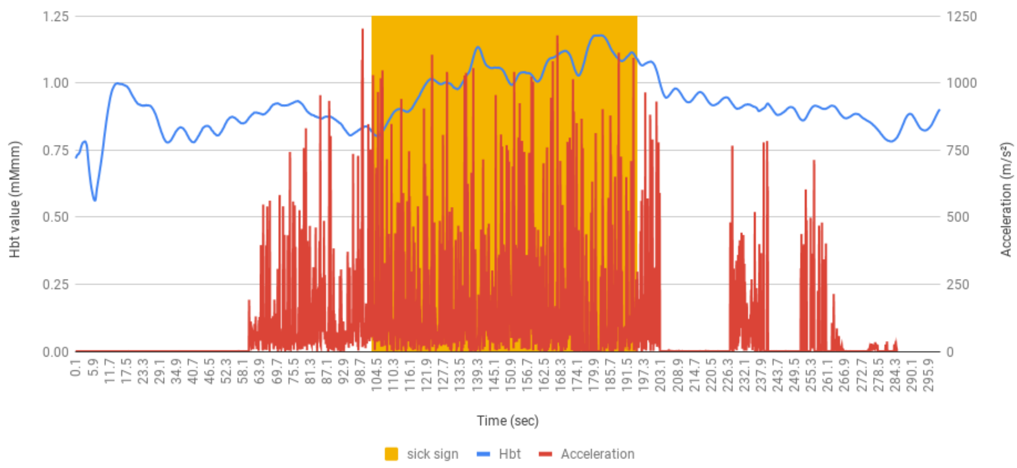


Figure 4.4 Hbt transition with acceleration in VR space

4.1.3 Detect Cybersickness

To detect the cybersickness in real-time, subjects experienced VR locomotion in an uncontrolled state which we ran with 17 subjects. They were exposure VR for 5 minutes and asked to press an arbitrary key when they feel subjective cybersickness. The total hemoglobin change(Hbt) value when the key was pressed(they feel cybersickness) was compared with the Hbt value when the key was not pressed (not feel cybersickness). We analyzed these Hbt value by Wilcoxon signed-rank test. The severity of cybersickness and immersive were evaluated by simulator sickness questionnaire(SSQ)(Kennedy et al. 1993) and immersive questionnaire(IQ). SSQ is widely used to evaluate cybersickness, while the IQ is a more abbreviated questionnaire that refers to the immersive experience questionnaire(IEQ)(Jennett et al. 2008) and is selected only for questions pertinent to this experiment. These questionnaire are formed of a Likert-scale question(1-4 level) and IQ includes items about positive and negative affect of immersion. Responses to each item will be processed appropriately and calculated as an IQ score. The questions used in the IQ are as follows.

- To what extent did you feel you were focused on the game?
- To what extent did you lose track of time?

- To what extent was your sense of being in the game environment stronger than your sense of being in the real world?
- To what extent did you feel consciously aware of being in the real world whilst playing?
- To what extent did you feel discomfort?

We formulated the hypothesis that *"Hbt value while they feel cybersickness is increased more than while they don't feel cybersickness"*.

4.1.4 Implementation

We use an HTC VIVE VR headset with the fNIRS device(model HOT-1000 provided by Hitachi, Figure 4.1) connected computer over bluethooth, and running Windows 10. The application was developed on unity (version 2019.4.12 f1). The VR space was created from unity free assets(Nature Starter Kit2 and Farm Animals Set).

