Identifying Cybersickness When Wearing a Head-Mounted Display through Heart Rate Variability Data

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Abstract. Cybersickness is one of the common problems related to Virtual Reality (VR). The symptoms are classified into three categories: nausea, oculomotor, and disorientation. The purpose of this study is to identify cybersickness symptoms based on simulator sickness questionnaire (SSQ) and physiological signal using heart rate variability (HRV) when wearing a head-mounted display. Fifteen participants performed a 15-min driving simulation task using head-mounted display. From the SSQ results, the most dominant category of cybersickness symptoms induced by participants are nausea and disorientation. The results showed a correlation between the nausea score and the high frequency (HF)/component of HRV (r=0.618, p=0.032) as well as the ratio of low and high frequency component (LF/HF) (r=-0.718, p=0.009). These findings confirm that the occurrence of nausea when wearing a head-mounted display is influenced by the activation of sympathetic nervous system.

1. Introduction

Virtual Reality (VR) and Head-Mounted Display (HMD) have been increasingly popular for professional use and entertainment use over the past years. VR technology has been used, for example, for military training simulations [1][2], medical procedures [3], and gaming or entertainment. Apart from various technological improvements, one of the common problems that is constantly associated with VR activities is dizziness and uncomfortable feelings. This phenomenon is called cybersickness [4].

Cybersickness is a common side effect of VR related activities. It is often indicated with nausea, dizziness and vomiting as the symptoms [5]. A study by Cobb et al. [6] stated that 80% of their participants showed cybersickness symptoms within 10 minutes during VR activities. Another study by Regan and Price [7] found that 60% of their participants showed cybersickness symptoms within 20 minutes during VR activities. These symptoms can last for more than five hours after they are no longer in the Virtual Environment [7].

The cybersickness symptoms are classified into three categories, namely nausea, disorientation, and oculomotor [8]. Those symptoms are usually measured using Simulator Sickness Questionnaire (SSQ), a subjective measurement developed by Kennedy et al. [8]. Measurement using physiological signal such as Heart Rate Variability (HRV) to obtain more objective results have received lack of attention. There are a few similar studies about HRV to identify cybersickness [9][1][10][11][12]. But a more detailed study about the correlation between HRV parameters and cybersickness symptoms need to be done to validate the findings of those studies.
Heart rate variability describes changes in heart rate intervals associated with automatic nerve regulation such as the sympathetic and parasympathetic nervous system [13]. Parasympathetic activity decelerates the HR and on the other hand, sympathetic activity elevates it. The dynamic balance between parasympathetic and sympathetic activity causes a continuous oscillation of the HR called HR variability [14]. Under resting conditions, parasympathetic activity is dominant [15]. The advantages of using physiological indices such HRV parameters is to understand participants’ physical condition. HRV parameters can be used to examine the participants’ conditions based on parasympathetic and sympathetic activities, so the most correlated HRV parameters to cybersickness need to be investigated.

From the aforementioned background, the purpose of this study was to identify the dominant categories of cybersickness symptoms when wearing HMD in a driving simulator. This study also sought to investigate whether HRV correlates with cybersickness occurrence when wearing HMD. In this study, cybersickness was measured objectively using HRV and subjectively using SSQ. HRV parameters used in this study are the time domain components (SDNN and RMSSD) and the frequency domain components (LF, HF, and LF/HF).

2. Methods

2.1. Participants

Fifteen students (Mean of ages=23.5 (± SE=0.57)) volunteered in this study. Participants had healthy eyes or had corrected to normal vision. All participants reported that they were infrequent game players (less than 5 times a month). Three from fifteen participants discontinued the experiment prematurely due to severe cybersickness and were excluded from the data analysis.

2.2. Apparatus

The driving simulation task was performed using a PC-based driving simulator (City Car Driving v 1.5.6, Forward Development, Russia) run on a PC with a quad-core Intel® CoreTM i7-6700K@ 4.00 GHz, 16GB of RAM, and a NVIDIA® GeForce® GTX 980 with 12GB of GDDR5. The virtual environment of the driving simulator was projected to an HMD (Oculus Rift, Oculus VR, Irvine, CA). The driving simulator was equipped with a driving chair, a manual gear controller, and a three-pedal set.

