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An On-Road Study in Mitigating Motion Sickness When Reading in Automated Driving

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Abstract: This on-road study explores the effect of a visual (VPIS) and haptic peripheral information system (HPIS) on a user's level of motion sickness when engaging in reading activity while being driven in a fully automated vehicle (AV). Both systems notify the user regarding the upcoming navigational information in the lateral direction, and HPIS also supports the user from being involuntarily moved by the lateral acceleration when cornering. It was hypothesized that both systems would reduce the experienced motion sickness compared to those without any intervention. Eighteen participants with severe motion sickness susceptibility were exposed to low-frequency lateral acceleration that induces a moderate-to-severe dose of motion sickness. The automated driving was simulated by an automated-like instrumented vehicle and performed with the Wizard-of-Oz approach. The participants were asked to perform reading while being exposed to three different conditions (control-, VPIS-, and HPIS-condition), each for about 15-minutes. Results from a self-rating questionnaire indicated statistically significant decreases in motion sickness found with the presence of HPIS but not with VPIS. Results showed HPIS produced the least experienced motion sickness while VPIS exacerbated the symptoms of motion sickness. Adaptation effects were also found due to the repetitive exposure to the same route of automated driving.

Keywords: automated driving, peripheral information system, motion sickness.

在自动驾驶阅读时缓解晕车的道路研究

摘要：这项正在进行中的研究探索了视觉（视觉信息系统）和触觉外围信息系统（信息系统）在全自动驾驶（影音）的同时进行阅读活动时对用户晕车程度的影响。两种系统都将在横向方向上即将到来的导航信息通知给用户，并且信息系统还支持用户在转弯时不会因横向加速度而随意移动。假设与没有任何干预的系统相比，这两种系统都将减少经历的晕车病。十八名患有严重晕动病的参与者被暴露于低频侧向加速度，该加速度诱发了中等至严重剂量的晕动病。自动驾驶由类似自动驾驶的仪表车模拟，并采用绿野仙踪（绿野仙踪）方法进行。要求参与者在暴露于三种不同条件（对照，视觉信息系统和信息系统条件）下进行阅读，每种条件持续约 15 分钟。自评问卷的结果表明，在存在信息系统的情况下发现的晕动病在统计学上显着降低，而在 VPIS 的情况下却没有。结果显示，信息系统产生的晕车病最少，而视觉信息系统加剧了晕车的症状。由于重复暴露于相同的自动驾驶路线，因此还发现了适应效果。

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关键词：自动驾驶, 外围信息系统, 晕车。

1. Introduction

Having a fully automated vehicle (AV), a user only decides on the destination, and the AV will handle all the driving tasks. Therefore, drivers will become users or occupants who have the freedom to do their preferred activities [1]. Studies showed that future AV users would like to focus on relaxation-, hobby-, and working-related activities when traveling inside the moving vehicle [2]. However, indulging in non-driving related tasks (NDRT) might contribute to the development of motion sickness. Performing an NDRT would create a mismatch between the sensory inputs. Besides, the occupants would not be able to anticipate the direction of the movement of the moving AV and therefore lead to motion sickness occurrence [3–5].

Studies also indicated that future AV's potential users ranked reading as their preferred NDRT compared to other NDRTs [6–8]. However, reading in a moving vehicle might not be a great combination. A study with 31 subjects on a moving vehicle, done by Isu, Hasegawa, Takeuchi, and Morimoto (2014), found that reading caused 3.5 times more motion sickness than not performing any NDRT [10]. Another study also found that motion sickness rating was higher when reading (3.3 times higher than not performing any NDRT) compared to when watching a video/television (2.9 times higher than not performing any NDRT) [11], [12].

One possible way to allow NDRT to be performed and avoid motion sickness from developing is by using a peripheral information system (PIS). PIS is defined as "aesthetically pleasing displays of information which sit on the periphery of a user's attention" [13]. Since a large amount of the user's attention is paid to performing an NDRT, the periphery of attention can help the user get relevant information and important. In addition, PIS is implemented not to distract its users from their primary task but would adequately inform or notify them when required in the least intrusive manner.

The PIS is also termed as an adaptive ambient display [14] in the automotive field and can be further categorized into a passive and active system. In the context of reducing motion sickness in a moving vehicle, a passive PIS would notify its user regarding the intention of the vehicle, and the user has to take action such as adjusting their body or head against the induced acceleration produced by the moving vehicle (e.g., centrifugal acceleration when cornering). For example, Hanau and Popescu investigated the use of visual signals as acceleration cues in reducing motion sickness experienced by twenty bus passengers who were reading using phones or tablets [16]. They found that participants experienced less motion sickness with a set of texts that moved proportionally with the vehicle acceleration for acceleration cue.

On the other hand, an active PIS will automatically adjust the user's body or head against the induced acceleration produced by the moving vehicle, with or without notifying the user regarding the vehicle intention or action. For example, an actuator-controlled seat automatically adjusts or compensates the user from being moved by the vehicle acceleration [17].

In the present study, one passive PIS (visual-based) and one active PIS (haptic-based) were developed and tested on the participants categorized as having mild to severe susceptibility to motion sickness. This study aims to explore if the proposed PISs manage to lower the users' experienced motion (i.e., occupants) who were instructed to perform reading while being driven in automated driving mode.

2. Methodology

2.1. Experiment Design

In this study, all the participants underwent three different conditions (control-, visual-, and haptic-condition) in three separate sessions (Session 1, 2, and 3). The control condition was without any intervention of a peripheral information system (PIS). The visual- and haptic-condition were the conditions with the implementation of a visual-based PIS (VPIS) and haptic-based PIS (HPIS), respectively. The dependent variable was the level of motion sickness, measured with a self-rating questionnaire. The independent variables were the conditions (control-, visual-, and haptic-condition) and sessions (Session 1, 2, and 3). The order of the three test conditions exposed to the participants was counter-balanced to mitigate any cross-over effects (3! = 6 orders), and each session was executed at least three days apart to make sure that if motion sickness did occur within the first session, it would not affect the following session. Since the susceptibility to motion sickness is different among individuals; therefore, the conditions of interest are evenly tested by each individual rather than by different individuals [10].