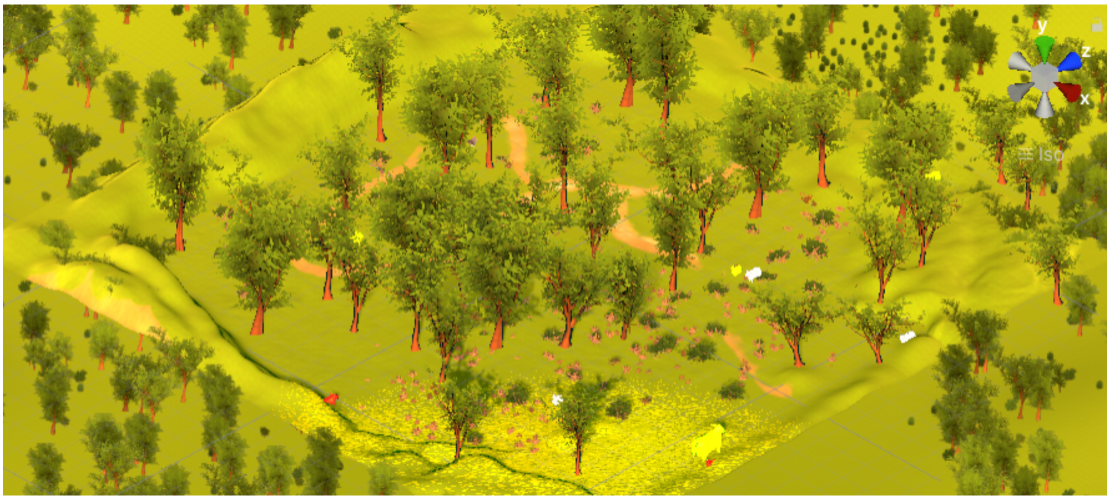


Figure 4.5 VR nature space with animals

4.1.5 Result and Discussion

As 4 out of 17 subjects did not press a key(don't feel cybersickness), we analyzed the Hbt value of the remaining 13 subjects (Wilcoxon signed-rank test, p=0.05).

No significant differences in Hbt values were identified for 2 of the 13 subjects analyzed. Of the 11 subjects for whom a significant difference was identified, 7 subjects had an increase in Hbt value. It means 4 subject's Hbt values did not turn out as hypothesized. Comparing the group with an increased Hbt value while they don't feel cybersickness (group A) and the group with a decreased Hbt value (group B) based on SSQ scores(Mann–Whitney's U test, p=0.05), group B confirmed that the difference between the SSQ score before and after the experiment was significantly lower than that of group A. This result implies cybersickness may not be detected accuracy from Hbt value if Hbt change is significantly slight compared to normal. However, the experimental results suggest that fNIRS can detect cybersickness when the degree of cybersickness changes above a certain level. As we hypothesized, group B had an average increase of 0.56 (mMmm) in Hbt value compared to Hbt value while they don't feel cybersickness. We set this mean value as a threshold for the occurrence of cybersickness.

