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Level of motion sickness based on heart rate variability when reading inside a fully automated vehicle

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This article contributes to:

Highlights:

- The level of motion sickness experienced while reading in fully automatic driving mode was investigated.
- Peripheral visual information system (VPIS) and haptic (HPIS) were used as interventions.
- The overall findings showed that mild motion sickness was found in the VPIS and HPIS conditions.
- Further studies with more rigorous time segment analysis are needed to provide more accurate dynamic changes in cardiac activity.

Abstract

This study investigates the level of experienced motion sickness when performing reading while being driven in fully automated driving under three different conditions. One condition was without any intervention while the other two conditions were with the visual (VPIS) and haptic (HPIS) peripheral information system. Both systems provided the upcoming navigational information in the lateral direction three seconds before the turning/cornering was done. It was hypothesized that with the peripheral information systems, the experienced motion sickness would be reduced compared to the condition where a peripheral information system was not present. Eighteen participants with severe motion sickness susceptibility were carefully chosen to undergo the conditions using an instrumented vehicle with the Wizard-of-Oz approach. The participants were required to read from a tablet during the whole 15-minutes of automated driving. Results from the heart rate variability (beats per minute, root means square of successive differences, and high-frequency component) indicated no statistically significant changes ($p < 0.05$) in motion sickness found with the presence of HPIS and VPIS when performing reading when being driven in automated mode. However, results from this study were mixed and inconclusive, but overall findings indicated mild motion sickness was found in both VPIS and HPIS conditions.

Keywords: Motion sickness; Heart rate variability; Automated vehicle

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1. Introduction

To the automotive consumers, the development of automated vehicles (AV) showed more than just a glimpse of hope when Tesla offered its first automation called the "Autopilot" by the end of 2014. The AV brings excitement and benefits that will shape the future of users and stakeholders in the automotive industry. One of the significant advantages is road safety [1], [2]. Another significant benefit is that AVs could make mobility more productive than just commuting. Since human is no longer required to operate the vehicle, they can engage in non-driving related tasks (NDRT) that are deemed useful and practical inside the AV.

Unfortunately, engaging in the NDRT as mentioned above will make the users of an AV become unaware of the vehicle's intention concerning its navigation and therefore unable to anticipate upcoming events [3], [4]. Most, if not all, of the attention will be channelled to performing the NDRT. Hence, the users or occupants will become vulnerable and unprepared for the upcoming changes in the accelerations (e.g., accelerating, braking, and cornering). Therefore, this would cause users to become susceptible to motion sickness due to the sensory conflict. When reading while being driven, a user's visual system is not detecting any motion, but his/her vestibular and somatosensory systems are sensing changes in motion. Thus, implications like experiencing motion sickness might lower the value of AV as a mobility solution that offers the freedom to its users to perform the task of their liking when the automation takes over the wheel.

Typically, passengers in a moving vehicle usually look out of the window to check the vehicle's trajectory concerning their position. It was found that passengers who could not see the road ahead suffered motion sickness three times more than those who could see the outside view of a moving vehicle [5]. However, regularly checking the earth-fixed horizon through the vehicle's window will likely interrupt the experience of performing the preferred NDRT. Strategies to mitigate motion sickness can be in the form of active and passive approaches for example adoption of a controller to compensate for lateral acceleration [6], [7] or presenting motion cues [8], [9]. One of the promising ways to maintain a high level of awareness of the vehicle's navigational trajectory and reduce the likelihood of motion sickness inside a moving vehicle is by using a peripheral information system or an ambient display [10]. Peripheral information systems are "aesthetically pleasing displays of information which sit on the periphery of a user's attention" [11]. This system is developed to assist the user in getting information that is relevant and important to them in an unobtrusive way.