2.3. Experiment Procedure

Before starting the experiment, the participants received the details of this study and were informed that they were free to abort the experiment at any time without being penalized. All participants gave written consent prior to the experiment and stated that they were in a normal state of health (no dysfunctional olfactory). Polar heart rate sensor (Polar H7, Polar, Finland) was attached to every participant’s chest during the experiment to record the inter beat interval (IBI). After the fifteen minutes driving task was completed, the participant was asked to fill in SSQ to indicate the cybersickness symptoms they experienced. All procedures in this study had followed the ethical clearance for human subjects.

2.4. Subjective Measurements

Participants’ cybersickness was measured using Simulator Sickness Questionnaire (SSQ) developed by Kennedy et al. [8]. It consists of 16 symptoms related to the simulator sickness. Participants were asked to rate these symptoms on a 4-point Likert scales (0 – not at all, 1 – slight, 2 – moderate, and 3 -severe) after the driving simulation task. The SSQ symptoms were categorized into three subscales, nausea (SSQ-N), disorientation (SSQ-D), and oculomotor (SSQ-D) and finally the cybersickness score (SSQ-Total) was calculated using the pre-defined weighting factor as explained in Kennedy et al. [8].

2.5. Heart Rate Variability Measurements

HRV was measured using a polar heart rate sensor (H10, Polar, Finland). The heart rate sensor was attached to participant’s chest before participants starting the experiment. Inter beat interval data (IBI) was recorded using the Polar Beat application in a smartphone. IBI data were then imported to Kubios HRV software (Kubios HRV Standard 3.2.0) to pre-process the data and to obtain the frequency and time domain components. The frequency domain data used in this study were Low Frequency (LF, 0.04 – 0.15 Hz) and High Frequency (HF, 0.15 – 0.40 Hz) and LF/HF ratio. The time domain data used in this study were Standard Deviation of Normal to Normal R-R intervals (SDNN) and Root Mean Square of Successive Heartbeat Interval Difference (RMSSD) as indicators.
2.6. Statistical Data Analysis
The data are presented in mean ± standard error (SE). Prior to statistical analysis, a normality test was used to check the parametric assumption of the data. If normality assumption is violated, then nonparametric test will be performed. RM ANOVA test was employed to test the significant difference among the SSQ subscales. If there is a significant difference, then post hoc test with Bonferroni correction would be administered. Maximum value of SSQ subscales are different so the data have to be normalized. HRV analysis with frequency domain were expressed in original units or as the natural logarithm (ln) of original units to achieve a more normal distribution [16]. Correlation test (Spearman’s rho test) was administered to find the relationship between physiological indices (HRV parameters) and cybersickness level. The significance level was set $\alpha = 0.05$. All statistical tests were performed using JASP software.

3. Results
3.1. Simulator Sickness Questionnaire
The mean SSQ score are shown in Figure 1, the results showed that Nausea and Disorientation had the highest score among all symptoms. Nausea mean score is 53.26 ± 13.46, Oculomotor mean score is 48.00 ± 9.43, and Disorientation mean score is 53.36 ± 12.57. However, the RM ANOVA test showed that there was no significance difference among these three subscales (F=3.093, p=0.066).

![Figure 1. Mean Ratio SSQ subscales scores](image)

3.2. Heart Rate Variability (HRV)
The mean HRV scores for Frequency Domain and Time Domain are shown in Figure 2, the results showed that the lnLF mean score is 4.55 ± 0.13, lnHF mean score is 1.95 ± 0.15, and lnLF/HF mean score is 2.46 ± 0.16. The mean HRV scores for Time Domain showed that SDNN mean score is 12.6 ± 0.69, and RMSSD mean score is 7.07 ± 0.44. High LF power means that sympathetic activity is more dominant than parasympathetic activity, sympathetic activity governs the “fight or flight” response while the parasympathetic activity controls the “rest and digest” response. The main overall end effect of the sympathetic activity is to prepare the body for physical activity [20].