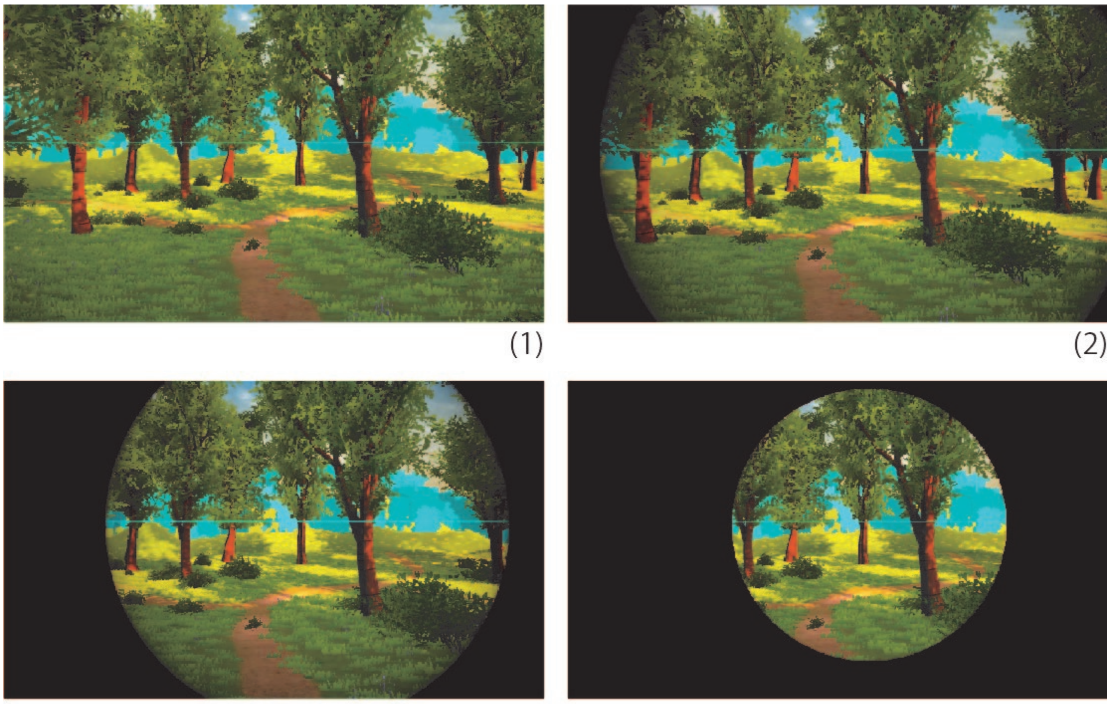
4.2. Adoptive FOV

4.2.1 Initial FOV Test

Initial experiments were conducted to determine the appropriate field of view (FOV) that would not cause discomfort to the user. After a certain amount of time had elapsed since the start of the VR locomotion, the FOV was changed, and an interview survey was conducted to see if there were any discomfort. The parameters were the FOV contraction speed and the FOV range. The purpose of this experiment is to obtain an appropriate FOV insight by changing these parameters. The FOV is a donut-shaped black object placed in front of the camera, and the FOV changes as the object moves back and forth (Figure 4.6).

4.2.2 Initial FOV Test Insight

Initial experiments reported a decrease in immersion, as donut-shaped objects have a clear boundary between visible and invisible areas. It was also found that the faster the FOV narrowed, the more anxiety and discomfort was felt. We also tried several kinds color of the FOV object and found that black was the least



(1) (2) (3) (4)

Figure 4.6 FOV controlled by Hbt value

uncomfortable.

4.2.3 FOV Experiment

FOV experiment was conducted to determine the FOV that could guarantee immersion during VR locomotion, which we ran with 9 subjects. Based on the results of the initial FOV test, postprocessing was adopted for FOV control and blurring was added to the boundary. Specifically, we determined the appropriate parameters for the following.

- The minimum FOV that users can retain the immersion.
- Suitable rate of FOV change while moving.
- Suitable rate of FOV change while subjects are shaking their heads to see their around.

In the FOV experiment, subjects wear the VIVE headset and move in VR space. The moving velocity was set at one meter per second and they were free to move with the joystick. To decide the minimum FOV, the subject's FOV is narrowed slowly while they're moving (Figure 4.7). They were not informed in advance that the FOV would change. Subjects were instructed to verbally tell us when they feel discomfort on the spot what the discomfort was. They were also interviewed after the experiment. To decide the rate of FOV change while moving and shaking their heads, we varied the FOV and gradually accelerated the rate of contraction. We then instructed them to verbally tell us when they felt discomfort in their vision, as they did in minimum FOV.

4.2.4 Result and Discussion

We found that the range of visual field constrictions that the subjects do not find uncomfortable is the range that completely blocks their peripheral 10 percent of their FOV and further blurs from their borders(Figure 4.8).

Most subjects did not report any discomfort when limiting 10 percent plus blurs of their FOV (Figure 4.8). Nor did participants who noticed a change in visibility have their immersion affected by it. For the FOV contraction speed,