Different kinds of physiological measurements have been used to investigate the severity of motion sickness experienced by a human. For instance, the measurement of changes in skin resistance [12] and the secretions of saliva [13] can be used to assess the level of motion sickness. In this study, we quantified motion sickness through heart rate and heart rate variability (HRV) measured using electrocardiogram (ECG) sensors. The reasons for using the heart rate and HRV to measure motion sickness in this study were twofold. First is its ability to obtain a continuous recording of one's physiological state and thus allow the experiment to be done without the need to stop and collect the data [14]. Secondly, both offer a quantitative view of the measurement of motion sickness. Parasympathetic nervous system withdrawal has been shown to indicate the development of motion sickness [15]–[18]. The withdrawal action shows a response in preparation for a defensive stance or escaping a potential threat such as motion sickness [19]. When motion sickness occurs, the stomach's activities will shut down, and the blood flow will be directed to the other parts of the body (i.e., the heart) per the "flight or fight" response. The digestion processes will be paused until the threat is no longer present [19]. The regulations of the autonomic events by the sympathetic and parasympathetic nervous systems can be quantified using the time- and frequency-domain analysis of ECG data.

The primary objective of this study is to measure the user's level of experienced motion sickness using psychological measurement under three different conditions. The users were asked to perform reading as an NDRT while being driven in automated driving. The first condition was termed as a control condition (without the presence of any peripheral information system), while the second and third condition was with a visual-based and haptic-based peripheral information system, respectively.

2. Methods

2.1. Experiment design

In determining the design of this study, two factors have been considered. First, since the susceptibility to motion sickness is different among individuals; therefore, the conditions of interest must be evenly tested by everyone rather than by different individuals [20]. Secondly, since heart rate variability (HRV) was taken as a physiological measurement from the participant throughout the experiment, to get optimal experimental control (fewer variations among participants due to factors such as alcohol consumption and body mass index (BMI)), a within-subject design was selected as recommended by experts in HRV research [21], [22].

In this study, all the participants went through three conditions in three isolated sessions. The three conditions were termed control-, visual-, and haptic-condition. The control-condition was

the condition without the presence of a peripheral information system. The visual- and haptic-condition were the conditions for implementing a visual (VPIS) and haptic peripheral information system (HPIS), respectively.

The dependent variable was the level of motion sickness measured using physiological measurement employing HRV, while the independent variable was the conditions. The order of the three test conditions was counter-balanced to moderate any learning effects (3! = 6 orders). The route comprised three laps of 22 turns to the right, and 16 turns to the left (cornering radii, Mean = 9.2 m, SD = 3.3 m). This research complies with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) [23].

2.2. Equipment – Mobility lab and peripheral information systems

The Mobility Lab was employed as an on-road automated vehicle simulator to provide a fully automated driving experience (see [24] for a detailed explanation of the test setup). The automated driving style that was selected was based on the previous studies in which a setting called defensive automated driving style [25], [26].

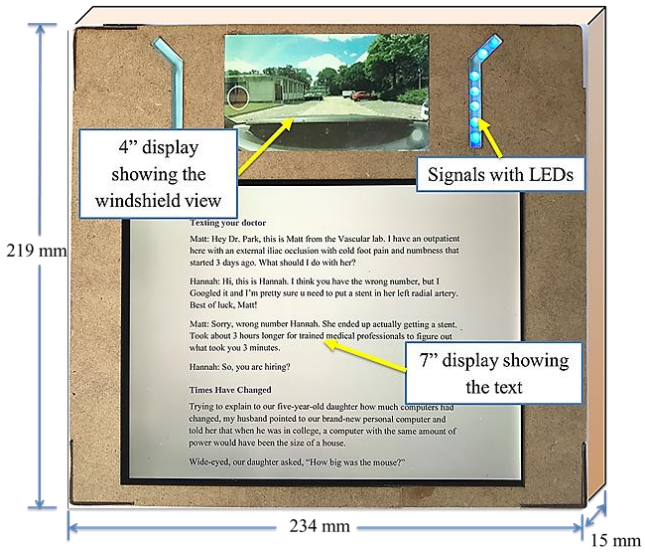

Figure 1. Visual peripheral information system (VPIS) [27]

