HemodynamicVR - Adapting the User's Field Of View during Virtual Reality Locomotion Tasks to Reduce Cybersickness using Wearable Functional Near-Infrared Spectroscopy

Hiroo Yamamura
Keio University
Yokohama, Japan
usurai-ligno@kmd.keio.ac.jp

Holger Baldauf
Keio University
Germany
holger.baldauf@gmail.com

Kai Kunze
Keio University
Yokohama, Japan
kai@kmd.keio.ac.jp

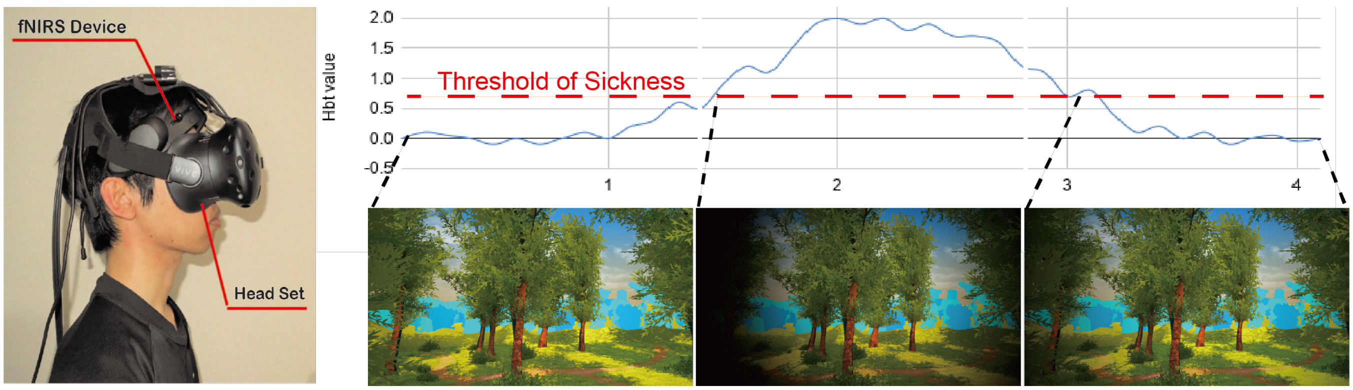

Figure 1: HemodynamicVR concept: Using hemoglobin changes measured by fNIRS to determine cybersickness symptoms and limiting the field of view during walking segments

ABSTRACT

We present HemodynamicVR, a virtual reality headset combined with functional near-infrared spectroscopy (fNIRS). We believe that sensing brain activity will enable novel interactions in virtual reality. In this paper, we assess a user's cybersickness based on the change of their total hemoglobin concentration measured via an fNIRS device, and we try to mitigate that by changing the field of view (FOV) in real-time. In this experiment, participants experienced VR locomotion with an added variable FOV controlled by velocity changes and by fNIRS. The results suggest that fNIRS can detect cybersickness as registered by the qualitative SSQ test.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

fNIRS, VR locomotion, Cybersickness, FOV

AHs '21, February 22–24, 2021, Rovaniemi, Finland

ACM ISBN 978-1-4503-8428-5/21/02...$15.00
https://doi.org/10.1145/3458709.3458994

ACM Reference Format:
Hiroo Yamamura, Holger Baldauf, and Kai Kunze. 2021. HemodynamicVR - Adapting the User's Field Of View during Virtual Reality Locomotion Tasks to Reduce Cybersickness using Wearable Functional Near-Infrared Spectroscopy. In *Augmented Humans International Conference 2021 (AHs '21), February 22–24, 2021, Rovaniemi, Finland.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3458709.3458994

1 INTRODUCTION

As the first virtual reality devices (e.g., Oculus Quest 2) are entering the mainstream consumer market[1], there are still a lot of unsolved problems in terms of interaction paradigms, especially related to personal adaptability. A simple example illustrating this is that interpupillary distances cannot be adjusted correctly for some users (e.g., 3 predefined IPD settings on the Oculus Quest 2), leading to an increase in cybersickness [6, 17]. Our research focuses on using physiological signals to dynamically personalize the user's virtual environment according to the user's current state. In this paper, we explore the use of a wearable fNIRS device to adjust users' VR experiences.