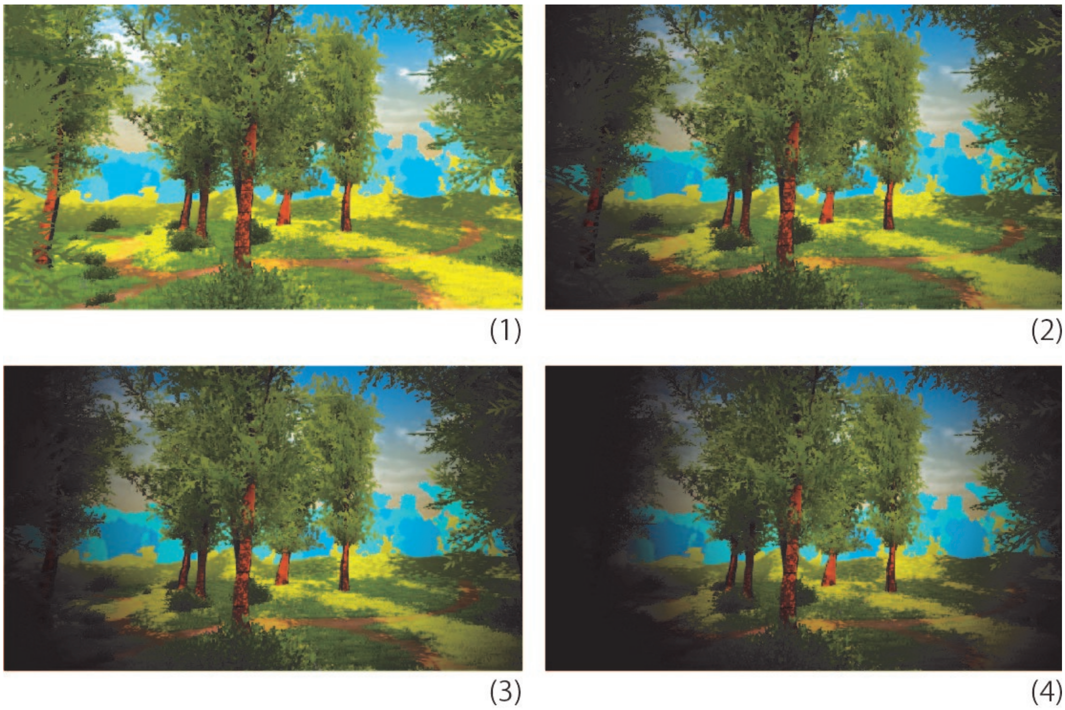


Figure 4.7 FOV change process

there was a significant difference between moving and shaking the head. It was found that while moving, a slow FOV contraction speed (0.67 percent/sec) was less discomfort, but while shaking their heads, a faster contraction speed (40 percent/sec) was less discomfort ($0 \leqq minimumFOV \leqq 10percent$).

Figure 4.8 FOV that subjects don't feel discomfort(left eye)

Some subjects complained of cybersickness and anxiety due to the sudden narrowing of FOV while moving. It was found that the narrowing of the FOV needed to be set at a speed that the subjects did not notice, or if they did, they did not care. Subject's effective visual field may be more focused on the center of their FOV while shaking heads than while moving, so that the subjects don't notice changes in their peripheral vision. Therefore, even if the FOV contraction speed is fast, they don't feel any discomfort.

4.3. Cybersickness Reduction System

4.3.1 Initial Reduction Test

1 subject experienced the 2 different VR sessions. First, we measured subject's physiological signals(hemoglobin data and pulse rate) for 10 minutes while subject was stationary and 10 minutes while subject experienced locomotion event in VR space. Their field of view(FOV) is not controlled at this time. In a second test (locomotion event), we set an experimental threshold based on the initial recording (non FOV) of double increase in total hemoglobin (Hbt) to introduce a controlled FOV to mitigate cybersickness. SSQ is used to evaluate the degree of their cybersickness after the each session.

4.3.2 Result and Insight

The figure 4.9 shows the Hbt values obtained from the experiment. The measurement was interrupted during the locomotion session because the subject complained of extreme cybersickness. Based on this we can see an increase Hbt value for the movement part (blue line in Figure 4.9) for the movement (locomotion event). The SSQ administered after the recording showed a score of 48 points indicating cybersickness. Apart from that, the setup is the same. When introducing the narrowed FOV based on the Hbt change is shown in the orange line (Figure 4.9). And the SSQ score after the locomotion event was 30, showed significantly reduction of cybersickness.

Previous studies have suggested that heart rate is correlated with cybersickness, and the pulse rate, which is also correlated with heart rate. Pulse rate (recorded also over the fNIRS sensors) increases when subjects feel cybersickness and decreases when cybersickness is reduced, as shown in figure 4.10. As the insight of initial test, we found fNIRS have possibility to detect cybersickness. Pulse rate also may have correlated with cybersickness but pulse rate change per second is slight, so that pulse rate is not suitable for detecting cybersickness. From the results of this initial test, we were able to obtain insights on how to reduce cybersickness by controlling the FOV with fNIRS. We found that appropriate FOV contraction speed and objects that narrow the FOV were necessary to avoid