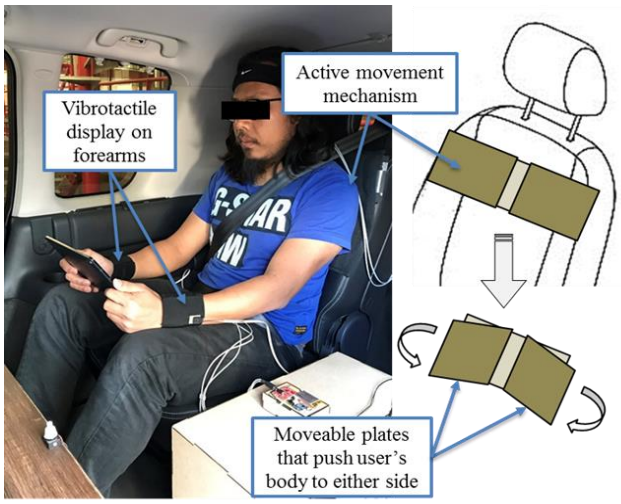

Figure 2. Haptic peripheral information system (HPIS) [27]

Two (VPIS, see **Figure 1** and HPIS, see **Figure 2**) peripheral information systems were used. VPIS consisted of a 4.0 inches screen and two LED-filled arrays, at around an 8.9 inches tablet. Each array was equipped with 7 LEDs, with blue-emitting colour, that switched on three (3) seconds before the Mobility Lab entered a corner/turning.

HPIS consisted of two sets of vibration motors and two movable plates that were fixed on the backrest of the car seat and were covered with foam cushion and fabric. Three (3) seconds before the car turned to the left or right, the vibration motors (the left forearm set if turning to the left, the right forearm set if turning to the right) were activated and deactivated for three cycles. Subsequently, the movable plate (the right plate if turning to the left, the left plate if turning to the right) was triggered, turning forward through servo motors at about 40° if the corner/turning occurred.

2.3. Participant and procedure

Nine (9) males and nine (9) females aged between 22 and 33 years old (Mean = 28.4, SD = 3.0) participated in this study. Stratified sampling was implemented to check participants' susceptibility to motion sickness, based on the short version of the Motion Sickness Susceptibility Questionnaire (MSSQ) with a 100% scale [28], [29]. Only participants with mild and severe susceptibility were selected based on the MSSQ's scores (Mean = 79.1%, SD = 17.3%). Since HRV was measured, all the selected participants were non-smokers, consumed not more than 5 to 7 alcoholic drinks per week, and had a BMI around 18 to 25 (Mean = 21.6, SD = 2.0) [30]–[33]. In addition, the participants were instructed to follow a regular sleep routine the day before the study and not to participate in intense physical training the day before the study [21]. High carbohydrate

meals (e.g., rice, bread, etc.) and caffeinated drinks were prohibited at least two hours before the experiment.

Each condition in this study consisted of seven stages (see **Figure 3**). Stage 1 and the ending part of Stage 7 took place in a meeting room while Stage 2 through 6 was done using the Mobility Lab. The study started with Stage 1 (Pre-Experiment stage), where participants arrived at the allocated meeting room and were briefed about the nature of the study. Informed consent was also obtained during this stage. Afterwards, the experimenter explained to the participants how to properly attach the disposable ECG electrodes (43 x 35 mm disposable pre-gelled ECG hydrogel) to their torsos themselves. The placement of ECG electrodes used in this study was based on lower torso placement, as suggested by [34]. This arrangement of ECG electrode placement is more robust to movement artefacts and allows participants to place the electrodes without exposing their chest [34]. Afterwards, the experimenter escorted the participant to the Mobility Lab and asked him/her to be seated and wear the seat belt inside the vehicle.

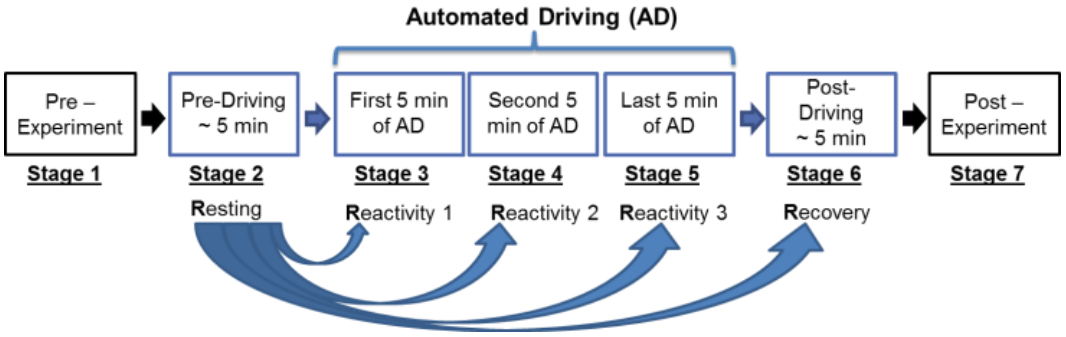

Figure 3. The seven stages of the experiment for the three conditions with the three-R structure of HRV measurement and analysis used in this study