All the AV test rides were done within the Eindhoven University of Technology's compound, where Dutch traffic laws and regulations apply (see Fig. 1).

The route consisted of three laps of 22 turns to the right and 16 turns to the left (cornering radii, Mean = 9.2 m, standard deviation (SD) = 3.3 m). For safety reasons, the security officers were informed about the study, and permission to use the designated route was

granted. Approval by the Research Ethics Committee of Universiti Teknikal Malaysia Melaka (UTeM) on a study with human subjects was obtained following the ethical standards of the 1964 Declaration of Helsinki. Besides, this research complied with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) [19].

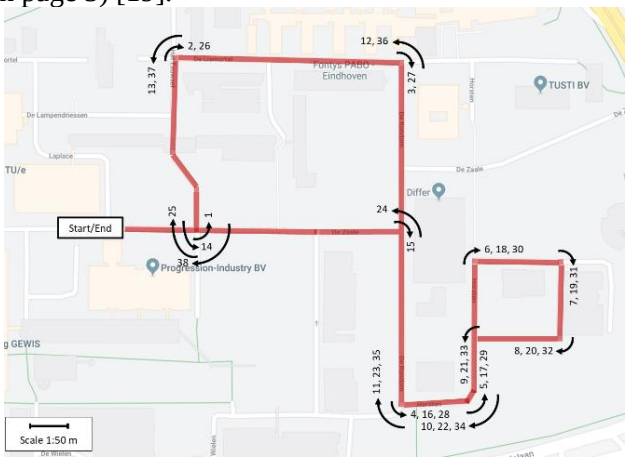

Fig. 1 Experiment route with the numbers depicts the sequence of the corners, and the arrows represent the direction of the corners [18]

2.2. Equipment – Mobility Lab and Peripheral Information Systems

An on-road AV simulator called the Mobility Lab (see [18] for elaborated description) was employed to provide a fully automated driving experience (see Fig. 2). Within this study, a TV display connected to a high-definition action camera (placed just behind the front windshield) was implemented to show the live front-windshield-view (as what the driver sees) to imitate a real AV without exposing the driver. This simulation was done by selecting the action camera location to include the windshield- and dashboard-view but not the driver's hands and the steering wheel. The projected video image was set at the resolution of 1080p with 60 frames per second, while the video image latency was kept to a minimum using an HDMI cable for the connection between the action camera and the TV display. The Mobility Lab exterior was also equipped with a rotating look-alike LIDAR device on the vehicle top to give a more realistic appearance for a real AV.

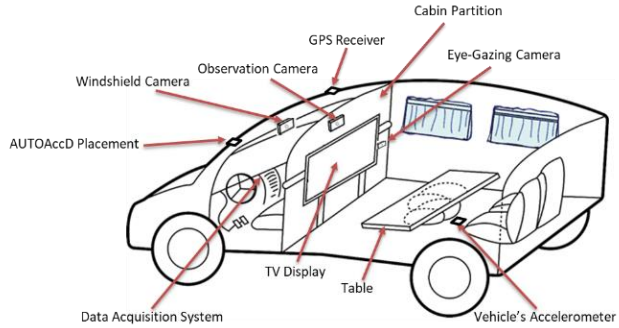

Fig. 2 Mobility Lab interior layout [18]

During the briefing process, the participants were told that this research aims to study motion sickness in AV in general. Explicit instructions were given about how both PISs will be operating; however, no specific instructions were given on how the participants should react to the PISs or what effects they will produce.

The first prototype, VPIS, (Fig. 3) was designed to utilize the functionality of the underused peripheral vision of a human user. VPIS aimed to eliminate the need to look outside of the vehicle to avoid motion sickness from the sensory mismatch. The design of VPIS was iterated from the previous study [20], where a PIS called Peripheral Visual Feedforward System (PVFS) was used to deliver the navigational information of the AV when the occupant of the vehicle was engaged in watching a video/movie on a 40" display that was mounted 1.2 meters in front of them. They found that the proposed PIS managed to reduce the participant's motion sickness compared to when no PIS was implemented.

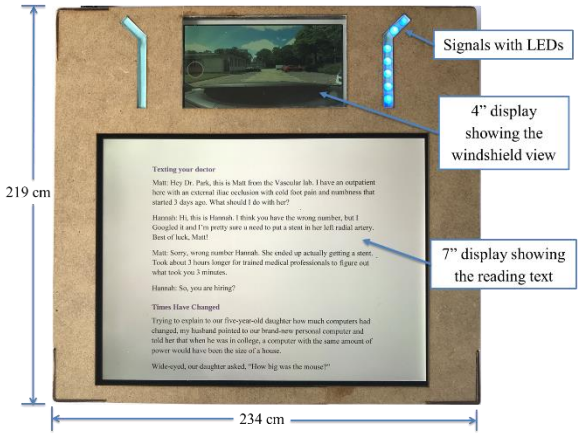

Fig. 3 Visual peripheral information system (VPIS)

In the current study, VPIS was also used to provide navigational information of the AV. However, in this study, the occupants were engaged in a different NDRT reading using a handheld tablet. VPIS consisted of a 4" display and two LED-filled arrays, at around an 8.9" tablet. Each of the arrays was equipped with 7 LEDs, with blue-emitting color, that switched on 3 seconds before the on-road AV simulator (Mobility Lab) entered a corner/turning. The LEDs moved three times from the bottom to the top of the tablet, at each of the corners/turnings. The LEDs were also diffused using a Perspex cover on top of the LEDs to make sure the VPIS notified its users but at the same time did not degrade the experience of the primary task (i.e., reading).

