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ORIGINAL ARTICLE

Gaining Situation Awareness through a Vibrotactile Display to Mitigate Motion Sickness in Fully-Automated Driving Cars

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ABSTRACT – Many previous studies mention that passive drivers or passengers of fully-automated driving cars have less awareness of the surrounding and more experience to motion sickness symptoms when engaging in non-driving tasks. This occurrence is especially magnified when riding in an urban area with lots of junctions and corners. The aim of the current study is to investigate the effects of peripheral information about upcoming manoeuvres through a vibrotactile display in increasing the fully-automated driving car passengers' awareness of situations and mitigating their motion sickness level. Twenty participants took part in the experiment which used a Wizard of Oz method to simulate autonomous driving, and the experiment was conducted in an instrumented car on a real road environment. Objective and subjective measurements were gathered. The results show that the implementation of the vibrotactile display increased situation awareness but failed to reduce the motion sickness. This study concludes that in order to mitigate motion sickness inside a fully-automated driving car, more specific information need to be included in the peripheral information. In addition, a device that can actively help in controlling the posture movements should also be implemented in the vehicle.

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Fully-automated driving; Motion sickness; Situation awareness; Tactile or haptic displays design

INTRODUCTION

The rapid development of current technologies, especially in the Advanced Driver Assistance System (ADAS), will make fully-automated driving a reality in the future. This allows passive drivers or passengers to involve in non-driving tasks, such as reading, talking with other passengers, watching movies, playing games or working [1]. However, such tasks/activities usually will require the fully-automated driving (FAD) car passengers' focus off the road, which leads to an inability to predict the future path of the vehicle. As a result, they might get motion sickness symptoms when riding in a fully-automated vehicle [2].

Two general theories aim to explain how someone might get motion sick (MS) especially in moving vehicles (either land, sea or air vehicles): the sensory conflict theory and the postural stability theory. The sensory conflict theory [3], is a theory about the mismatch of sensory inputs between visual, vestibular and/or somatosensory inputs. In other words, what you see is different from what you feel. This phenomenon commonly happens when car passengers are actively involved in non-driving tasks. In addition, Riccio and Stoffregen presented the postural stability theory [4], holding that actions are needed to minimise uncontrolled movements. Lack of actions leads to instability which eventually causes MS. Hence, car passengers need to react accordingly in time to balance the posture of the body when unexpected forces are acting on the vehicle. For instance, when riding in a car on a winding road with reverse curves, where a curve to the left or right is followed immediately by a curve in the opposite direction, a higher chance of MS occurs.

The general idea to overcome this situation is using human senses to provide sufficient situation awareness (SA). SA is defined in various ways, depending on the theoretical and methodological approaches. Fracker mentioned that SA should be defined based on what to measure [5] and Dominguez highlighted which elements should be in the SA definition [6]. Both authors reviewed a number of SA definitions in their works. Endsley mentioned in a simple way that SA is "knowing what is going on around you" [7]. In driving contexts, SA is described as knowing about the car's current position in relation to its destination, the relative positions, and behaviour of other road users and potential hazards, and knowing how these critical variables are likely to change in the near future [8]. That is why drivers rarely get sick as they can anticipate what will happen [9] and can predict required actions based on previous experiences. For example, when taking a corner, drivers actively tilt their head toward the centre of the corner, which helps in reducing MS [10]. Hence, when the drivers become passengers in the FAD car, knowing what to expect and anticipating the future action of the car and acting accordingly on time can minimise the MS symptoms [11].

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Information regarding the intention of imminent motion of the car needs to be conveyed in a very subtle way, so, the FAD car passengers can keep their focus on their non-driving tasks, but remain aware of the information given and prepare for any required actions. This alteration between the main focus and periphery of attention is called peripheral interaction [12], a part of the calm technology [13]. Thus, peripheral displays can be used as an approach to providing information to passengers.

The visual and auditory modalities are the modalities that mostly have been studied by researchers as peripheral displays [14]. However, as mentioned before, most non-driving tasks require the visual focus of the passengers and different tasks can lead to a different line of sight. For example, working on a laptop or reading a book requires the passengers to take a downward viewing angle [11], compared to watching a movie on a big screen in the dashboard. Besides, auditory cues become ineffective in a loud environment (for example, when listening to the music or in the middle of a conversation) and might add more noise inside the FAD car [14]. A survey was done to investigate drivers' opinion on auditory interfaces in FAD and highly automated driving (HAD) cars [15]. One of the interfaces called future system aimed at providing comfort in the FAD car, and was designed to remove undesired sounds (e.g., tires or engine) and to amplify desired sound (e.g., the sound of birds from the environment). Based on over 1200 respondents, the system was considered somewhat annoying with most of the respondents choosing a neutral score. Thus, using haptic cue offers a promising direction to provide information peripherally to increase situation awareness inside the autonomous vehicle.

The sensation of haptic cues come from the tactile sense (sensors from the skin and right underneath it) and kinaesthetic sense (sensors from muscles, joints or tendons). Gibson described active touch as a deliberate movement or action to touch in searching for stimulation or perception [16] while Lepora stated that passive touch is when an unanticipated tactile event occurs [17]. In the context of FAD, passive touch, either vibration or pressure, can help in providing necessary information in a very subtle way to passengers about what may happen when they are not aware of the situation. However, the pressure is considered as a slowly-varying tactile display, unless the frequency of touching is high (or vibrating) due to rapid adaptation of the tactile sense to static stimuli [18, 19]. In addition, another point that should be taken into consideration when using the vibration sensation (also called vibrotactile) is when the vibration is indirectly touching the passengers' skin through the thickness of the cloth. According to [20], only a winter coat significantly decreased the intensity of the vibration compared to several cotton layers (T-shirts stacked together or one pullover jacket). Despite these drawbacks, studies have confirmed that a vibrotactile display alone is sufficient to generate subjective sensations, for example, as warning signals [21–24] or as navigation tools [25, 26]. Other studies also found that a vibrotactile display can improve awareness while driving, such as providing information in blind spot area [27] and information regarding the position of an approaching car from the back when resuming control in HAD [28].