Stages 2 and 6 were done when the Mobility Lab was static with the engine turned on. In contrast, Stages 3, 4, and 5 were performed when the Mobility Lab was driven continuously for about 15 minutes on the designated route. The ECG measurements were recorded continuously, from Stage 2 until Stage 6. Three different sets of reading materials were used for three separate sessions, and the reading materials were compilations of jokes from Reader's Digest magazine [35]. Participants were asked to perform the reading task from Stage 2 continuously through Stage 6. However, there was a stop button to stop the experiment at their own will. In addition, the temperature inside the Mobility Lab was controlled by the vehicle's air-conditioning at 20°C at all times during the experiment [36]. At the end of Stage 7, the experimenter gave a debriefing and compensation to the participants for their participation in this experiment.

2.4. Data collection and analysis

The recorded ECG measurements were later quantified into HRV using time- and frequency-domain analysis. In terms of time-domain analysis, the root means square of successive differences (RMSSD) is usually used to indicate the activity of the parasympathetic nervous system (PNS) or also known as the vagal tone [37], [38]. The decrement of PNS activity has been shown to indicate the development of motion sickness [15]–[18]. RMSSD is also the most robust indicator of PNS activity and is less affected by the effect of respiration compared to the other indicators (i.e., Percentage of successive normal sinus RR intervals more than 50 ms (pNN50; [39], [40]). In addition to RMSSD, the heartbeat in terms of beats per minute (BPM) was also measured. Past studies found that increased motion sickness was positively correlated with increased BPM [16], [41], [42]. In terms of frequency-domain analysis, the high-frequency (HF) component (between 0.15 to 0.40 Hz) was extracted by using the Fast Fourier Transform (FFT). The HF component used in this study is also highly associated with the activity of the PNS [21], [43]. A minimum window size of five (5) minutes of heart rate recording per stage was applied as recommended by [44] for short-term heart rate measurement. The measured data from the accelerometers and ECG were sampled at 250 Hz, synchronised, and stored using a data acquisition system (DAQ). A 250 Hz was employed as a conservative approach as 125 Hz is deemed a minimum sampling rate in collecting HRV data in psychophysiological studies [21].

The HRV data were continuously collected from Stage 2 to 6. The automated driving phase was about 15 minutes, and the analyses of the HRV during those particular stages were performed at each individual stage (Stage 3 to 5) with a time window of 5 minutes. In addition, the HRV data were analysed according to the three-R structure (i.e., resting HRV, reactivity HRV, and recovery

HRV) as suggested by [21] (see **Figure 3**). Stage 2 is the baseline HRV or also known as resting HRV in which the HRV measurement was taken when the participants were reading inside the Mobility Lab and the vehicle was static. Reactivity 1 was the changes in the HRV measurement when the participants were reading, and motion sickness was induced from the automated driving, or simply the difference in the HRV measurement between Stage 3 and 2. Reactivity 2 and 3 were the changes of the HRV measurement when the participants were reading the next 5 and 10 minutes, or the changes between Stage 4 and 2, and Stage 5 and 2, respectively. Stage 6 is a recovery stage, where the changes between Stages 6 and 2 were recorded.

3. Results and Discussion

3.1. Results

For the measurements (BPM, RMSSD, and HF-component), Wilcoxon signed-rank tests were performed to check whether there was a statistically significant difference in motion sickness, indicated by a decrease in BPM or increase in RMSSD and HF-component, in the visual- and haptic-condition compared to the control-condition. However, it was found that there were no statistically significant differences in motion sickness for the HRV measurements between the control-condition and the condition with the presence of the VPIS (visual-condition). The median (Mdn) and interquartile ranges (IQR) for the BPM, RMSSD, and HF-component measurements are presented in **Table 1**.