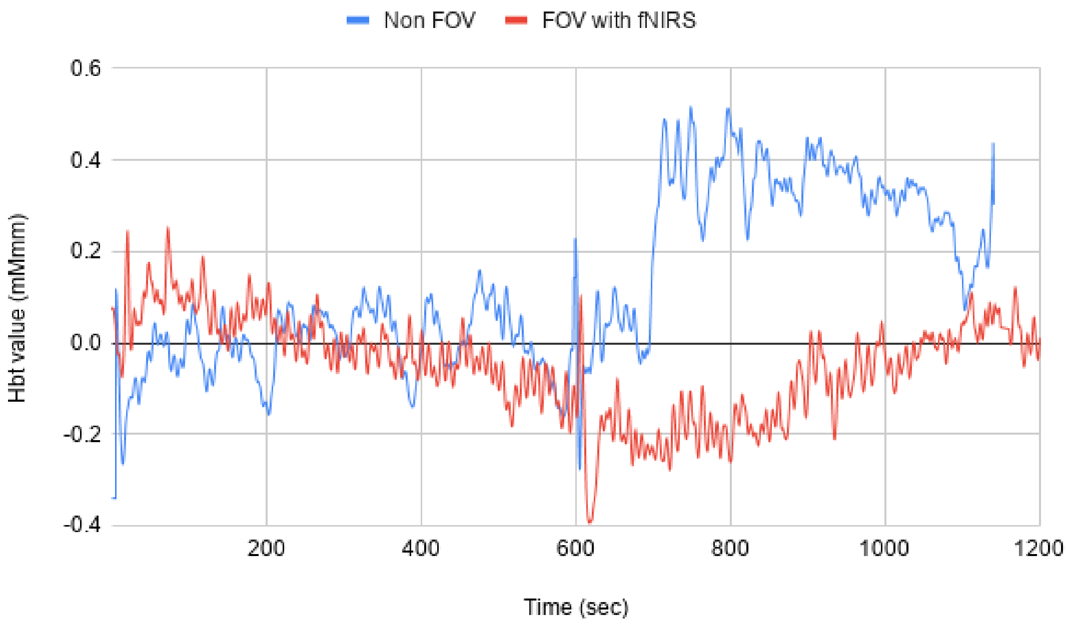


Figure 4.9 Hbt change in non FOV vs FOV controlled by Hbt value

interfering with the sense of immersion.

In the next experiment, we will evaluate the validity of the FOV control using fNIRS by comparing the FOV control methods.

4.3.3 fNIRS vs Velocity

The purpose of this experiment is to validate reliability of a cybersickness reduction system suitable for tolerance to individual cybersickness. Based on the initial reduction test, this experiment was designed that modified some problems. And we got subjects and investigate the effectiveness. The main changes are follows.

- Compared the 2 sessions that FOV controlled by fNIRS and FOV controlled by velocity.
- Immersive Questionnaire(IQ) was added to evaluate immersion in VRE

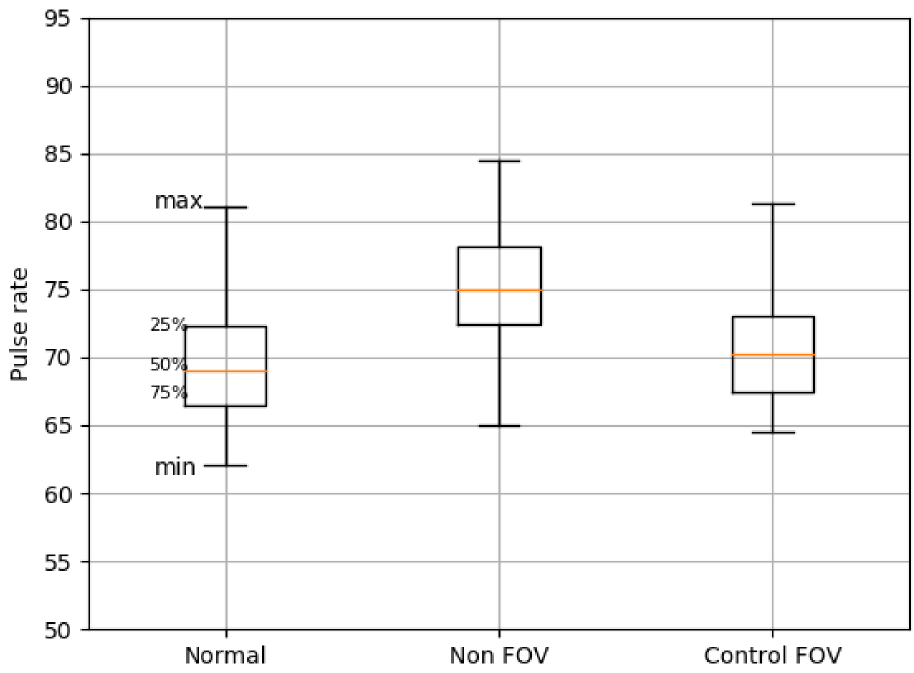


Figure 4.10 Pulse rate in each session(Normal, Non FOV and FOV controlled by Hbt value)

4.3.4 Comparison Experiment

This experiment was conducted with 10 subjects. The age range was 16-59 years old and people with less than one VR experience per week were recruited to exclude those who are accustomed to VR and therefore don't feel cybersickness. Subjects search for animals in the forest generated on unity. The reason for the animal search game was to have the subjects move frequently and shake their heads to look for the animals. The position of the animals was changed to the extent that it did not change the level of difficulty for each session to prevent subjects from getting used to it. Subjects wear an HMD with the fNIRS device integrated and can move freely with the VIVE controllers(Figure 4.11).