A 4" display, located above the tablet viewing area, showed the windshield-view live video streamed from the camera mounted on the front windshield. The displayed live video image was set at the resolution of 1080p with 60 frames per second. The video image latency was kept to a minimum with an HDMI cable was used as the connection between the action camera and the 4" display. The implementation of the 4" display as part of the VPIS, placed in the periphery of attention of the participants, was to avoid any conflict

of expectations that might arise from the disagreement between the previously stored memories in the participants' "internal model" with the one that the participants were experiencing at that moment.

The internal model, believed to be located in the cerebellum, is where all the sensed signals from a human body are interpreted and stored in the human's memory [21], [22]. Sensory conflict theory [23] postulates two components: a network of sensory inputs that integrate currently experienced signals and an "internal model" that compares the currently experienced signals with what is stored or experienced before. This result is supported by the previous work of Prothero [24], known as the "rest frame hypothesis," in which he explained motion sickness in terms of the perception of space [24]. Prothero [24] explained that the human brain creates a "rest frame" in which the brain will look for something stationary to be the reference point, and if the brain finds any motion, a mental comparison to this frame will be made. Hence, the conflict between what is expected and what is experienced will lead to motion sickness. Thus, humans need to have a reference frame to associate any movements that would deviate from this frame.

The 4" display was designed to provide a reference frame on which the users can relate their motion with the true horizon seen on the screen, without the need to access the view outside of the Mobility Lab. In this study, the participants were also asked to hold the tablet as naturally as possible to replicate the real situation scenario while also giving them the freedom to determine how they wanted to use the tablet for reading.

HPIS, the second prototype used in this study, is an active PIS that was developed based on the idea of conveying the navigational information (i.e., cornering/turning left or right) through a vibrotactile display on the user's forearms and also providing an active movement that adjusts the user's body in the direction of the corner/turning (Fig. 4).

Fig. 4 Haptic peripheral information system (HPIS)

HPIS was developed based on 1from the previous study where a passive PIS called vibrotactile display was used, and the studied NDRT was watching a video in a moving vehicle [25]. In this study, a mechanism that will automatically adjust the user's body was implemented to improve its performance based on the finding that the previous passive haptic-based PIS did not manage to reduce the user's motion sickness just by providing the navigational information.

For improvement, an additional active feature was added to the HPIS, where a mechanism consisted of two movable plates, which were fixed on the backrest of the car seat and covered with foam cushion and fabric. Three seconds before the Mobility Lab 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. Immediately afterward, the movable plate (the right plate if turning to the left, the left plate if turning to the right) was activated, turning forward the user's shoulder through servo motors at about an angle of 40° and stayed for as long as the cornering took place, to align the gravitoinertial force. Since the defensive driving style was the preferred autonomous driving style with 0.29 g of lateral acceleration, the expected tilt angle of the gravitoinertial force to align with the gravity vector is about 16° (see Fig. 5). Hence, about 40° turning forward of the moveable plate is enough to push the participants' shoulder at about 16° sideways.

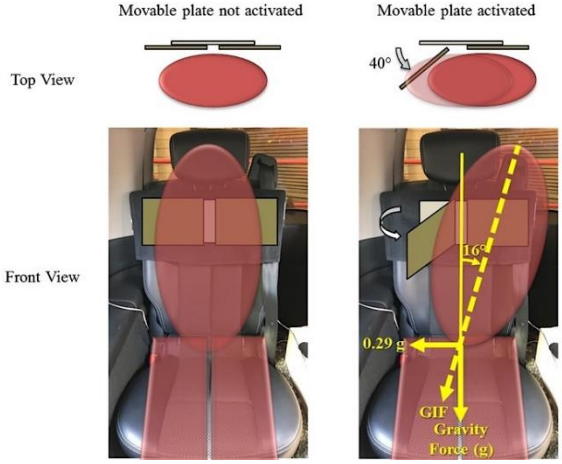

Fig. 5 Mechanism of haptic peripheral information system (HPIS)

Although constraining the head from uncontrollable movements might probably reduce the likeliness of the occurrence of motion sickness [26], [27], actively aligning gravitoinertial force by pushing the head can lead to whiplash injury, a neck injury caused by a sudden movement of the head forwards, backward, or sideways. Thus, for HPIS, the participants' shoulder was instead selected to be pushed at the corners/turnings rather than the head.

2.3. Participants and Procedure

Eighteen participants (nine male and nine female) aged between 22 and 33 years old (Mean = 28.4, SD = 3.0) participated in this study. Stratified sampling was implemented based on the short version of the Motion Sickness Susceptibility Questionnaire (MSSQ) [28],

[29] to check for participants' susceptibility to motion sickness. Within this study, only participants with mild and severe susceptibility (25th to 100th percentile) were selected based on the MSSQ's scores (Mean = 79.1%, SD = 17.3%). Participants who fall under the first quartile of the MSSQ (0 to 25th percentile) are considered immune to motion sickness. Therefore, the effects of the proposed PISs on participant's motion sickness levels might be hard to determine.

Motion sickness Assessment Questionnaire (MSAQ) was used to assess the level of experienced motion sickness. MSAQ was developed by Gianaros et al. (2001), and it comprises 16 questions on a 9-point scale *(1= not at all, 9 = severely)* [30]. MSAQ consists of 16 questions that can be grouped into four constructs: gastrointestinal -, central-, peripheral-, and sopite-related symptoms of motion sickness. MSAQ can be presented on a single cumulative score and as four sub-scores for each of its constructs. The participants twice filled MSAQ, once before entering the Mobility Lab (pre-MSAQ) and once after Mobility Lab has been stopped (post-MSAQ). MSAQ was used in this study as it is composed of multi-dimensional constructs rather than other tests like the Pensacola Diagnostic Index (PDI) [31], which is composed of a one-dimensional continuum.