Problems with virtual reality systems often arise due to a mismatch between a user's perception of motion and the system's corresponding rendering of motion. Sensory conflict theory provides a framework to understand these problems [11]. We explore a particular common problem in VR locomotion using a gaming controller without physically moving. The gaming controller method is widely used as a movement method in a VR space which is much

[1]https://www.theverge.com/2020/10/30/21541535/oculus-quest-2-preorders-sales-developers-zuckerberg

bigger than the available physical space. Although it is easy to implement and widely used in VR games, it increases cognitive load, sensory conflict and can cause cybersickness[3]. We propose to detect the higher cognitive load related to sensory conflict during locomotion sequences in order to adjust the field of view (FOV) of the user automatically. The contributions of this paper can be summarized as follows:

- We present a prototype implementation that dynamically controls the user's FOV in virtual reality using fNIRS.
- We show in a study with 11 participants that we can detect total hemoglobin change (Hbt) with a high enough level of sensitivity to identify cybersickness during VR locomotion events.
- We compare the dynamic FOV adjustment using fNIRS with a standard method using movement velocity in an experiment with 10 participants.

2 RELATED WORK

Our work can be seen in the context of implicit interactions, using physiological signals to recognize the user's state and seamlessly provide feedback. There is a lot of work in implicit interactions in VR/AR environments using physiological signals [1, 5, 12, 14]. Common sensing technologies use various targets: tracking facial expressions to body movement, eye tracking and brain activity sensing (mostly EEG). The applications also vary widely, for example, redirected walking and re-targeting of hand movements using visual/haptic illusions[12, 13]. As the field is so broad, we will focus on this paper's use case: locomotion related research and works related to cybersickness.

The symptoms evoked by cybersickness are similar to simulator sickness. Furthermore, teleportation is a well-known technique for reducing cybersickness[2]. Since the screen changes instantly, teleportation reduces the sensation of moving and can suppress cybersickness. A study comparing severity of sickness for steering (the user continuously perceives the scene along the path to the destination) and jumping reported significantly lower scores for jumping. In the same experiment, steering tended to be preferred for the task of allowing users to freely explore the VR space[18]. Besides, changing the screen instantly reduces immersion, so it is not suitable for VR locomotion. Controlling the FOV can also reduce cybersickness[7]. Both methods can reduce cybersickness, but at the expense of immersion and presence. In other words, there is a trade-off between avoiding cybersickness and reducing immersion. Some studies have minimized decreasing presence by dynamically controlling the FOV. They obtain the user's movement velocity and angular velocity and control the FOV accordingly to ensure a sense of presence while reducing cybersickness[7]. There are some quantitative metrics for evaluating cybersickness. The simulator sickness questionnaire (SSQ) is a widely used tool to assess them [9].

Some studies have attempted to assess cybersickness using physiological signals. Currently, no physiological indicators that can accurately assess cybersickness have been established, but some seem to be possible. An increase in arousal leads to changes in respiratory rate and causes a decrease in the concentration of carbon dioxide in the cerebral bloodstream. These changes may cause symptoms of VR sickness [4]. It was suggested that gastric tachycardia, blinking, heart rate and EEG delta waves were positively correlated with SSQ scores [10]. When cybersickness symptoms were mild, respiratory variability and ventilation were reduced, and when severe sickness occurred, markedly larger respiration and increased respiratory variability were observed[15].

There is a great deal of individual variation in the degree of cybersickness[16]. We follow a study from Bruck et al. postulating that subjects experiencing cybersickness have increased cerebral blood flow (total hemoglobin concentration increase) during movement sequences (caused by symptoms like an increased breathing rate) [4]. This principle is the basis of our system.

Other researchers are exploring fNIRS setups in virtual reality. Yet, to our knowledge, we are the first to present a fully interactive system with an evaluation in 2 user studies.

Figure 2: Experimental setup: Participant wearing the VIVE VR headset and an fNIRS (model HOT-1000 from Hitachi connected to the computer over Bluetooth).

3 APPROACH

As mentioned in the related work, serveral researchers are focusing on intuitive interactions in virtual/ augmented reality. The most obvious related to cognition and higher level reasoning are EEG and eye tracking.

We decided to use fNIRS for a dynamic detection of cybersickness during walking events. The signal is also affected by movement, yet the resulting noise is less than for EEG. One problem with fNIRS measurements is the delay (from 30 sec. to 3 min). As cybersickness during locomotion usually builds up slowly, it is applicable for our use cases. Additional advantages of using fNIRS is that we do not require user-dependent calibration (eye tracking) or careful sensor placement (EEG). Our system is looking for relative changes in total hemoglobin (Hbt) concentration measured in the prefrontal cortex. It detects symptoms of cybersickness in subjects by measuring changes in cerebral blood flow (hemoglobin concentration changes) caused by hyperventilation using fNIRS based on the experiments of Bruck et al.[4]. In the following, we present our prototype implementation, as well as an initial test detecting cybersickness using our prototype, and a study to evaluate a shrinking FOV if cybersickness is recognized.