Figure 4.11 Subjects wear an VIVE head-set with the fNIRS device which connected computer over the bluetooth

They can move at a speed of about 1 m/sec. This is an average walking speed. The experiment is divided into two parts, each lasting 5 minutes. In the velocity session, we attempted to reduce cybersickness by changing FOV based on the subject's velocity and angular velocity (Figure 4.7). In the fNIRS session, we changed FOV based on the subject's Hbt value during the experience. The average of Hbt values during the first minute of the experience was obtained, and FOV was contracted when Hbt value was greater than or equal to the set value based on the results of detect cybersickness experiments. Hbt value is collected each sessions. After each session, subjects answered the SSQ and IQ.

4.3.5 Result and Discussion

Figure 4.12 is a violin plot of the mean Hbt values in the velocity and fNIRS sessions. Compared to the velocity session, the mean Hbt values significantly reduced in the fNIRS session for all subjects(Wilcoxon signed-rank test, p=0.05).

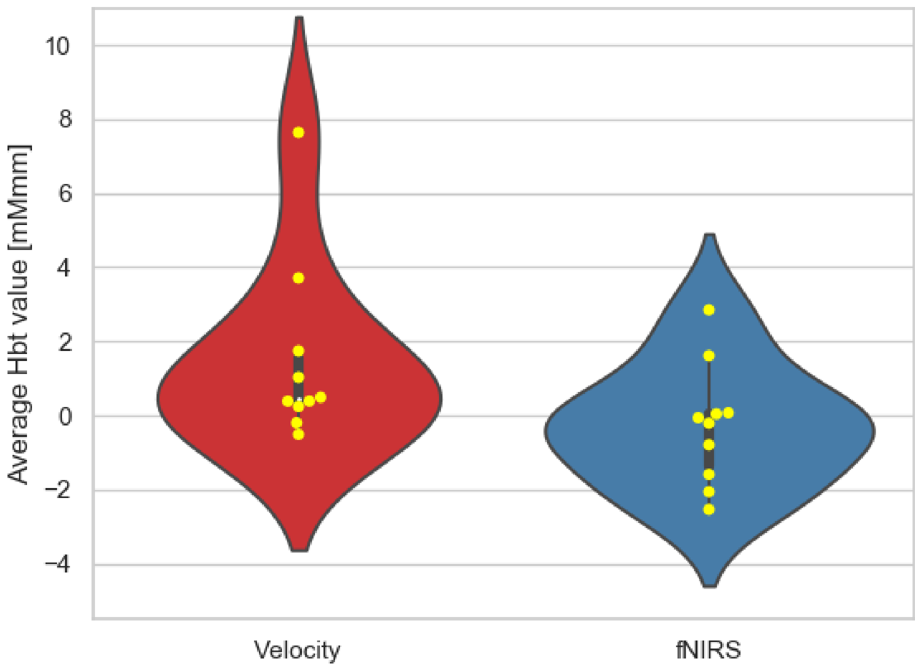


Figure 4.12 Violin Plot for Hbt values Velocity session vs fNIRS session

A comparison of the mean SSQ scores showed a decrease in the total SSQ score in six participants (Figure 4.13). Also, one subject showed no change in the total score, but there was a change in each item. Particularly large changes were found in the items related to fullness of head and dizzy (eye open). We learned from the interviews after the experiment that one of the reasons why the SSQ of the fNIRS session increased more than that of the velocity session was that eyes were tired from concentrating too much on the game (fNIRS session). The subject reported an increase in scores on the eye-related items (eyestrain, difficulty focusing, dizzy, vertigo), but an increase in IQ scores on focus and lack of time. As a result of