Further analysing the BPM measurements (see **Figure 4**), the pattern of results for each condition was about the same at the beginning of Stage 2 (control-condition, mean = 71.3 ± 10.5 BPM; visual-condition, mean = 73.0 ± 14.5 BPM; haptic-condition, mean = 75.0 ± 14.1 BPM). Then, the BPM measurements increased and peaked at Stage 3 (control-condition, mean = 74.9 ± 8.9 BPM; visual-condition, mean = 76.8 ± 13.1 BPM; haptic-condition, mean = 77.6 ± 13.2 BPM) for all the conditions before the readings steadily decreased starting from Stage 3 through Stage 4, 5, and 6. The difference in BPM measurement from Stage 2 to Stage 3 was about 3.6 BPM for the control-condition, 3.8 BPM for visual-condition, and 2.6 BPM for the haptic-condition.

For the RMSSD (see **Figure 4**), a general trend can be observed for each of the conditions once the driving has begun the RMSSD value increases and finally goes back to around the baseline's value once the driving has stopped. For the HF-component (see **Figure 4**), the value fluctuated under different conditions. For the control-condition, the HF-component increased in Stage 3 and went down after 10 minutes of driving before it rose again in the last 10 minutes of the experiment. The visual-condition, started to decrease in Stage 3 and increased and stabilised in the last 10 minutes of the experiment. For the haptic-condition, the HF-component values were relatively stable within 25 minutes of HRV recording.

Table 1. Results for petrol usage

Variation	Condition	BPM		RMSSD		HF-component	
		Mdn	IQR	Mdn	IQR	Mdn	IQR
Reactivity 1	Control	3.5	(-2.5 - 7.0)	10.0	(-0.3 - 59.3)	35.5	(-16.3 – 249)
	Visual	3.5	(1.0 - 7.0)	4.5	(-2.0 - 57.0)	-3.0	(-183.0 – 29.5)
	Haptic	3.0	(0.8 - 5.0)	7.0	(-1.5 - 67.3)	-3.0	(-183.0 – 29.5)
Reactivity 2	Control	2.0	(0.50 - 6.5)	-0.5	(-3.8 - 10.5)	8.0	(-22.8 – 121.5)
	Visual	3.5	(0.8 - 6.0)	8.0	(-4.0 - 32.3)	-9.0	(-249.0 – 93.3)
	Haptic	2.0	(-0.3 - 5.0)	14.5	(-1.0 - 39.8)	-4.5	(-42.5 – 182.0)
Reactivity 3	Control	2.0	(-1.0 - 5.0)	4.5	(-5.3 - 51.0)	-86.5	(-174.3 – 29.0)
	Visual	2.5	(0.0 - 4.3)	10.0	(-0.5 - 35.0)	-1.5	(-92.5 – 84.3)
	Haptic	1.0	(-2.0 - 4.3)	7.2	(-2.3 - 45.3)	-8.0	(-143.8 – 80.1)
Recovery	Control	-1.0	(-5.8 - 0.3)	7.5	(-1.5 - 63.3)	-30.5	(-79.0 – 108.8)
	Visual	0.0	(-5.0 - 1.3)	0.0	(-3.0 - 7.8)	7.0	(-66.5 – 84.0)
	Haptic	-2.0	(-5.5 - 0.5)	0.0	(-6.3 - 7.5)	14.0	(-56.8 – 83.8)

3.2. Discussion

From the statistical analyses of the HRV measurements, no statistically significant differences were found between the conditions. Further analysis of the BPM measurement revealed the same trend the participants showed in each exposed condition. All the BPM measurements were increased rather sharply in Stage 3 before gradually stabilizing in Stage 4 and 5 and decreasing in the final stage (Stage 6) (see **Figure 4**). A past study from literature reviews has shown that BPM is

positively correlated with motion sickness severity [16], [41], [42]. In this study, the average recorded BPM in Stage 3 was 74.9 for the control-condition, 76.8 for the visual-condition and 77.6 for haptic-condition. Cowings et al. [12] in their study found that a BPM value of 77 indicated mild motion sickness while a value of 87 indicated severe motion sickness experienced by the participants. Therefore, the level of motion sickness experienced by the participants of this study was at the mild level, and both VPIS and HPIS did not significantly decrease the experienced motion sickness based on the measured BPM values.