4 HEMODYNAMICVR PROTOTYPE

We use an HTC VIVE VR headset with an fNIRS device (model HOT-1000 provided by Hitachi, Figure 2) connected over Bluetooth to a computer running Windows 10. The application was developed with Unity version 2019.4.12f1. The VR space was created from free Unity assets (Nature Starter Kit2 and Farm Animals Set).

5 PROTOTYPE EVALUATION

In the following, we present several use cases of the HemodynamicVR prototype to show its functionality and provide evidence that fNIRS can be used for implicit VR interactions. All experiments were conducted under the guidelines and approval of the ethics committee of X (blinded for review).

5.1 Use case: Detecting Cybersickness

In a use case evaluation, we assess if we can detect cybersickness episodes in users using the HemodynamicVR prototype. Our hypothesis, based on Buck et al.[4]: if the user is moved significantly in the VR environment, there is an increased cognitive load indicated by an increase in total hemoglobin change.

To induce cybersickness in real-time, the study participants experience VR in an uncontrolled state. The user is passively moved in random directions on a VR forest landscape. We ask the user to press a button if they feel sickness. We use the HemodynamicVR prototype to record the Hbt values during the experience. Users can stop at anytime; the experiment lasted for a maximum of 5 minutes. We performed the SSQ test before and after the experience. We had 11 participants (5 female, average age 24.2, std=1.33).

From the results, it seems only for 7 participants the Hbt values increased when experiencing cybersickness. 4 participants pressed the button sometimes (indicating they felt sick), yet their Hbt values did not increase significantly. These 4 participants' score difference (before experiment - after experiment) was very low on the SSQ score. Comparing them with the 7 participants in terms of SSQ, we can detect a significant difference in the 2 groups (Mann–Whitney's U test, p=0.05). For the 4 participants, the SSQ scores are significantly lower than for the 7 others, meaning although they had indicated they had felt sick, it seems like it had been relatively mild and does not register as cybersickness according to the SSQ score.

The experimental results suggest that fNIRS can detect cybersickness when its degree is above the level registered by the qualitative SSQ test. As we hypothesized, participants with a strong increase in cybersickness (SSQ score) had an average increase of 0.56 in Hbt value compared to the Hbt value when they did not feel sick. We set this mean value as a threshold for the occurrence of cybersickness.

5.2 Use case: Field of View (FOV) Adjustment

We conducted a short FOV test to experimentally determine the FOV that could retain immersion during VR locomotion without inducing sickness. Specifically, we determined the appropriate parameters for the minimum FOV to limit cybersickness during locomotion events and to retain as much immersion as possible.

11 participants (6 female, average age 24.9 years, std = 2.21) conducted the setup. In the FOV use test, subjects wore the VIVE headset and moved in virtual space. The velocity was set to one meter per second and they were free to move with the joystick. To decide the minimum FOV, the subjects' FOV was narrowed slowly while they were moving. They were not informed in advance that the FOV would change. The subjects were instructed to verbally tell the experimenter if they felt a loss of immersion. They were also interviewed after the experiment. We also varied the rate at which the FOV narrowed while they were moving to determine the appropriate rate of FOV change. We then instructed them to verbally tell us when they felt uncomfortable regarding their vision.

As a result of the short FOV test, most subjects did not report any discomfort/loss of immersion when being limited to 10 percent of their FOV plus blur (see Figure3). In minimum FOV, 10 percent of the subject's FOV is completely blocked and the blur comes in at the boundary where transparency is 0 (Figure 3).

Figure 3: Field of View adjustment (rendering for the left eye).

6 DYNAMIC FOV ADJUSTMENT

To show the usefulness of HemodynamicVR, we implemented a dynamic FOV adjustment based on the cybersickness and FOV use case evaluations. An increase in Hbt value during locomotion events (moving with a gaming controller) leads to a decrease in FOV. We compare it to a standard implementation of a restricted FOV using velocity: the faster the user moves, the smaller the FOV gets. We use the empirically determined parameters described in the previous section for the FOV.