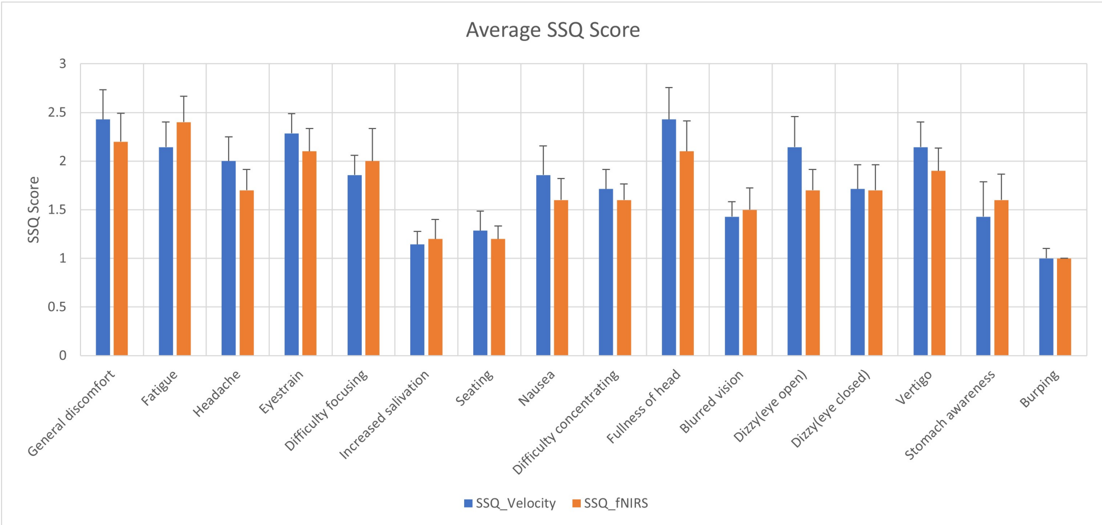


Figure 4.13 Average SSQ Score

comparing the mean IQ scores, an increase in the IQ scores of the six participants was confirmed (meaning an increase in immersion). One subject showed no change in the total score. The items that changed the most were comfort and lose track of time (Figure 4.14, 4.15).

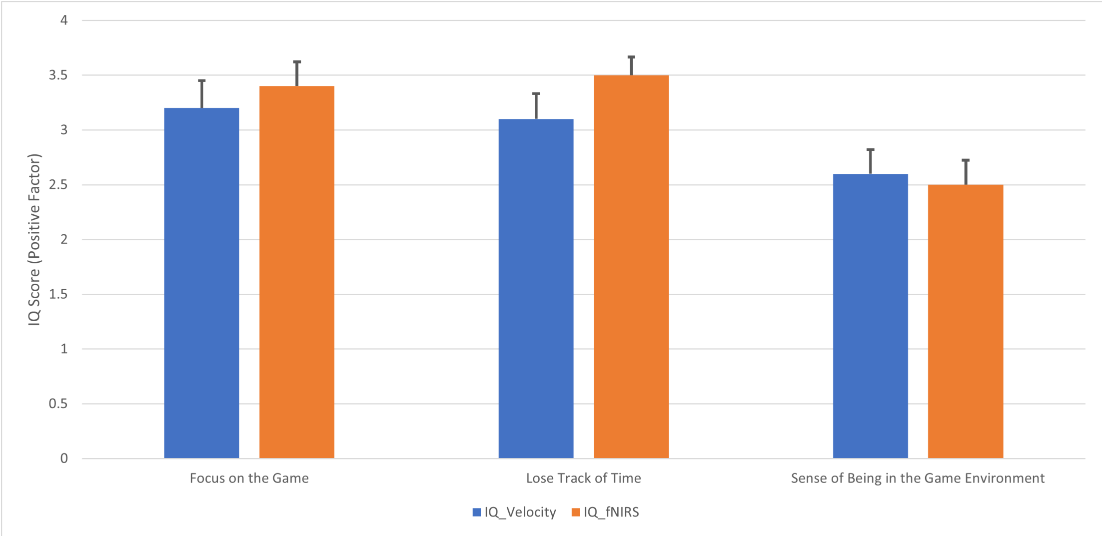


Figure 4.14 Average IQ Score(Positive Factor)