In the present study, we aim to investigate the effects of peripheral information (when taking a corner) from a vibrotactile display to increase SA and to mitigate MS of FAD car passengers when performing a non-driving task, which is watching a video, inside an instrumented car. Two experimental conditions (with and without vibrotactile display) were conducted to examine whether the peripheral information can lead to reducing the MS. Subjective and objective measurements were taken to measure the SA and MS levels. An earlier study has pointed out that processing information not only can influence the SA but also can affect mental workload. Hence, we used a questionnaire to measure this element. The lateral acceleration, which is induced when the car takes a corner, was utilized as the cause of increasing MS symptoms. This acceleration was manipulated by driving in an urban area, including various corners with a predefined range of acceleration from a previous study [29]. Thus, motion evaluation was analysed to check the consistency of each experiment sessions. In general, we want to test two hypotheses:

i. H1: level of SA with peripheral information is higher compared to without any information condition
ii. H2: level of MS with peripheral information is lower compared to without any information condition

METHODOLOGY

Participants

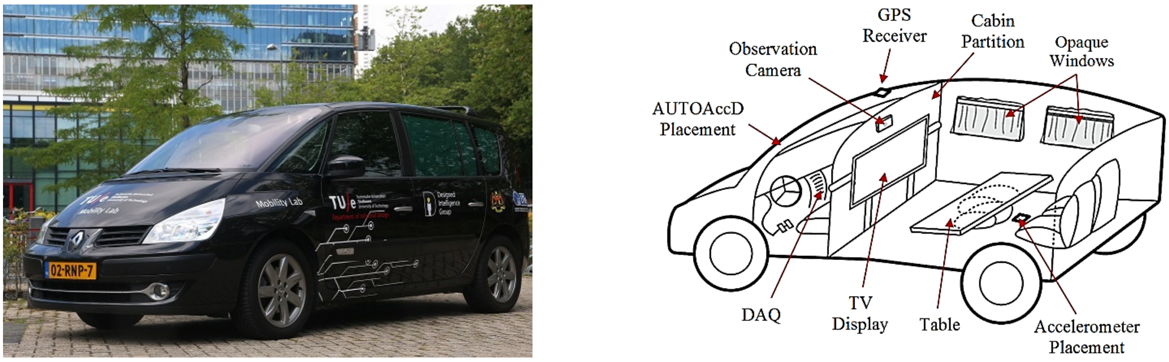
Using a within-subject experimental design, 20 healthy participants (12 male, eight female), aged between 18 and 47 years old (median (Mdn) = 26, standard deviation (SD) = 6), took part in the study. One participant was recruited from the staff, and the rest were students of the Eindhoven University of Technology. All participants were selected based on their score on the motion sickness susceptibility questionnaire (MSSQ) [30], which asks for previous sickness occurrences, resulting in a single MSSQ percentile rating. They answered the questionnaire a few days before the experiment day. Since this study focuses on the FAD car, the MSSQ score used here was based on the land vehicle elements only between 25 to 100 percentile rating, which represents mild-moderate and high susceptibility to MS [31]. The first quartile of the percentile (0 to 25) is considered a low-susceptibility to MS and anyone who falls under this quartile is treated as immune to MS. In addition, all participants reported no heart-related sickness, and none of them was pregnant.

Wizard

To simulate FAD car riding experience, the driving wizard (DW) was implemented based on [32] with the help of a device called Automatic Acceleration and Data controller (AUTOAccD) [33]. The function of AUTOAccD was to guide the DW to induce a certain range of accelerations when simulating the FAD on the real road. The defensive FAD style was used in this study because it is generally preferred by drivers in the previous study [29]. However, only the lateral acceleration is defined at around 0.15 g, while the fore-and-aft acceleration was controlled to be kept at a minimum, as it predicted that a FAD car could cross a junction without stopping due to car-to-car communication [34]. The experimenter assisted participants (or passengers), and he was the only one that interacted with the participants for the whole study. During the riding phase of the experiment, the experimenter seated at the front passenger seat, next to the DW.

Instrumented Car

The study was conducted using a customized Renault Espace as an instrumented car, called Mobility Lab as shown in Figure 1(a) [35]. The interior of the car was modified to replicate a fully-automated vehicle of the future. The car consists of a rear cabin, where the passengers were seated. This cabin was isolated completely using a cabin partition that separates the frontal area (Figure 1(b)).



(a) (b)

Figure 1. (a) The instrumented car Mobility Lab; (b) The layout inside Mobility Lab [35].

A 42-inch TV was attached to the partition and located about 1.2 m in front of the passengers. For the current study, to avoid saccadic eye movements that can lead to eye strain, only a smaller video size of about 24-inch (aspect ratio of 16:9) was displayed on TV, with the black colour of the rest background of the TV display [36, 37]. The car windows were made opaque to prevent passengers from looking outside so that they could only get the information about upcoming manoeuvres (the car turning to the left or right) from the display and not from looking outside. This aspect, while not exactly representing the current situation inside a car, ensured that passengers would be prevented from interrupting their non-driving related activity and would be completely unaware of the route of the vehicle and future direction changes. For safety purpose, an emergency button was available on the table for the passengers to push if any of them felt severe nausea and could not continue the study. An alarm buzzer would be triggered to notify the DW to stop the car immediately if road conditions allow.