After arriving and answering the pre-MSAQ, the participant was escorted to the Mobility Lab and was asked to take a seat and always wear the seat belt inside the Mobility Lab. Inside the Mobility Lab, the participants were then asked to wear a headband accelerometer, sit comfortably, and then look straight ahead for 10 seconds for calibration (see Fig. 6) of the wearable headband accelerometer. The headband accelerometer was used to measure the participants' head movements, and the calibration position is where the user's vestibular system is assumed to be in its natural position. A vestibular system consists of semi-circular canals and otoliths. The function of the former is to detect the rotational movements, while the purpose of the latter is to identify the translational movements. A vestibular system function is to maintain balance and spatial orientation and stabilize the vision through vestibular-ocular reflexes. It is a crucial component in determining the experienced motion sickness. In an experiment done by Kennedy et al. (1968), they found that patients with a dysfunctional vestibular system did not suffer from motion sickness [32].

(a) (b)

Fig. 6 Wearable accelerometer headband: (a) Calibration position and (b) reading position

Three different sets of reading materials were used for three separate sessions, and the reading materials were the compilations of jokes from Reader's Digest magazine [33]. Participants were asked to continuously perform the reading task from the beginning until the end of the experiment. There was a stop button if the participant wishes to stop the experiment at any time during the experiment.

The automated driving test ride was performed with the participant using the Wizard-of-Oz method for about 15 minutes. Baltodano's work inspired the method Wizard of Oz; however, in this study, two operators were operating the Mobility Lab; one was called the driving wizard, and the other was the experimenter [34]. The driving wizard task was to simulate fully automated driving using the Mobility Lab as if it would be produced in an actual fully automated vehicle. A driving style can be consistently controlled using the Automatic Acceleration and Data Controller (AUTOAccD) [35]. The AUTOAccD was developed to assist the driving wizard in driving according to the defined acceleration condition called defensive automated driving style. This style was based on previous findings, that regardless of the type of driver or driving style, most people prefer the fully AV to be driven in a more defensive driving style [36], [37]. For this defensive automated driving style, the driving speed was set at 30 km/h, and the lateral acceleration generated at the turning/cornering was aimed to be about 0.29 g or 2.84 ms^{-2}.

A standard called Motion Sickness Dose Value (MSDV) is calculated to measure the level of motion sickness experienced by the participant in each session of the automated driving based on the simulated acceleration. The earliest characterization of motion with motion sickness was done in [38]. The researchers found that motion with frequencies around 0.2 Hz was the most provoking in motion sickness development. Later work also confirmed that longitudinal and lateral motions with frequencies below 0.5 Hz and peaking at around 0.2 Hz are highly correlated with motion sickness [39]–[42]. MSDV can be calculated individually in each of the three axes (x-, y-, and z-axis).

The participants were asked to answer a post-MSAQ immediately inside the Mobility Lab after the vehicle is stopped. At the end of all the sessions, compensation (€30) was given to the participants for their participation in this study.

3. Results

3.1. The Consistency of the Automated Driving Sessions

The distributions of tri-axial accelerations across the frequency spectrum for all 54 sessions (three conditions for each of 18 participants) were first plotted as a function of power spectral density (PSD) in three semi-log graphs (Fig. 7). This is done to check the consistency of the automated driving generated by Mobility Lab by the driving wizard. The accelerations in x- (longitudinal acceleration) and y-direction (lateral accelerations) were found to dominate at below 0.2 Hz, while the acceleration in the z-direction (vertical acceleration) was peaking between 1.0 and 2.0 Hz. The maximum amplitude of the lateral acceleration was almost ten times higher than the maximum amplitude of the longitudinal acceleration, while the maximum amplitude of the vertical acceleration barely exceeded 0.25 $ms^{-4}Hz^{-1}$.

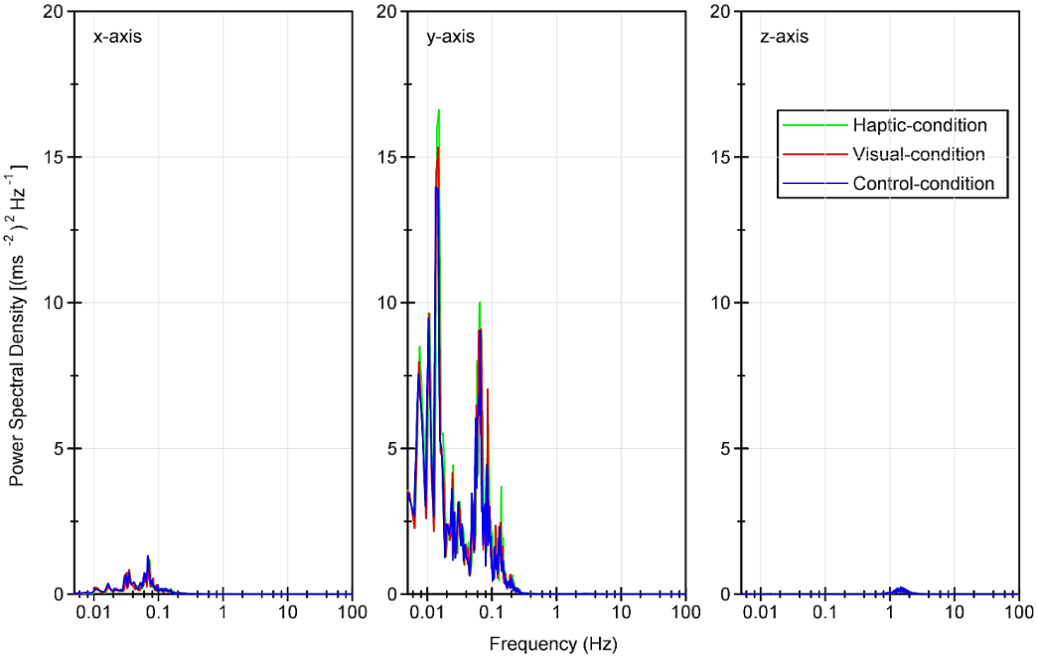

Fig. 7 Power spectral densities (PSDs) of mean acceleration in x-, y- and z-directions for the control-, visual-, and haptic-condition