6.1 Experimental Setup

We use the HemodynamicVR prototype for the experimental setup. We created an animal search game in a forest with the Unity game engine (randomly spawning animals, see Figure 4). Participants have to move using a gaming controller and search and count the animals in a given area. This task was chosen as it requires exploring the area as well as moving the head around. The position of the animals was randomised. Participants wore the HemodynamicVR.

The participants' movement speed is 1 m/sec at maximum (around average walking speed). The experiment is divided into two parts, each lasting 5 minutes. The parts are counter-balanced. In the velocity session, we reduce cybersickness by changing the FOV based on the subject's velocity (Figure1). In the fNIRS session, we change the FOV based on the subject's Hbt value during the experience. We obtain the average of Hbt values during the first minute before starting the experience and use this as the baseline.

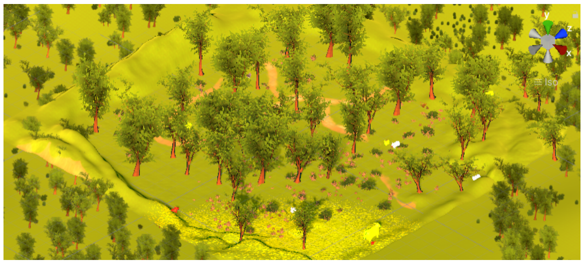

Figure 4: Subjects look for animals in this VR environment

The FOV shrinks when Hbt is greater than or equal to the set value based on the cybersickness evaluation. We record the Hbt values during the sessions. After and before the session, the user fills out the SSQ for cybersickness [9]. After each session, the user also answers the immersion questionnaire (IQ) [8].

This experiment was conducted with 10 participants (6 female, average age 24.5 years, age standard deviation 1.27).

6.2 Results

Figure 5 is a violin plot of the mean Hbt values in the velocity and fNIRS sessions. Compared to the velocity session, the mean Hbt values were significantly reduced in the fNIRS session (Wilcoxon signed-rank test, p=0.05).

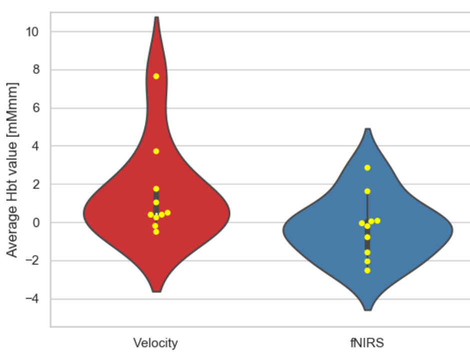

Figure 5: Violin plots: Hbt values, velocity vs fNIRS session

A comparison of the total SSQ scores showed a decrease in 6 participants (Figure 6). But both of total SSQ scores are compared and no significant differences were identified (Wilcoxon signed-rank test, p=0.05). As a result of comparing the total IQ scores, an increase in scores of 6 participants was confirmed (Figure 7). However, no significant differences were identified (Wilcoxon signed-rank test, p=0.05). We learned from the interviews that one of the reasons why the SSQ of the fNIRS session increased more than that of the velocity session was that two participants' eyes were tired from concentrating too much on the game in fNIRS session. The subjects reported an increase in scores of the eye-related items ("eye strain", "difficulty focusing") and also an increase in IQ scores on "focus" and "losing track of time".