For vehicular data measurements, a three-axis accelerometer sensor, ADXL335 [38], was placed in the middle of the car on the floor to measure acceleration in longitudinal, lateral and vertical directions. It was calibrated using the same method as [39]. Furthermore, a global positioning system (GPS) receiver, an Adafruit Ultimate GPS Breakout [40], was implemented inside the car to measure latitude and longitude coordinates, including the velocity of the car. For passengers' data measurements, a pulse sensor was attached to a specifically designed finger clip to measure the heart rate of the passengers (Figure 2(a)). The heart rate was measured in terms of beats per minute (BPM) of the participants as continuous motion sickness measurement. This is because the increase in heart rate reading is highly correlated with the occurrence of motion sickness [41, 42]. In addition, a device called clicker was used to measure reaction time, the time taken for the clicker to be pressed by the participants after peripheral information was given from the prototype (Figure 2(b)). It had two buttons which designated the direction of the car (either turning left or right). All measurements were synchronized at the rate of 250 *Hz* using National Instrument compact RIO-9030 (NI cRIO 9030) data acquisition system (DAQ) and stored in a laptop.

(a) (b)

Figure 2. (a) Pulse sensor finger clip and (b) the clicker for reaction time measurement.

Prototype

The prototype used consisted of a vibrotactile display which was provided via two sets of three shaftless vibration motors in a coin shape with a dimension of 10 mm in diameter and 2.7 mm in thickness (Figure 3). The motors had a maximum speed of 11000 rpm which translates to a frequency of 183 Hz at 5 V of a power supply, and they were connected to Arduino Mega R3 board as the main controller processor. The frequency that is higher than 60 Hz can avoid temporal masking in conveying in-vehicle information [43]. Furthermore, three motors were placed equidistant (25 mm) from each other and attached to a strip of hook-and-loop fasteners in each set as shown in Figure 3. Each set presented information on the forearm of the passengers that indicated the intention of the car either turning to the left (left-hand set) or to the right (right-hand set). The motors were activated for 0.6 seconds and deactivated for another 0.6 seconds, and this cycle repeated for 3 seconds before the car was turning into a corner.

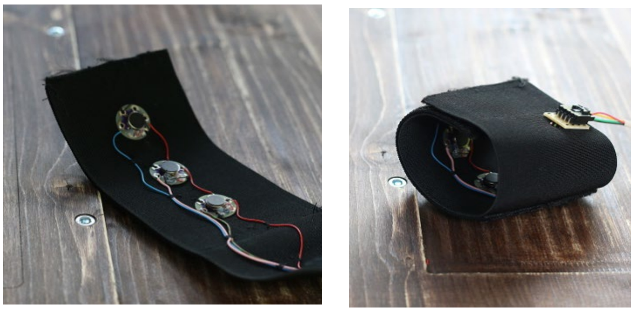


Figure 3. The vibration motors attached to the stretchable fabric.

Questionnaires

In measuring the level of experienced MS, the Motion Sickness Assessment Questionnaire (MSAQ) was used [44]. It consists of 16 items on a nine-point rating scale. It is a multidimensional questionnaire consist of gastrointestinal- (sick to the stomach, queasy, nauseous, may vomit), central- (faint-like, lightheaded, disoriented, dizzy, spinning), peripheral- (sweaty, clammy/cold sweat, hot/warm), and sopite-related (annoyed/irritated, drowsy, tired/fatigued, uneasy) dimensions. The presence of these different dimensions helps differentiate between the different symptoms of MS rather than attribute to a single MS score in percentage from 11.1 (no symptoms) to 100. In this study, the passengers answered the MSAQ as pre- and post-experimental questionnaires and the difference of the score between those two is considered as the changes in MS level of passengers. For example, if a passenger answered a 2 in “drowsy” at the pre-experimental questionnaire and answered a 5 at the end of the experiment, the exact score would be a 3 (= 5 - 2), and the percentage range was changed, from 0 (no symptoms) to 88.9.

The Situation Awareness Rating Technique (SART) was used [45]. It consists of 10 items on a seven-point rating scale that divided into three dimensions: understanding (U), attentional demand (D) and attentional supply (S). The obtained ratings were then combined and calculated to a single score of SA of passengers, SA = U-(D-S). Since the SART was developed originally for aviation purposes, the ten items were modified specifically for this study and for a better understanding of the passengers. For example, in attentional demand construct, the “Number of variables which require one’s attention” item was changed into “How many variables (e.g., the speed of the car, forces felt inside the car, etc.) are changing in the situation?” item. Furthermore, the Rating Scale Mental Effort (RSME) was implemented as a unidimensional tool to assess the subjective mental workload of passengers [46]. It consists of a vertical line with a length of 150 mm long (1 mm is equal to 1 point) and having nine anchor points which represent descriptive labels of indicating a degree of effort from absolutely no effort (about 2 points on the scale) to the extreme effort (about 112 points on the scale). Besides, the passengers evaluated the riding experience by rating the quality of the FAD on a 10-point Likert scale from 1 (very unrealistic) to 10 (very realistic). In addition, the passengers assessed the implemented vibrotactile display by answering the User Experience Questionnaire (UEQ) to indicate their feelings, impressions, and attitudes that arose when they used the vibrotactile display [47]. It consists of 26 items that fall into six categories (attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty) and the range of the scale is between -3 (horribly bad) and +3 (extremely good).

Procedures

All passengers were subjected to two experimental conditions, with (haptic condition (HC)) and without (control condition (CC)) vibrotactile display. They were paid €10 for their time at the end of both conditions. A minimum gap of three days between the two conditions was administered for each passenger to diminish the MS effects that might have occurred from the first condition of the experiment. A counterbalanced order was applied to avoid any carry-over. In order to ensure experimental consistency, all sessions were conducted outside office hours on the exact same route inside the first author’s university terrain where there was no or only limited traffic present, and a speed restriction of 30 km/h was indicated. The route consisted of 18 corners, either to the left (8 times) or right (10 times), with various radii ranging from 6.0 to 17.6 m. A marker, which helped the experimenter to trigger the vibrotactile display at almost exactly 3 seconds before each corner, was deployed at a certain distance from the corner based on the predefined speed of the car. The marker was a straight coloured line drawn on the route, and the speed of the car was equal to the tangential velocity needed (ranging from 10.7 km/h to 18.3 km/h) to induce 0.15 g centrifugal force of the upcoming corner. The inside temperature of the car was maintained at 20° Celsius. The independent variable was the conditions of the experiment, CC and HC, and the dependent variables were scores on SA, MS, workload and perceived FAD realism, and also the heart rate of the passengers.