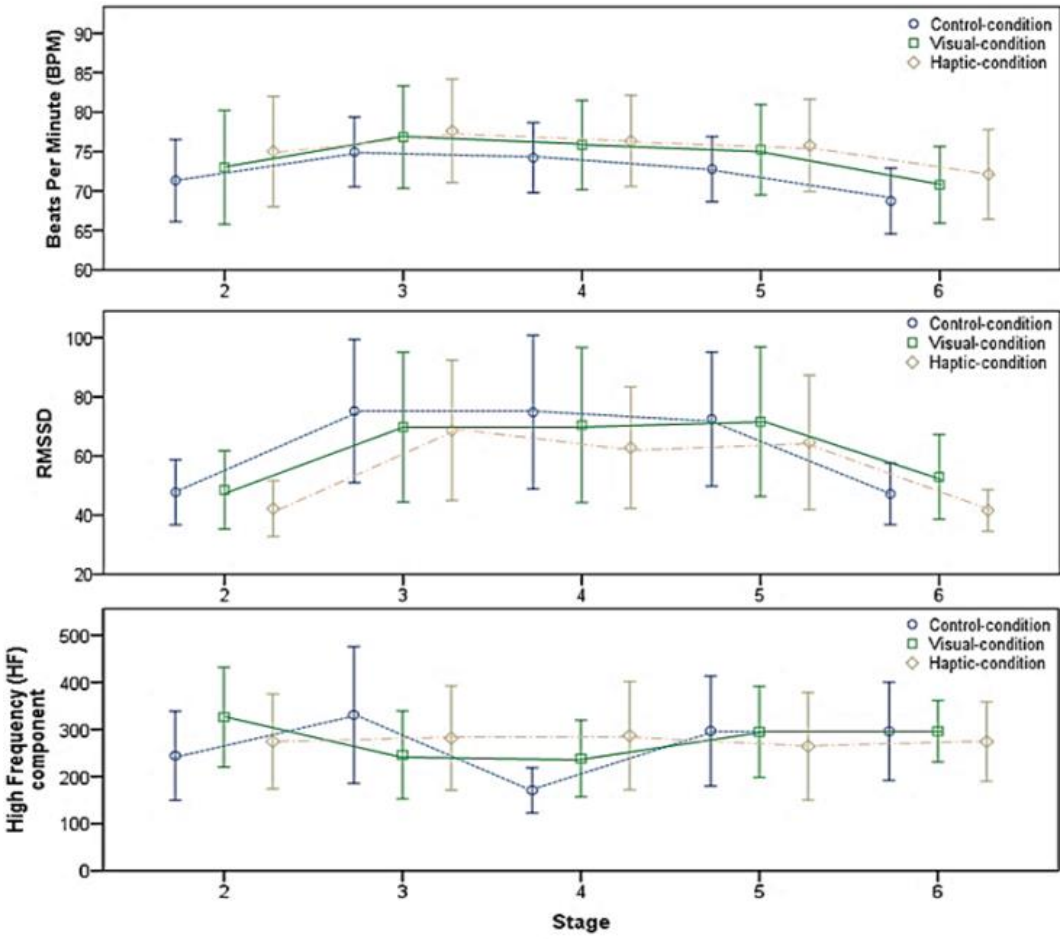

Figure 4. Mean score heart rate in BPM, RMSSD, and high HF-component of HRV frequency domain for the three conditions (control, visual, and haptic). Error bars represent the 95% confidence intervals (CI)

For the RMSSD and HF-component, no statistically significant differences were found between any conditions, indicating that changes in the PNS activity between the conditions were minimal. In general, past studies showed that the development of motion sickness is usually indicated by the PNS withdrawal [15]–[18]. A recent study with virtual reality that elicited cyber-sickness also reported a reduction in RMSSD [45]. However, in our findings, the average values of RMSSD were increased during the driving stages (Stage 3 to Stage 5) and decreased back to the baseline measurement when the vehicle was stopped. Increases in PNS indicated "rest and digest" activity, or in other words, the participants became more relaxed and possibly sleepy.