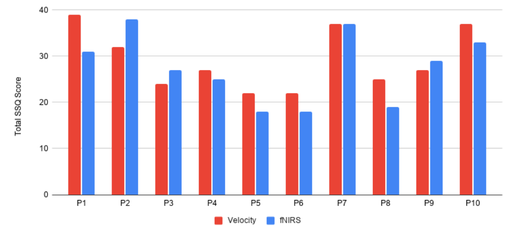

Figure 6: SSQ score comparing the FOV adjustment using velocity and fNIRS

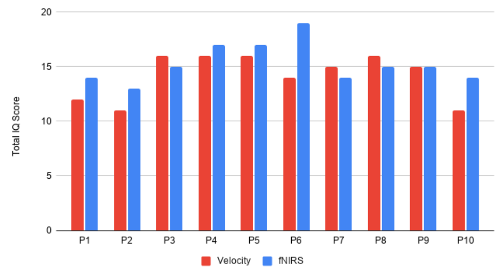

Figure 7: IQ score comparing the FOV adjustment using velocity and fNIRS

7 DISCUSSION AND CONCLUSIONS

In this study, we were able to detect cybersickness taking the current cognitive load of the user into account. As tolerance for sickness could vary given the current state of mind and condition of the user (for example: fatigued versus well-rested, hungry versus satiated, etc.) and the VR experiences they play (users might be more prone to sickness for specific scenarios, e.g. underwater, in the sky), FOV control by velocity only cannot adapt to these factors. Therefore, we need a dynamic solution adapting the VR experience to the current sickness condition of the user. The questionnaire didn't confirm a significant difference between the two methods, but this may be due to the fact that some of the questions apply to both focus on the game and sickness. A disadvantage is that the weight of the HMD is increased by our prototype due to the additional fNIRS device, leading to more fatigue for the user. There are limitations to our system's initial implementation as higher hemoglobin levels can also be induced by other cognitive states (e.g., a user trying to solve a very hard math problem). This is a current limitation we addressed by only measuring hemoglobin changes when the user is actually moving (in walking segments). In future work, we also need to take cognitive tasks while walking into account, predict or recognize them and adjust the FOV accordingly.

In this paper, we present a prototype implementation that dynamically controls the user's FOV in VR using fNIRS. We detected Hbt changes with a high enough level of sensitivity to identify cybersickness. We also controlled the FOV using two methods (velocity and fNIRS) and compared the effects of each method on cybersickness reduction.

REFERENCES

[1] Sergi Bermúdez i Badia, Aleksander Valjamae, Fabio Manzi, Ulysses Bernardet, Anna Mura, Jônatas Manzolli, and Paul FM J Verschure. 2009. The effects of explicit and implicit interaction on user experiences in a mixed reality installation: The synthetic oracle. *Presence: Teleoperators and Virtual Environments* 18, 4 (2009), 277–285.

[2] Laurenz Berger and Katrin Wolf. 2018. WIM: fast locomotion in virtual reality with spatial orientation gain & without motion sickness. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*. 19–24.

[3] Costas Boletsis. 2017. The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction* 1, 4 (2017), 24.

[4] Susan Bruck and Paul A. Watters. 2011. The factor structure of cybersickness. *Displays* 32, 4 (oct 2011), 153–158. https://doi.org/10.1016/j.displa.2011.07.002

[5] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D Wilson. 2017. Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 3718–3728.

[6] James E Cutting. 1997. How the eye measures reality and virtual reality. *Behavior Research Methods, Instruments, & Computers* 29, 1 (1997), 27–36.

[7] A. S. Fernandes and S. K. Feiner. 2016. Combating VR sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. 201–210.

[8] Charlene Jennett, Anna L Cox, Paul Cairns, Samira Dhoparee, Andrew Epps, Tim Tijs, and Alison Walton. 2008. Measuring and defining the experience of immersion in games. *International journal of human-computer studies* 66, 9 (2008), 641–661.

[9] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.

[10] Young Kim, Hyun Kim, Eun Kim, Heedong Ko, and Hyun-Taek Kim. 2005. Characteristic changes in the physiological components of cybersickness. *Psychophysiology* 42 (10 2005), 616–25. https://doi.org/10.1111/j.1469-8986.2005.00349.x

[11] Eugenia M Kolasinski. 1995. *Simulator sickness in virtual environments*. Vol. 1027. US Army Research Institute for the Behavioral and Social Sciences.

[12] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 1471–1482.

[13] Fabien Lotte, Josef Faller, Christoph Guger, Yann Renard, Gert Pfurtscheller, Anatole Lécuyer, and Robert Leeb. 2012. Combining BCI with virtual reality: towards new applications and improved BCI. In *Towards Practical Brain-Computer Interfaces*. Springer, 197–220.

[14] Sebastian Marwecki, Andrew D Wilson, Eyal Ofek, Mar Gonzalez Franco, and Christian Holz. 2019. Mise-unseen: Using eye tracking to hide virtual reality scene changes in plain sight. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 777–789.

[15] Chizuru Nakagawa. 2008. "Studies on motion sickness using physiological responses". (2008).

[16] Lisa Rebenitsch and Charles Owen. 2014. Individual variation in susceptibility to cybersickness. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. 309–317.

[17] Kay Stanney, Cali Fidopiastis, and Linda Foster. 2020. Virtual Reality Is Sexist: But It Does Not Have to Be. *Frontiers in Robotics and AI* 7 (2020), 4. https://doi.org/10.3389/frobt.2020.00004

[18] T. Weißker, A. Kunert, B. Fröhlich, and A. Kulik. 2018. Spatial Updating and Simulator Sickness During Steering and Jumping in Immersive Virtual Environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 97–104. https://doi.org/10.1109/VR.2018.8446620