The experiment started at the entrance of the first author's university building. At the beginning of each condition, the nature of the experiment was introduced to the passenger by the experimenter, including his/her right to withdraw from the study at any time. Then, the passenger signed the informed consent and answered the pre-experimental questionnaire. Next, the experimenter led the passenger to the car from behind in such a way that passenger entered the car from the right side rear door to avoid him/her seeing the DW who was already in the driver seat (refer to Figure 4).

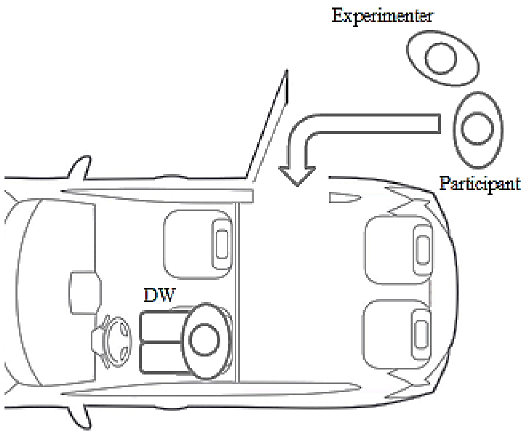


Figure 4. Illustration of procedure for passengers entering the Mobility Lab.

The passenger sat in the back seat on the right side and wore the seat belt. The experimenter explained how to use the emergency button, and attached the pulse sensor finger clip on the left-hand index finger. In addition, the passenger was instructed to keep an open palm facing upwards and minimise the left-hand movement for the whole experiment. Two neutral emotion videos (one for each condition) were used in the experiment to avoid any feelings or emotions that could affect heart rate measurement. The videos were Amsterdam and The Netherlands: Beyond Amsterdam from Rick Steve's' YouTube Channel [48, 49]. Only in HC, the vibrotactile display was placed on both left and right passenger's forearms, and the clicker was held on their right hand, as shown in Figure 5. At the same time, the experimenter showed how to use the clicker.

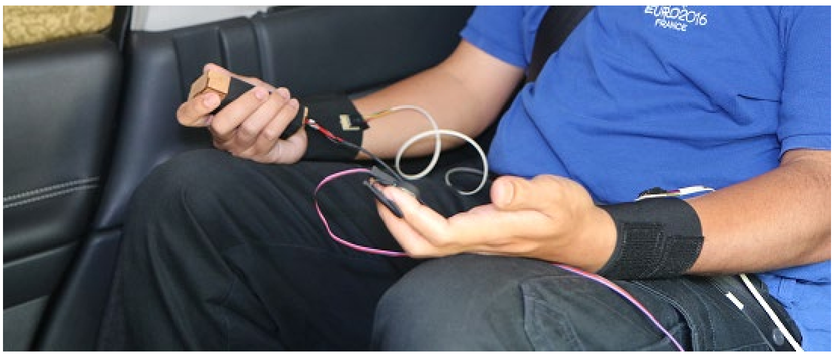


Figure 5. The position of the clicker, pulse sensor finger clip, and vibrotactile display.

The experiment itself was divided into three phases (Figure 6). In the first phase, defined as pre-rest (PR1) phase, the passenger was seated in the car and watched the video for the first five minutes. In this phase, the car was idle, and the engine was turned on. In the second phase, defined as driven around (DA) phase, the DW drove the car in the predefined route while the passenger was continuing watching the video. The role of the DW was to drive at an about similar pace, entering and exiting the corners at almost the same time, and inducing almost the same lateral acceleration at every corner. It was to make sure that the forces applied to induce MS to the passengers should be the same each session. Thus, the motion sickness dose value (MSDV) was calculated at the end of each session. It is a measure of the probability of getting nausea which the longer the duration of the motion exposure, the higher of chances of getting MS [50, 51]. Although the MSDV was developed only to assess MS based on vertical acceleration with the application of the W_f frequency weighting, MSDV could also be used to evaluate MS from horizontal acceleration motion [52, 53]. The whole riding experience took about ten minutes to be completed. In the third phase, defined as post-rest (PR2) phase, the car was idle for five minutes. In this phase, the passenger was still watching the video until the experimenter brought him/her back to the building.

Then, the passenger answered the post-experimental questionnaires and was reminded to answer the questionnaires based on his/her experience after the end of the DA phase only. The questionnaires were not presented between DA and

PR2 phases because of avoiding any interruption of the heart rate measurement. In the DA phase of CC, the only task for the passenger was watching the video. However, in HC, every time the car approached a corner or junction, the experimenter triggered the vibrotactile display at the marker. The passenger had to press the left or right button on the clicker when he/she felt the vibration to indicate either the car taking a left or right turn.

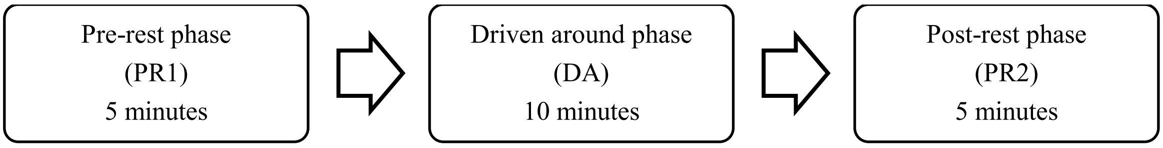


Figure 6. Schematic process of experiment phases.

Statistical Analysis

Statistical analyses were performed using the IBM SPSS software [54]. If data were normally distributed, a parametric test was used whereas if data were not normally distributed, a nonparametric test was used. In other words, a paired samples t-test (if data is normally distributed) or Wilcoxon signed-rank test (if data is not normally distributed) was used to compare the means between two conditions (CC and HC). If there was no significant difference, a power analysis with a probability of making a type II error ($\beta = 20\%$) with a large effect size ($r = 0.5$) [55] was conducted using the software package, G*Power software [56]. This analysis was done to determine if the test contained enough sample size to reject the alternative hypothesis (i.e., failed to reject the null hypothesis) [57].