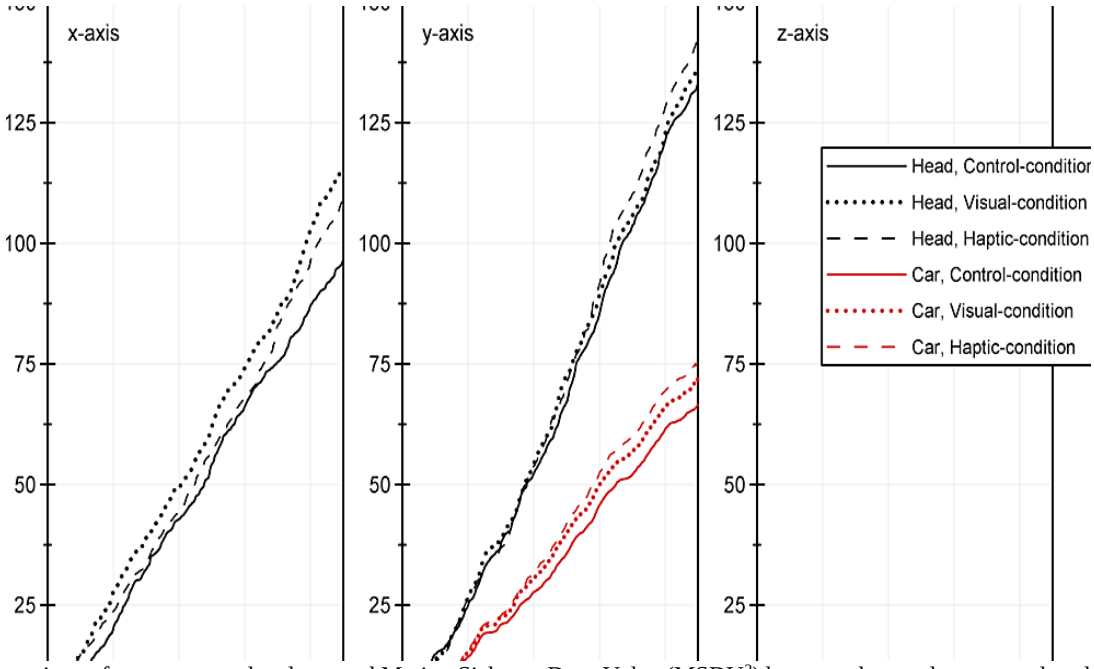

Fig. 8 Comparison of mean accumulated squared Motion Sickness Dose Value ($MSDV^2$) between the accelerometer placed inside the Mobility Lab and worn by passengers (head movements) in tri-axial directions for the three conditions

The Motion Sickness Dose Values (MSDV) were calculated and showed to be highly correlated with the low-frequency motions (i.e., below 0.5 Hz) [43], [44] while the high-frequency motions (i.e., above 1.0 Hz) are found to be not provocative to motion sickness [45]. For the whole 15 minutes of automated driving, the calculated motion sickness dose values (MSDVs) were similar in the longitudinal acceleration for control-condition (mean = 3.049 $ms^{-1.5}$, SD = 0.530), visual-condition (mean = 2.987 $ms^{-1.5}$, SD = 0.437), and haptic-condition (mean = 3.092 $ms^{-1.5}$, SD = 0.410) and also in the lateral acceleration for control-condition (mean = 8.756 $ms^{-1.5}$, SD = 1.194), visual-condition

(mean = 9.028 $ms^{-1.5}$, SD = 1.187), and haptic-condition (mean = 9.286 $ms^{-1.5}$, SD = 0.852) (Fig. 8).

2.2 Measurement of Motion Sickness

First, a comparison was made between the result of pre-MSAQ from the three conditions to check whether there are differences in the level of motion sickness among the participants at the beginning of the experiment. Wilcoxon signed-rank tests were performed to determine if there were statistically significant differences (two-tailed) for the pre-MSAQ score across the conditions and sessions. There was no statistically significant difference found in the pre-MSAQ score either across the conditions or sessions. Table 1 shows the median and interquartile range (IQR) of the pre-MSAQ score across the conditions and sessions.

Table 1 Median and IQR for the MSAQ in the pre-MSAQ across conditions and sessions (MSAQ = 100%-point scale; 11.1% = no symptoms, 100.0% = most severe symptoms)

Pre-MSAQ Constructs	**By Condition**			**By Session**		
	Condition	**Median**	**IQR**	**Session**	**Median**	**IQR**
Gastrointestinal	Control	11.1	(11.1 – 11.1)	Session 1	11.1	(11.1 – 11.1)
	Haptic	11.1	(11.1 – 11.1)	Session 2	11.1	(11.1 – 11.8)
	Visual	11.1	(11.1 – 11.1)	Session 3	11.1	(11.1 – 11.1)
Central	Control	11.1	(11.1 – 11.1)	Session 1	11.1	(11.1 – 13.9)
	Haptic	11.1	(11.1 – 11.7)	Session 2	11.1	(11.1 – 14.4)
	Visual	11.1	(11.1 – 13.9)	Session 3	11.1	(11.1 – 11.7)
Peripheral	Control	11.1	(11.1 - 11.1)	Session 1	11.1	(11.1 - 15.7)
	Haptic	11.1	(11.1 - 15.7)	Session 2	11.1	(11.1 - 18.5)
	Visual	11.1	(11.1 - 14.8)	Session 3	11.1	(11.1 - 12.0)
Sopite	Control	15.3	(13.2 - 20.8)	Session 1	16.7	(13.2 - 20.1)
	Haptic	13.9	(11.1 - 17.4)	Session 2	13.9	(11.1 - 19.4)
	Visual	13.9	(11.1 - 19.4)	Session 3	13.9	(11.1 - 16.7)
Total MSAQ	Control	13.5	(12.3 - 15.3)	Session 1	13.9	(12.5 - 14.6)
	Haptic	12.8	(11.8 - 14.1)	Session 2	13.2	(12.3 - 15.6)
	Visual	12.5	(11.8 - 14.6)	Session 3	12.5	(11.8 - 13.9)