One of the explanations could come from the experimental setup of this study compared to other studies that also induced motion sickness in the participants. Most past motion sickness-inducing studies involved the participants keeping their heads still and looking straight inside a rotating drum (or optokinetic drum) [46]. Alternatively, in some other studies, the participants must endure a virtual ride, such as a rollercoaster [45]. Both motion sickness-inducing studies found a withdrawal in PNS (decrement in RMSSD) during the exposure. However, in this study, the participants were instructed to perform a reading task while sitting comfortably on a cushioned seat inside an air-conditioned vehicle and being driven with low-frequency motions. From the HRV analysis, it was found that the PNS was increased (increment in RMSSD) pointing to the presence of sopite-related syndrome (e.g., sleepiness, drowsiness) which is also one of the main symptoms of motion sickness [47]. However, it is often not recognized as such [48]. Recently, a study was done by [49] whose setup was similar to the current study and investigated the symptoms of motion sickness related to sopite syndrome. In the study, the participants were asked to comfortably sit upright on a chair with a vacuum cushion and foam blocks. The chair was fixed on

a movable platform that moves back and forth in low-frequency sinusoidal linear accelerations. Although no statistically significant differences were also found, it was discovered that something similar in which the RMSSD values was higher in the exposure stage compared to the RMSSD values in the baseline condition.

Moreover, in this study, there was no measurement of sympathetic nervous system (SNS) activities. Therefore, it cannot be concluded that while the changes in the PNS were being measured to indicate the development of motion sickness, nothing happened to the SNS. Measuring SNS is not a straightforward task as there is no direct indicator from the HRV analysis. Ruth et al. [19] explained that PNS withdrawal is a response in preparation for a defensive stance or escaping a potential threat such as motion sickness. He further mentioned that the flow of the blood would be directed to the other parts of the body (e.g., the heart) following the "flight or fight" response (activation of the SNS). Some of the past studies (i.e., [50], [51]) used the understanding that SNS is highly correlated with the low-frequency (LF) component of HRV, and the ratio of LF/HF is the autonomic balance between the PNS and SNS. However, experts from HRV analysis, such as [21] and [49] criticized the loose relationship between the LF-component and the activities of the SNS. It is because the LF-component is not merely composed of the SNS's activity but also a mixture of other markers such as the thermoregulation's activity and PNS's activity [21], [52]. Billman, [52] has also pointed out that the relationship between the PNS and SNS is not always linear. Both the PNS and SNS can affect each other when operating [19] and co-activate and co-deactivate at the same moment of time [53]. Therefore, within this study, although the activities of the PNS have been shown to increase, there is a possibility that the SNS was also activated, but it cannot be proven since it was not measured.

4. Conclusion

In summary, the analysis of heart rate variability (beats per minute, root means square of successive differences, and high-frequency component) indicated no statistically significant changes ($p < 0.05$) in motion sickness found with HPIS and VPIS when performing reading when being driven in automated mode. However, the results were mixed and inconclusive. Still, most findings showed that motion sickness was experienced higher during the automated driving stages than in the baseline stage for all three conditions. The level of motion sickness measured using heart rate variability (HRV) for the passengers inside a fully automated vehicle can be assessed using electrocardiograms (ECG). However, a higher motion sickness dosage might need to be imposed on the participants to yield a significant result. For this study, one of the limitations was that the RMSSD was analyzed with a time segment of 5-minutes, but a recent study found that typical 5-minute time segments might lose the dynamical information of the HRV [54]. Future research can implement rigorous 1-minute time segments analysis to provide a more accurate dynamical change in cardiac activity.

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Authors' Declaration

Authors' contributions and responsibilities - Conceived and designed the experiments (J.K, N.M.Y, J.T, F.D, M.R); Performed the experiments (J.K, N.M.Y); Analysed and interpreted the data (J.K, N.M.Y); Wrote the original paper (J.K, N.M.Y, J.T, F.D, M.R); and Wrote the revised manuscript (J.K, N.M.Y, J.T, F.D, M.R).

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Availability of data and materials - All data are available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

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