RESULTS

Consistency

Each session was evaluated to make sure all collected data were reliable. This was done by analysing whether the acceleration forces generated from the cornering motions are the same across passengers. Over the 40 sessions of the experiment, the mean of root mean square (r.m.s.) accelerations were similar in lateral direction in both conditions, CC (range = 0.85 ms^{-2} to 1.65 ms^{-2}, Mdn = 1.34, SD = 0.22) and HC (range = 0.87 ms^{-2} to 1.61 ms^{-2}, Mdn = 1.39, SD = 0.22).

Power spectral densities (PSD) were calculated from the accelerometer representing the distribution of tri-axial acceleration across the frequency spectrum. A Hanning window was applied with periodic amplitude attenuation corrections. In other to illustrate the results, we plotted a semi-log graph of the PSD of the mean acceleration PSD in Figure 7. Both conditions showed almost identical distributions, where several peaks of acceleration were overlapped at different frequencies, especially in fore-and-aft (x-direction) and lateral (y-direction) accelerations. Both accelerations were dominant at below 0.25 Hz while vertical (z-direction) acceleration peaked between 1 to 2 Hz.

Past studies showed that low-frequency motions below 0.5 Hz are highly correlated with MS [50, 58, 59] whereas high-frequency motions at 1 Hz and above can cause discomfort or injury but do not provoke MS [60]. Hence, only accelerations in fore-and-aft and lateral directions were reflected in the MSDV in Figure 8. The mean MSDV given to all passengers at the end of the riding phase was almost similar in both conditions in fore-and-aft (mean = 2.31 $ms^{-1.5}$, SD = 0.37) and lateral (mean = 6.60 $ms^{-1.5}$, SD = 1.00) directions.

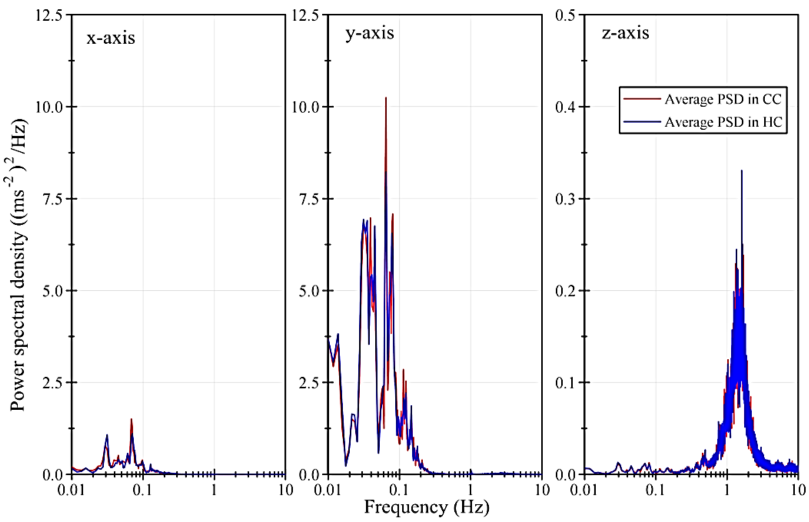


Figure 7. Mean acceleration power spectral densities in fore-and-aft (x-axis), lateral (y-axis) and vertical (z-axis) for both conditions.

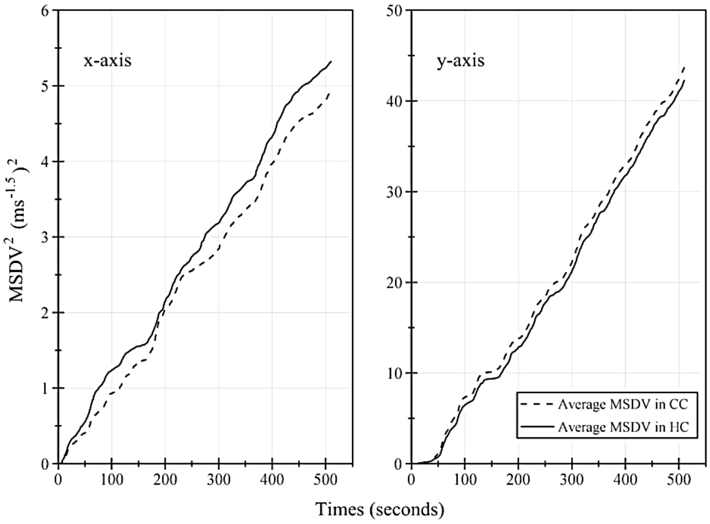


Figure 8. Mean accumulated squared motion sickness dose value (MSDV^2) in the fore-and-aft and lateral directions in CC and HC.

In addition, the induced MSDV was evaluated subjectively by the passengers based on the MSAQ ratings. In both CC and HC conditions, 15 passengers indicated higher MS level in post-experiment, whereas three passengers reported reduced MS level in post-experiment, and two passengers showed no change at all. The WSRT was conducted to compare the MS level of passengers between pre- and post-experiment in both conditions (see Table 1). There were significant effects in the total and all dimensions of MSAQ except in the peripheral-related dimension in both conditions.