Wilcoxon signed-rank tests were then performed on the post-MSAQ's scores to determine if there were statistically significant differences in the level of motion sickness reported by the participants between the control-condition and the conditions where the peripheral information systems were implemented (visual- and haptic-condition) (see Table 2 and 3). A statistically significant difference was found for the post-MSAQ total score between the haptic- and control-condition; however, not between the visual- and control-condition. For the post-MSAQ total score, the result indicated that the visual condition induced more motion sickness compared to the control condition as indicated by higher reported median values. Power analysis for the actual sample size of 18 participants revealed power of 0.06. Since the achieved power was low (< 0.80 [46]), a power analysis with a probability of making a type II error (β = 20%) and with a large effect size (r = 0.5) was conducted for the visual-condition post-MSAQ total score. The total sample size needed was found to equal 1940 to show any significant difference between the two conditions.

Table 2 Median and IQR for the MSAQ in the pre-MSAQ across conditions and sessions (MSAQ = 100%-point scale; 11.1% = no symptoms, 100.0% = most severe symptoms)

Post-MSAQ Constructs	**Conditions**	***Median* (n = 18)**	***IQR***
Gastrointestinal	Control	19.5	(11.1 – 19.5)
	Visual	18.1	(13.2 – 66.0)
	Haptic	13.9	(11.1 – 13.9)
Central	Control	22.2	(18.9 – 61.1)
	Visual	26.7	(15.6 – 69.4)
	Haptic	18.9	(15.6 – 34.4)
Peripheral	Control	11.1	(11.1 – 26.9)
	Visual	14.8	(11.1 – 20.4)
	Haptic	11.1	(11.1 – 23.4)
Sopite	Control	30.6	(18.7 - 30.6)
	Visual	33.3	(19.4 – 67.3)
	Haptic	23.6	(18.7 – 40.3)
Total MSAQ	Control	23.3	(17.4 – 54.2)
	Visual	23.6	(15.3 – 58.7)
	Haptic	18.4	(14.9 – 32.1)

Table 3 Wilcoxon signed-rank test for comparison between control-condition and visual-/haptic-condition for post-MSAQ and its constructs

Post-MSAQ constructs	**Conditions**	**Z**	**Effect size (r)**	**p-value (two-tailed)**
Gastrointestinal	Control Visual	- 0.421	0.07	0.67
	Control Haptic	- 1.767	0.29	0.08
Central	Control Visual	- 0.044	0.01	0.97

Peripheral	Control Haptic	- 1.962	0.33	0.05
	Control Visual	- 0.851	0.14	0.40
	Control Haptic	- 0.984	0.16	0.33
Sopite	Control Visual	- 0.233	0.04	0.82
	Control Haptic	- 1.734	0.29	0.08
Total	Control Visual	- 0.305	0.05	0.76
	Control Haptic	- 2.298	0.38	0.02*

* Indicates significant effect ($p < 0.05$)

There was a statistically significant decrease in the post-MSAQ total score and two of its constructs, namely central and sopite. For the sopite-construct, it was found that Session 3 showed a statistically significant decrease when compared to Session 1. For the post-MSAQ total score and central construct, Session 2 indicated a statistically significant decrease from Session 1. Power analysis for the actual sample size of 18 participants revealed power of 0.40. Since the achieved power was low (< 0.80 [46]), a power analysis with a probability of making a type II error (β = 20%) and with a large effect size (r = 0.5) was conducted for the post-MSAQ total score. The total sample size needed for this Wilcoxon signed-rank test was found to be 46 to show any significant difference between the post-MSAQ total score for Sessions 1 and 3.

Wilcoxon signed-rank tests were also performed to determine if there were statistically significant differences in the level of motion sickness reported by the participants between the sessions. It is particularly interesting to check whether adaptation to motion sickness occurred when the participants were repeatedly exposed to the same motion sickness dose with the same motion profiles (see Table 4 and 5).

Wilcoxon signed-rank tests were performed to determine if there were statistically significant decreases in motion sickness level determined by the participants' head movement between the control and test condition. In this study, the participant's head movement was measured by analyzing the MSDV of the participant's head accelerations from a wearable headband accelerometer.

Table 4 Median and interquartile range (IQR) for post-MSAQ total score and its constructs for different sessions. (MSAQ = 100%-point scale; 11.1% = no symptoms, 100.0% = most severe symptoms)

Post-MSAQ Construct	Conditions	*n*	*Median*	*IQR*
Gastrointestinal	Session 1	18	26.4	(13.9 – 62.5)
	Session 2	18	13.9	(11.1 – 65.3)
	Session 3	18	13.0	(11.1 – 25.9)
Central	Session 1	18	31.1	(20.0 – 67.2)
	Session 2	18	15.3	(11.1 – 42.4)
	Session 3	18	23.6	(16.7 – 56.3)
Peripheral	Session 1	18	16.7	(11.1 – 24.0)
	Session 2	18	20.0	(15.0 – 48.9)
	Session 3	18	22.2	(18.7 – 46.5)
Sopite	Session 1	18	38.9	(21.5 – 66.7)
	Session 2	18	21.1	(15.6 – 32.8)
	Session 3	18	17.7	(13.7 – 52.4)
Total	Session 1	18	27.4	(18.8 – 57.8)
	Session 2	18	11.1	(11.1 – 14.8)
	Session 3	18	18.1	(15.3 – 31.1)

Table 5 Wilcoxon signed-rank test for comparison between Session 1 and Session 2/Session 3 for post-MSAQ and its constructs

Post-MSAQ constructs	Group	Z	Effect size (r)	p-value (two-tailed)
Gastrointestinal	Session 1 Session 2	- 1.011	0.17	0.31
	Session 1 Session 3	- 1.399	0.23	0.16
Central	Session 1 Session 2	- 2.134	0.36	0.03*
	Session 1 Session 3	- 1.483	0.25	0.14
Peripheral	Session 1 Session 2	- 1.183	0.20	0.24
	Session 1 Session 3	- 0.051	0.01	0.96
Sopite	Session 1 Session 2	- 1.847	0.31	0.07
	Session 1 Session 3	- 2.205	0.37	0.03*
Total	Session 1 Session 2	- 2.070	0.35	0.04*
	Session 1 Session 3	- 1.587	0.26	0.11

* Indicates significant effect ($p < 0.05$)

A similar method was used to assess the dose of MS given to the participant through the Mobility Lab's movements. However, there was no statistically significant decrease found between the control condition and the condition with the VPIS and HPIS. The median and IQR were presented in Table 6.