3.3. Correlation between SSQ and HRV
Correlation test (Spearman’s rho test) was performed to find the correlation between SSQ subscales (Nausea, Disorientation, and Oculomotor) and HRV subscale (LF, HF, LF/HF, SI, SDNN, and RMSSD). The result showed that there is a strong positive correlation ($r=0.618$, $p=0.032$) between HF and Nausea score. A strong negative correlation is found between LF/HF ratio and Nausea score ($r=-0.718$, $p=0.009$). But there was no significance difference between the other HRV parameters and SSQ subscales. The
correlation plots between HRV (HF and LF/HF) and SSQ nausea score, and the correlation coefficient are shown in Figure 3.

![Figure 2](image1.png)

**Figure 2.** Frequency Domain and Time Domain HRV Analysis

![Figure 3](image2.png)

**Figure 3.** Correlation Plot between HRV and SSQ Subscales

4. Discussion

This study used subjective and objective measurements to identify cybersickness symptoms induced by participant through participant’s Heart Rate Variability. Subjective responses measured by Simulator Sickness Questionnaire (SSQ) and objective responses measured by Heart Rate Variability (HRV).

The SSQ mean score showed that Nausea and Disorientation had the highest score compared to Oculomotor. It means that Nausea and Disorientation are the strongest symptoms induced by participants that caused Cybersickness. But there was no significance difference among these three subscales (p>0.05).

HRV analysis using Frequency Domain method showed the high score of LF power and the low score of HF power. Psychological stress was significantly associated with an increase in the LF/HF ratio [17]. The LF power is associated with sympathetic activities and the HF power is associated with parasympathetic activities [18]. It means that cybersickness induced by participant caused the increased of LF power and the decreased of HF power. The increased of LF power means that sympathetic nervous system (SNS) is dominant. The SNS governs the “fight or flight” response while the PNS
(parasympathetic nervous system) controls the “rest and digest” response. The main overall end effect of the SNS is to prepare the body for physical activity [19].

Correlation test (Spearman’s rho) was performed to find the coefficient correlation between SSQ subscales (Nausea, Disorientation, Oculomotor and Total SSQ) and HRV subscales (LF, HF, LF/HF, SDNN, and RMSSD). The Coefficient Correlations showed that there is a strong positive correlation between HF and Nausea score. And a strong negative correlation was found between LF/HF ratio and Nausea score. The results are statistically significant. But there was no significance difference between the other HRV variables and SSQ subscales.

A strong positive correlation between HF power and Nausea score showed that increasing Nausea induced by participants caused the increase of HF power. HF or High Frequency range of HRV is considered to be representative of vagal activity [20]. Previous study [20] also has the same findings that there is a transient trending increase in HF power right before strong nausea. Findings confirm gradual sympathetic activation with increasing nausea and further evidence of increase in vagal tone before strong nausea. Vagal activity results in various effects such as heart rate reduction [20].

A strong negative correlation was found between LF/HF ratio and Nausea score. The increased of LF/HF ratio showed the decreased of nausea experienced by participant. It means that the balance of autonomic nervous system correlated to nausea induced by participants. From Correlation test performed in this study, we can conclude that there are relationships between HRV parameters and SSQ subscales. Further research with more participants needs to be done.

5. Conclusion

The purpose of this study is to find the correlation between the induced cybersickness and participant’s heart rate variability. From the SSQ results, Nausea and Disorientation had the highest score among all symptoms. The Coefficient Correlations showed that there is a strong positive correlation between HF power and Nausea score, also a strong negative correlation between LF/HF ratio and Nausea score. The results are statistically significant. But there was no significance difference between the other HRV parameters and SSQ subscales. These findings confirm that the occurrence of nausea when wearing a head-mounted display is influenced by the activation of sympathetic nervous systems. Further research with more participants needs to be done.

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