Table 1. MSAQ ratings analysis between pre- and post-experiments (GI = Gastrointestinal, C = Central, P = Peripheral, S = Sopite)

MSAQ dimensions	Pre- and post-experiments in CC		Pre- and post-experiments in HC	
	Mdn diff	WSRT	Mdn diff	WSRT
GI	2.78	z = -2.867, p = 0.004*, r = -0.453	1.39	z = -2.497, p = 0.013*, r = -0.395
C	7.78	z = -3.519, p < 0.0005**, r = -0.556	6.67	z = -3.105, p = 0.002*, r = -0.491
P	0.00	z = -0.770, p = 0.441, r = -0.122	0.00	z = 0.000, p = 1.000, r = 0.000
S	9.72	z = -3.034, p = 0.002*, r = -0.480	5.56	z = -2.957, p = 0.003*, r = -0.468
Total	5.56	z = -3.180, p = 0.001**, 3r = -0.503	5.21	z = -3.115, p = 0.002*, r = -0.493

**Indicates significant effect (p < .05)*
***Indicates highly significant effect (p < .001)*

The whole riding experience was also assessed subjectively by passengers by evaluating the realism of the FAD itself. On average, all passengers rated high in both CC (Mdn = 7.00, SD = 2.00) and HC (Mdn = 8.00, SD = 1.50). A non-parametric analysis, the Wilcoxon signed-ranks test (WSRT), was used to determine whether there are differences between both conditions, CC and HC, on the realism of the FAD rating. The WSRT determined that there were no statistically significant differences in the autonomous riding rating between CC and HC (z = -1.116, p = 0.265, r = 0.176, two-tailed). Effect size r was converted into Cohen's d (0.359) [61]. A power analysis was conducted using the software package, G*Power software [56], revealed the statistical power for this analysis was 0.32.

Controlled Condition (CC) and Haptic Condition (HC)

To investigate the effect of with and without vibrotactile display implementation on SA of the passengers, we analysed the SART scores using paired t-tests or WSRT (Table 2). SA of 18 passengers increased in HC compared to CC while the other two passengers had reduced SA. One outlier was detected that was more than 1.5 box-lengths from the edge of the box in a boxplot (Figure 9). Inspection of this value did not reveal it to be extreme, and it was kept in the analysis.

The clicker measurement in HC showed that two passengers had pressed only once the button on the clicker in the wrong directions (2 out of 720 corners from the whole study). All the other passengers had a perfect perception of direction induced by the vibrotactile display, and the average of the measured reaction time was 1.093s (SD = 0.316s).

As the RSME scale is an ordinal scale, the WSRT analysis was conducted. There is no statistically significant difference between CC and HC on the RSME. The median mental effort of the CC where passengers were not presented with peripheral information from the vibrotactile display was 37.50, compared with the HC whose the median was 27.50 (z = -1.645, p = 0.100, r = 0.260, two-tailed). Effect size r was converted into Cohen's d (0.539). By using G*Power software, a power analysis was conducted and revealed the statistical power for this analysis was 0.73.

In comparison between the two conditions, the WSRT determined that there were no statistically significant differences for the total score of MSAQ between CC (Mdn = 5.56) and HC (Mdn = 5.21), z = -1.811, p = 0.070, r = 0.286, two-tailed. Effect size r was converted into Cohen's d (0.597). By using G*Power software, a power analysis was conducted and revealed the statistical power for this analysis was 0.69. However, only gastrointestinal-related dimension was significantly lower in HC (Mdn = 1.39) than in CC (Mdn = 2.78), z = -2.554, p = 0.011, r = -0.40, two-tailed.

Table 2. Results of paired t-tests or Wilcoxon signed-rank test on SART scores between CC and HC (U = Understanding, D = Demand, S = Supply).

SART Constructs	CC		HC		t or z	df	p-value
	mean (SD)	Mdn (SD)	mean (SD)	Mdn (SD)			(two-tailed)
U	3.37 (1.39)	-	3.73 (1.40)	-	1.376	19	0.185
D	-	4.17 (1.21)	-	2.33 (0.92)	-3.282†	-	0.001**
S	3.38 (1.26)	-	4.05 (0.86)	-	2.631	19	0.016*
Total	-	2.38 (2.79)	-	4.50 (2.34)	-3.547†	-	< 0.0005**

**Indicates significant effect (p < .05)*
***Indicates highly significant effect (p < .001)*
†Wilcoxon signed-rank test

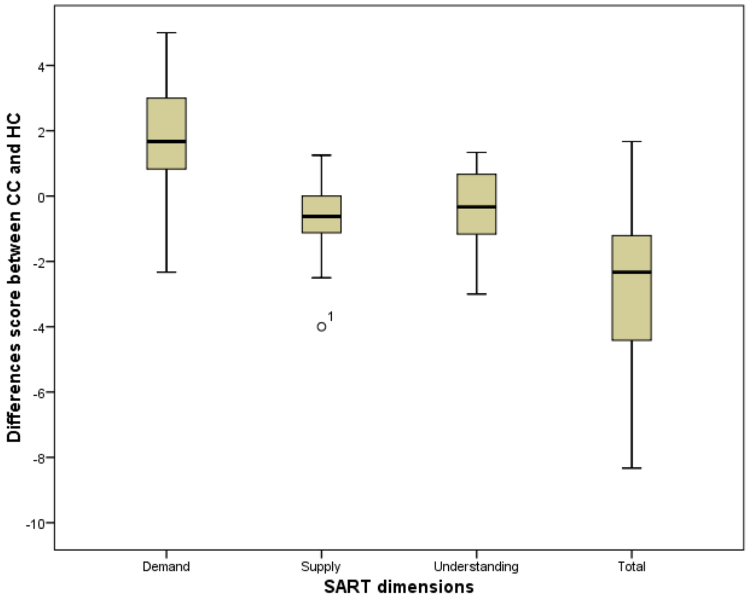


Figure 9. Boxplot of SART score differences between CC and HC.

As the heart rate was measured in beats per minute (BPM) in the PR1, DA and PR2 phases, a two-way repeated-measures ANOVA was conducted to determine the effect of vibrotactile display implementation on the heart rate. The two conditions (CC and HC) and the three phases were within-subject factors (or independent variables). There were no outliers, as assessed by examination of studentized residuals for values greater than ±3 (Figure 10), and the measurement data were normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals (p > 0.05). Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi^2(2) = 3.483$, p = 0.175. There was no statistically significant two-way interaction between conditions and phases, and the main effect of phase showed a statistically significant difference in mean heart rate between phases (Table 3). Heart rate was notably lower in HC than CC in post-rest phase (Figure 11). A post hoc analysis of paired t-test was conducted and revealed a statistically significant different of heart rate between CC (mean = 74.03, SD = 11.47) and HC (mean = 70.52, SD = 12.83) in PR2 phase only, t(19) = 2.183, p = 0.042.