Table 6 Median and interquartile range (IQR) for participant head movement's MSDV in three directions for both across the condition and session

Constructs	Condition	By Conditions		Session	By Sessions	
		Mdn	*IQR*		*Mdn*	*IQR*
$MSDV_x$	Control	10.3	(8.9 – 12.6)	1	10.3	(9.3 – 13.8)
	Visual	10.6	(9.6 – 13.2)	2	10.2	(9.2 – 13.3)
	Haptic	9.9	(9.2 –13.9)	3	10.5	(8.5 – 12.0)

	Control	6.7	(6.2 – 7.4)	1	7.2	(6.5 – 7.8)
$MSDV_y$	Visual	7.0	(6.5 – 7.5)	2	7.0	(6.3 – 7.5)
	Haptic	7.1	(6.4 – 8.0)	3	6.7	(6.3 – 7.9)
	Control	9.4	(7.0 – 12.1)	1	10.2	(8.6 – 12.3)
$MSDV_z$	Visual	10.2	(8.1 – 12.8)	2	8.9	(6.5 – 14.0)
	Haptic	9.3	(7.8 – 11.8)	3	10.0	(7.4 – 12.1)

4. Discussion

4.1. Validation of the Consistency of the Automated Driving Sessions

In general, all the test rides performed by the Mobility Lab showed almost identical distributions over the frequency spectrum for all the conditions. The dominant frequencies both in the longitudinal (x-axis) and lateral direction (y-axis) were low-frequency motions that are highly correlated to the development of motion sickness [39], [41], [44]. On the other hand, the dominant frequency in the z-direction was considered as high-frequency (>1.0 Hz) motions that are found to be physically uncomfortable but not a factor that contributes to the development of motion sickness [45]. The big difference between the amplitude of the accelerations in the longitudinal (2.0 $ms^{-4}Hz^{-1}$) and lateral direction (16.0 $ms^{-4}Hz^{-1}$) was expected since it was intended that the longitudinal (x-axis) accelerations were to be kept to a minimum while the lateral (y-axis) accelerations were to be manipulated to reach the intended range.

In this study, the high-frequency motion in the vertical direction (z-axis) was contributed by the designated route made of cobblestone. Calculation of frequency resulted from direct measurement of the cobblestone's geometry, and the average speed of the vehicle at 30 km/h revealed a frequency of 55 Hz. However, due to the vehicle suspension system and weight, the dominant frequency in the z-direction was found to be much lower. For comparison, Griffin and Newman also reported a similar finding that the vertical accelerations were peaked between 1.0 and 2.0 Hz with an acceleration magnitude of about 0.25 $ms^{-4}Hz^{-1}$ [47].

MSDVs for all three conditions were quite similar, and this indicated a good consistency in providing the dose of motion sickness to the participants. The calculated MSDV also indicated that the dose of motion sickness was three times higher in the lateral direction (about 9.0 $ms^{-1.5}$ = considered as mildly to severely dose of motion sickness) compared to the one in the longitudinal direction (about 3.0 $ms^{-1.5}$ = considered as slightly or no dose of motion sickness) [48].

4.2. Motion Sickness Assessment – Effect of Conditions

For the total score of Post-MSAQ results, participants experienced lower motion sickness with HPIS but not with the VPIS than when no peripheral information system (PIS) was present. However, further analyzing the individual construct of Post-MSAQ results for HPIS did not indicate better performance than the control condition.

For the HPIS, the reduction of the motion sickness levels was because HPIS was built with the idea of an active movement on which the mechanism with the flappers actively aligns participants' shoulder into the direction of the corner rather than being passively moved by the centrifugal acceleration towards the opposite direction of the corner. This finding was consistent with the findings by [27], [49], [50]. They found that an active head tilting or under external control (e.g., active suspension) is able to lessen motion sickness symptoms. When taking a corner, drivers usually do not just lean but also tilt their head toward the curve center or centrifugal force, whereas the passenger's head usually is tilted in the opposite direction. Bles, Bos, de Graaf, Groen, and Wertheim mentioned that the changes of head orientation relative to the gravity vector, also called gravitoinertial force (GIF) [51] can also provoke motion sickness. As found in [27], [49], active head tilting could reduce motion sickness symptoms. Within this study, the head tilting toward the direction of the corner was assisted by the HPIS mechanism.

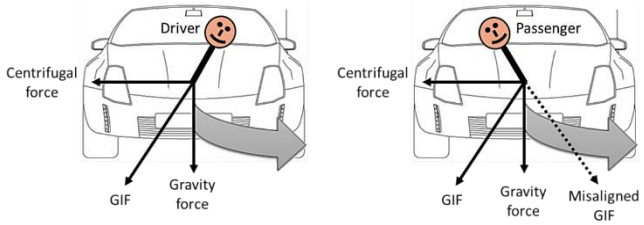

Fig. 9 Typical head postures of the driver and passenger when taking a corner (Adapted from [27])

The second PIS, VPIS, was built on the idea of notifying and alerting the participants in a passive approach, which means that VPIS informs the user about the upcoming (i.e., 3 seconds before arriving at the corner/turning) navigational intention of the vehicle. Consequently, the user has to initiate an action to adjust his/her body according to the induced lateral acceleration. VPIS was designed to give real-time information that would match the participants' expectations from their "internal models" and with one they are experiencing at that moment. Thus, avoiding the sensory mismatch from occurring, which would lead to the development of motion sickness.