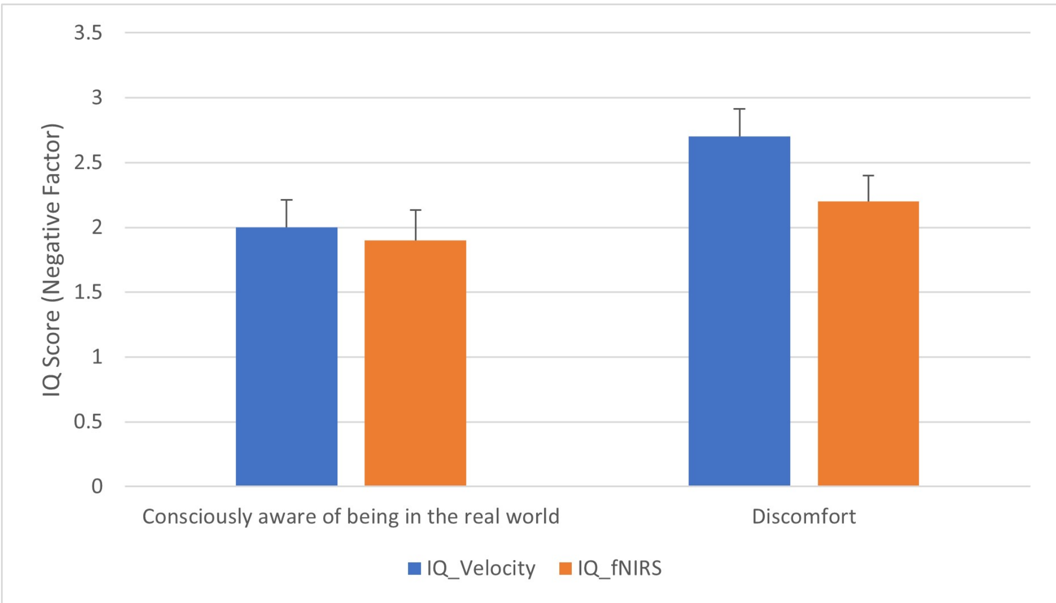


Figure 4.15 Average IQ Score(Negative Factor)

Chapter 5
Discussion

In this paper, we attempted to detect cybersickness using fNIRS. We also controlled FOV using two methods, velocity and fNIRS and compared the effects of each method on cybersickness reduction. The results suggest that FOV control using fNIRS may reduce cybersickness better than velocity control.

Regarding the detection of cybersickness, we were able to generally detect the cybersickness of the users by the Hbt value. However, the Hbt value tends to increase in people with a high tolerance for cybersickness even if they don't feel cybersickness, and this may lead to false detection. It was also found that accurate detection was difficult to even when the users felt slight cybersickness (change in total SSQ score was less than 4). The possibility of detecting a wide range of cybersickness factor by using fNIRS was also discovered. Some subjects felt cybersickness due to the occurrence of game bugs (felling into a tree or the ground) and basic physical discomfort that unrelated to the VR locomotion. Since FOV control by velocity cannot detect the cybersickness caused by these factors, fNIRS control is superior in this point.

Regarding the comfortable VR locomotion (Figure 4.14, 4.15), it was found that the FOV control using fNIRS was able to reduce cybersickness and maintain the sense of immersion better than the FOV control based on velocity and angular velocity, except for one positive immersion factor (sense of being the game environment).

On the other hand, a disadvantage of fNIRS devices is that the weight of the fNIRS device is increased by being attached to the HMD, which leads to fatigue for the user. One possible solution is to reduce the weight of the fnirs device or to integrate the fNIRS sensor into the headset itself.

Chapter 6
Conclusion

6.1. Conclusion

As it was previously discussed, the purpose of this thesis is to achieve comfortable locomotion in VR space. And the requirements are detecting individual cybersickness in real-time, reduction of cybersickness without lack of immersion and that the two methods mentioned earlier do not interfere with the comfort of the VR locomotion. We tried to meet the above requirements controlling FOV with fNIRS. As a result of the experiment, we succeeded in detecting the cybersickness of users who felt a certain level of discomfort. In the comparison experiment with the FOV controlled velocity, successfully reduced cybersickness without interfering with the sense of immersion by controlling FOV with fNIRS. Besides, we found that fNIRS may be able to deal with various cybersickness factors such as user's physical condition and game bugs that cannot be dealt with by velocity control FOV. However, integrating fNIRS increases the weight of the headset and some users reported discomfort.

6.2. Future Work

Since the detection of cybersickness was an important point in this study, integrating fNIRS device into the HMD was adopted. However, the weight increase associated with the device remained an issue. One possible solution is to reduce the weight of the HMD and use a different sensing technology. If a simple wristwatch-type sensing device can accurately detect cybersickness, the burden on the user will be greatly reduced.

Also, the temporal relationship between Hbt value and cybersickness was not clarified in this experiment, and we did not know the possibility of predicting cybersickness by fNIRS. By clarifying this in the future, we may be able to adopt a cybersickness reduction method other than controlling FOV for the prevention of cybersickness.

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