Table 3. Overview of the results of the two-way repeated-measures ANOVA for heart rate measurement.

Source of variation	Sum of squares	df	Mean square	F	p-value	η2
Effect of condition (CC, HC)	119.900	1	119.900	1.019	0.325	0.051
Effect of phase (PR1, DA, PR2)	613.446	2	306.723	22.889	0.000*	0.546
Effect of condition x phase	42.385	2	21.192	2.617	0.086	0.121
Error (condition x phase)	307.770	38	8.099			

**Indicates highly significant effect (p < .001)*

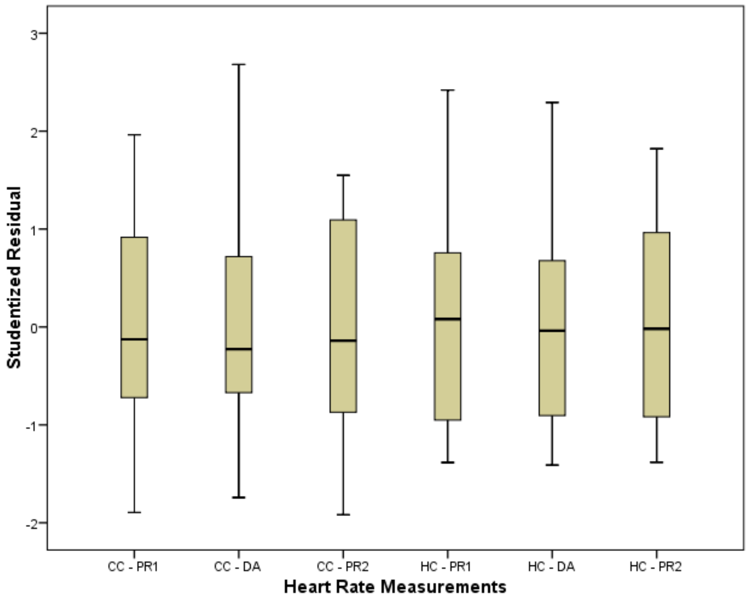


Figure 10. Studentised residual of heart rate measurements (CC = control condition, HC = haptic condition, PR1 = pre-rest phase, DA = driven around phase, PR2 = post-rest phase).

The vibrotactile display was assessed subjectively by passengers in HC. All mean values of the UEQ score were above 0.8, indicating that the overall rating for each category was positive. In addition, the Cronbach's α was calculated, and revealed all mean values for all category are acceptable (α > 0.7) except for perspicuity and dependability (Table 4).

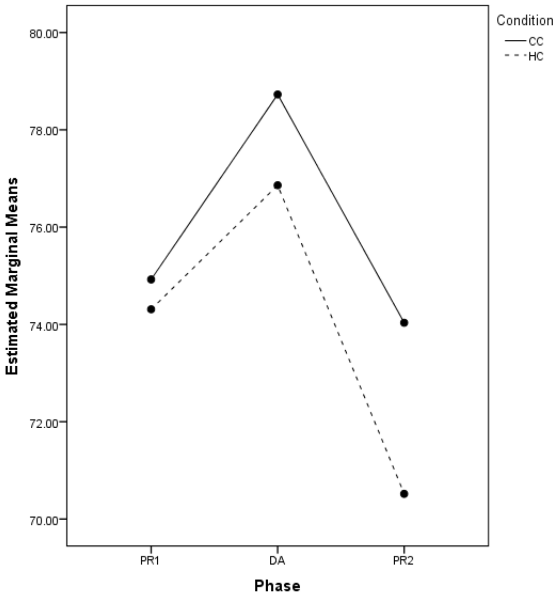


Figure 11. Interaction plot of estimated marginal means calculated for heart rate at each phase.

Table 4. Overall UEQ scores of the vibrotactile feedback (with a range from -3 to 3).

Category	Mean	SD	Cronbach's α
Attractiveness	0.950	1.063	0.92
Perspicuity	1.663	0.943	0.53
Efficiency	1.338	0.974	0.73
Dependability	1.025	0.892	0.39
Stimulation	0.963	1.098	0.88
Novelty	1.013	1.168	0.86

DISCUSSION

Consistency

In some corners, the r.m.s. accelerations were lower than the intended value (0.15 g or 1.47 ms^{-2}). This was due to unexpected traffic conditions occurred during experiment, especially at the corner. However, based on PSD result, all sessions have been consistently executed in the defensive driving style. The large differences between fore-and-aft and lateral amplitudes were expected as previously mentioned in this study setup where the fore-and-aft acceleration is controlled to be minimum.

In all sessions, the MSDVs were similar in both CC and HC which indicated the MS doses given to the passengers were almost constant (see Figure 8). Compared to [62], the MSDV value of 6.60 $ms^{-1.5}$ in lateral direction should be enough to provide mild MS. Furthermore, in our study, the severity of induced MS was assessed subjectively by the passengers when calculating the total MSAQ scores in CC (5.56) and HC (5.21), and these value considered as mild MS too [63, 64]. Only peripheral-related dimension did not show any differences between pre- and post-experiment in both conditions (see Table 1). This might be because the peripheral-related dimension represents sweaty, clammy/cold sweat, and hot/warm items in the questionnaire, while the temperature inside the car that was maintained at a fixed value of 20° Celsius and may affecting the level of MS [65].

Passengers reported that the riding experience in all sessions was almost similar to the real FAD in their expectation. With the power of 0.32, there were no significant differences in the rating, which can be assumed the FAD was consistent for all passengers. However, a post hoc analysis revealed, that in order for an effect size d of 0.359 to be detected (80% chance) as significant at the 5% level, a sample of 66 passengers would be required. Therefore, the result should be interpreted with caution.