However, the post-MSAQ results for visual-condition (VPIS) indicated the opposite. In this study, VPIS was shown to exacerbate the experienced motion sickness as compared to the control condition. The reason might be determined by the movement from both the array of lights from the LEDs and the live display from the 4" screen, along with performing the reading task, might amplify motion sickness development. It was suspected that the multi-movements presented in front of the participants' field of view induce a phenomenon called Visually Induced Motion Sickness (VIMS). VIMS is technically a different kind of vestibular-visual conflict than a typical motion sickness but characterized by similar symptoms such as nausea, headache, fatigue, and drowsiness [53], [54]. VIMS develops when an observer is in a stationary position, or at least the vestibular system detects that the human is static (i.e., being driven at a constant speed). However, at the same time, the human is being exposed to moving visual images [55]. These moving visual images induce the illusionary sensation of self-motions, also known as "vection" [56]. Hence, VIMS might explain why in certain post-MSAQ-constructs, visual-condition indicated higher motion sickness than the control condition. The condition with the VPIS might mimic the scenarios like using a simulator with fixed-based or watching a 3D movie where motions are detected by the visual system but not the vestibular system [54].

Compared to the previous study [20], they found a statistically significant decrease in the motion sickness from the score of the total MSAQ and its constructs for their PIS called Peripheral Visual Feedforward System (PVFS). However, the PVFS was mounted on each side of the television display, located about 1.2 m from the participant. In this study, the location of the VPIS was much closer to the participants and was held typically on the lap area of the participant. A recent study done by Kuiper et al. found that this particular position is more susceptible to motion sickness development [1]. In addition, in the previous study [20], the given non-driving related task (NDRT) was watching a video on the television display, while in this study, the given NDRT task was reading from a tablet. Hence, there might be a possibility that the distance between where the PIS was located and the NDRT might play a crucial role in determining the experienced level of motion sickness.

In terms of the participants' head movement, no statistically significant decreases were found between the control condition with the visual- or haptic condition. One of the interpretations of why the MSDV results by head movements were higher than the Mobility Lab motions was probably due to the participants' head alignment. Although the accelerometer on the headband was calibrated each session by looking straight ahead, the participants tilted their heads down once the reading task began. Hence, the accelerometer x-axis already registered certain acceleration values rather than zero value, and the z-axis (vertical direction) was not equal to the gravity vector anymore. On the other hand, the y-axis (lateral direction) of the accelerometer should not be affected by the tilted head if the participants were sat up straight and only tilted their head in a down-forward direction. However, the positions of the x-, y- and z-axis of the accelerometer-equipped headband were aligned with the semi-circular canals of the vestibular system. Thus, the recorded accelerations were exactly in the tri-axial directions of the semi-circular canals, and the head movements were defined in these vectors' quantity.

Another interpretation of why we obtained higher MSDV results in the head movements compared to the Mobility Lab motions is that perhaps the participants could not control the movements induced by the Mobility Lab motions to their head. As mentioned in [57], these uncontrolled movements can induce motion sickness because all selected participants were highly susceptible to motion sickness who might have difficulties controlling their bodies in an unexpected motion environment.

4.3. Motion Sickness Assessment – Effect of Sessions

Comparing the post-MSAQ scores between the sessions (see Tables 4 and 5) indicated the possibility of adaptation to motion sickness, particularly in the post-MSAQ total score and two of its constructs, namely central and sopite. A trend was found in which the post-MSAQ score for Session 1 was always the highest (about 15% reduction from Session 1 to Session 2 for the central-construct, and about 18% to 21% reduction for the sopite-construct from Session 1 to Session 2 and from Session 1 to Session 3). However, there were no further reductions of the motion sickness level from Session 2 to Session 3 (less than 0.6% reduction, except for the sopite-related dimension with a reduction of 1.7%).

Adaptation to motion sickness is a weakened response over time when being continuously exposed to stimulation [58]. In addition, adaptation to motion sickness is only specific to the repeated stimulation that someone is exposed to. It can only occur when the head or body movements are involved [58]. Repetitive exposures to the same motion resulted in adaptation over time [59]. In this study, the general pattern of the experienced motion sickness in the first session was always the highest, and the last session was always the lowest. Therefore, the effect of the peripheral information systems and, in general, the effects of different conditions may have been weakened.

Since all of the participants experienced the same dose of motion sickness given in every condition, therefore, ideally, the participants should also yield different reactions according to the different conditions they were exposed to. In this study, each participant was subjected to three different conditions on three

different days. Even though a precaution measure was taken by restricting at least three days apart between the two consequent sessions to make sure if motion sickness occurs during one of the sessions, the effect of adaptation to motion sickness might still occur. Three days intersession was based on a study with repeated exposure to motion sickness stimulus that found that humans returned to resting level after 48 hours [60]. The adaptation to motion sickness might be caused by the participants' exposure to an identical route and motion profile for all three conditions. Therefore, participants might show fewer motion sickness symptoms in the later sessions compared to the first session, which would weaken the effect of the tested peripheral information system.

5. Conclusion

In conclusion, the realization of the test rides was consistently achieved, as shown by the Motion Sickness Dose Values (MSDVs) in the tri-axial direction. In addition, from the Power Spectrum Density (PSD), the motions of interest in longitudinal (y-axis) direction were realized in the low-frequency region, which has been proven to be inducing motion sickness.

In terms of motion sickness assessment, Haptic Peripheral Information System (HPIS) managed to reduce the experienced motion sickness caused by the low-frequency acceleration in the lateral direction and when reading inside a moving automated vehicle (AV). On the other hand, Visual Peripheral Information System (VPIS) seemed to exacerbate the experienced motion sickness. When comparing the results between the consequent sessions, adaptation to motion sickness was found likely to occur. It is believed that it happened because the participants exposed to the same motion profiles were used throughout the three conditions.

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