Controlled Condition (CC) and Haptic Condition (HC)

In general, passengers' level of SA is higher with peripheral information in HC compared to without any information condition in CC. However, there were no statistically significant differences found between HC and CC in the understanding-construct score. On the other hand, based on the clicker measurement, all passengers can understand clearly the given peripheral information from the vibrotactile display. Thus, the result in the SART's understanding construct is expected to have a significant difference between both conditions. The inconsistency outcome might be due to the inability of participants to rate their own SA [66], which could be that they do not know what exactly they should know.

This outcome also could be explained by the RSME findings. In CC, the only task that the passengers did was watching the video. When the car was taking a corner, an unexpected acceleration force exerted on the passengers' body might increase their mental workload to know what exactly happened at that moment. In HC, even though the vibrotactile display can provide the information needed (the car will turn to the left or right), processing the received information while watching the video could also increase the mental workload which can affect the understanding part in SA. This could happen due to the fact that the vibrotactile display itself was designed only to provide information regarding the direction of the turning. No additional information about when the turning could happen, precisely how big or small is the radius of the corner, and either the length of the arc of the corner is short or long.

Initially, it was hypothesised that providing peripheral information about the intention of the car (either turning left or right) could reduce or lessen MS symptoms. With the Cohen's d (0.597) indicating a medium to large effect sizes and a power of 0.69, the MSAQ result showed that the implementation of vibrotactile display did not help in reducing MS in general. One of the reasons could be that the passengers were unable to maintain control of their posture when the car was entering a corner. This involuntary movement of the body might happen even though the passengers already wore a seatbelt. As described by [4], the postural instability may occur when someone cannot perceive the new dynamics (or forces) and cannot control the appropriate actions to the new dynamics. As a result, the prolonged exposure to this postural instability may induce MS symptoms. This MS occurrence can also be supported by our statement before, that the provided peripheral information from the vibrotactile display could be insufficient for participants to execute a proper control of the posture.

Although the use of a seatbelt restrains the passengers' body from moving, their head still can move freely. When taking a corner, drivers usually do not just lean but also tilt their head toward the curve centre or toward centrifugal force whereas passengers' head usually is tilted in the opposite direction. [67] mentioned that the changes of head orientation relative to the gravity vector, also called gravito-inertial force (GIF), can also provoke the MS. Studies found that an active head tilt or under external control (e.g., active suspension) could reduce the MS symptoms [10, 68]. Similar to the current study, participants might not actively control the movement of their head. Although participants knew which directions the car will be turned in, the exact moment to react (to tilting their head) probably was too late or too early. This may lead to a misalignment between the head and the GIF.

Only gastrointestinal-related dimension from MSAQ was found lower in HC than CC. As explained by [69] based on [3], exposure to a long period of mild nauseous motion resulted in "head" symptoms first before proceeding to "gastric" symptoms. While a short exposure to severely nauseous motion (as in the current study) quickly develop "gastric" symptoms, and any "head" symptoms could be unnoticeable. In addition, during the briefing of the nature of the experiment to the passengers, the passengers were explained about the functions of the vibrotactile display. This explanation could lead to an expectation of a positive outcome of reducing motion sickness, a placebo effect [70, 71], and influence the gastrointestinal-related dimension result. But, it needs to be kept in mind that even though the result for gastrointestinal-related dimension was significant, the medians in both conditions were low and therefore should be interpreted with caution.

Results from heart rate measurement were comparable to the current MSAQ results where there were no differences in MS level when comparing the CC and HC. In both conditions, the heart rate increased during the DA phase and dropped in the PR2 phase. Earlier studies [41, 42, 72] also found similar results with a heart rate decrease immediately following nausea stimulus termination. In general, heart rate was higher in the first phase (PR1) can be explained by the passengers' expectancies of possible discomfort at the beginning of the experiment. Furthermore, the heart rate in PR2 phase in HC was much lower than in CC. One of the possibilities might be that the vibrotactile display was actually reducing the passengers' general arousal levels [73].

Overall, the vibrotactile display was evaluated with high scores using UEQ. The low value of Cronbach's α in perspicuity and dependability categories might be that several passengers interpreted these categories' items in an unexpected way. For example, item number 17 in the dependability category represents a "secure - not secure" scale, which can be understood differently from one passenger to another passenger [74].

Although the general rating can be considered explicitly positive, some items were rated below 0.8, representing a neutral evaluation. These items were item 1 ("annoying - enjoyable" scale), item 6 ("boring - exciting" scale), item 8 ("unpredictable - predictable" scale), item 9 ("fast - slow" scale) and item 24 ("attractive - unattractive" scale). The low score of item 6 is preferred since the main idea was to provide the peripheral information in a subtle way that would not interrupt the non-driving task. On the other hand, items 8 and 9 were closely related to the functionality of the vibrotactile display. These evaluations result can be used for improvement in optimizing the vibrotactile display in future work.

CONCLUSION

In this paper, a vibrotactile display has been proposed to help passengers of a FAD car in increasing their SA to reduce MS symptoms when they are doing a non-driving task. The vibrotactile display was designed to provide the information in a peripheral manner. The study was done in a real road environment using Mobility Lab as an autonomous vehicle. The results of the study show a clear trend: the peripheral information from the vibrotactile display could increase the SA (H1: supported) but did not help in reducing the MS (H2: unsupported). Even though passengers knew the directions of the car, some information was not presented, such as the exact time of the induced forces and the intensity of the magnitude forces when entering the corners. As mentioned by [4], these could lead to uncontrolled movements of the head because the passengers were unable to react appropriately to the new dynamic forces. Thus, when they are exposed to prolonged postural instability, the MS symptoms might occur. Furthermore, it is possible that the induced MS dose in this study was enough to provide mild MS only and not enough to show any significant changes in both conditions. Similar findings found in [75] and mentioned that moderate or severe MS might result in significant effects.

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