Reading During Fully Automated Driving: A Study of the Effect of Peripheral Visual and Haptic Information on Situation Awareness and Mental Workload

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***Abstract*— This study investigates the effect of peripheral visual and haptic information in providing information about upcoming motions of a fully automated vehicle to an occupant engaging in a non-driving related task, i.e. reading. Two peripheral displays, one visual and the other haptic, were designed and tested. It was hypothesized that the peripheral information would enhance the users' situation awareness and reduce their mental workload. The study was conducted with 18 participants driven around in a real-road environment in a multi-purpose vehicle that simulated a fully automated vehicle. The peripheral visual and haptic information significantly enhanced situation awareness but did not reduce the mental workload. Implications and future work are discussed.**

***Index Terms*— Situation awareness, mental workload, peripheral visual information, peripheral haptic information, autonomous vehicle, user experience.**

I. INTRODUCTION

SINCE a fully automated vehicle (FAV) (level 5 in driving automation system that is based on the SAE taxonomy [1]) will drive itself and perform all driving-related tasks, its users can shift their focus to other tasks to be more productive during a journey. These tasks include working on a laptop, watching a video, relaxing or enjoying the route's scenery. Previous research found that future users of a FAV ranked reading as their top choice of non-driving related tasks (NDRT) in automated driving compared to other tasks [2]–[4]. However, the reading task will require the users' visual focus off the road, which leads to low situation awareness (SA).

SA in a lower level of automation (level 4 and below) is crucially important to keep the users in the control loop of driving tasks [1]. On the other hand, SA at a higher level is also vital to the users when they are engaging in NDRT [5], especially awareness of the navigational intention of the FAV [6]. For example, passengers regularly interrupt the NDRT to look outside at the horizon and collect information to anticipate the vehicle's trajectory. It is one of the coping mechanisms that passengers usually apply to achieve SA [5]. Indeed, visual information providing an artificial earth reference has been shown to increase anticipation and reduce carsickness [7]–[9]. Hence, even though FAV occupants don't need to care about driving the vehicle, and therefore SA-relevant information isn't needed to support the driving task, they will still interrupt the NDRT to gain situational awareness because it makes them feel comfortable. Clearly, the shift of attention from the reading task to the environment will affect the reading experience and reduce the reading performance.

One of the ways to counter the negative effect of looking outside on the reading experience is to allow users to process SA-related information in parallel with the NDRT. Borrowing ideas from calm technology and ubiquitous computing [10], it may be assumed that users during reading may collect SA-related information in the periphery of their attention through peripheral or ambient displays. The use of such peripheral displays has been explored before [11], [12]. In the context of automotive, peripheral displays have been studied among others by Löcken [13]. By providing low complexity information in the periphery of the user's attention, peripheral displays allow users to continue their primary task while still picking up information from the environment.

So far, we have treated the concept of situation awareness in a rather loose way. To be more precise, it should be decomposed into different sorts of information. For instance, in driving, SA is at least about other entities on the road, their whereabouts, speed, and direction. Good situation awareness allows drivers to build a model of the

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current situation and predict how it will evolve to enable drivers to anticipate upcoming situations and decide about actions enabling safe driving. In the context of FAVs, however, as expressed above, occupants are primarily looking for information that makes the future actions of the FAV predictable [14]. In particular, this includes information about acceleration and deceleration and lateral movements such as resulting from left and right turns. Since lateral movements have been found to contribute to discomfort and motion sickness [15], for the current study, peripheral displays were developed that provide information about upcoming left and right turns.

According to Multiple Resource Theory [16], a proper modality is needed to process parallel information. During reading, the focal visual cue is already in high demand. Thus, other modalities such as auditory, haptic, or even peripheral visual cues can also work as a channel with less demand compared to using the focal visual cues. [17] stated that the auditory and visual modalities had been studied most by researchers of peripheral display systems. Auditory cues become ineffective in loud environments (for example, when listening to music or in the middle of a conversation) and might add more noise inside the car. Furthermore, a survey by [18] investigated drivers' opinions on auditory displays in fully- and highly-automated driving cars. One of the displays aimed to remove undesired sounds (e.g., tires or engine) and amplify desired sounds (e.g., the sound of birds from the environment). Based on over 1200 respondents, the system was considered somewhat annoying, with most respondents giving a neutral score.

[19] implemented a peripheral visual display as a wearable device, a pair of eyeglasses. The peripheral display was designed to increase the SA when the vehicle occupants were not paying attention to the road and focusing on reading. They found that although the SA improved without requiring users to observe the environment outside the vehicle, the light from the system distracted the occupants from enjoying their NDRT (i.e., reading). [15] implemented a peripheral information system called Peripheral visual feedforward system (PVFS) to increase the SA regarding the intention of the FAV manoeuvres while watching a video on a TV [15]. The PVFS was attached to the left and right sides of the TV that placed 1.2 meters in front of the occupants. They found that the SA of the occupants was enhanced and did not degrade the performance of the NDRT (i.e., watching a video). Based on these findings from both studies, a proper modality is needed based on the task demands (i.e., a peripheral visual cue may work better if it is not too close to the eyes). Although peripheral visual cues can be processed without an unsubtle visual reorientation, in theory, they are most typically processed with a saccade, which pulls the eyes away from the reading task (and costs time to re-orient on the reading task).

A haptic display is another modality commonly implemented in a vehicle to convey information to a driver [20], [21]. The haptic display is usually used for safety aspects in driving as a warning signal. In the context of fully automated driving, this type of display may be used to provide peripheral information to increase the SA about the direction of the FAV movement to the user. For example, [22] explored a tactile belt for drivers to provide turn-by-turn information. The vibration actuator locations provided information about the direction, while the number of pulses provided information about the distance. They found that the drivers' orientation performance was better than a typical (built-in) car navigation system with audio feedback.

In principle, providing information through a peripheral display introduces a secondary task for the user, which might increase the mental load and impede the reading experience. However, as argued above, without a peripheral display, users are likely to interrupt the reading task to collect information that enables them to anticipate lateral movements of the car. Such interruptions are possible to induce mental load by themselves. Therefore, we expect that a peripheral display will not increase mental load; on the contrary, the mental load will stay the same or even decrease compared to a condition without a peripheral display.

The primary objective of this study was to investigate the effects of peripheral information systems on SA and mental workload on the users of a FAV, specifically when engaging in reading. Two types of modalities (visual and haptic) of the peripheral information systems were designed to provide information about the upcoming manoeuvres of the FAV. It is hypothesized that the two proposed peripheral information systems (haptic and visual) effectively enhance the SA regarding the future lateral direction of the FAV. We also hypothesized that both of the peripheral information systems produce a lower mental workload when compared to no peripheral information system present. In addition, it was hypothesized that both of the peripheral information systems allow for full engagement in reading, as an NDRT in this study.

II. METHODOLOGY

A. Experimental Design

Eighteen participants experienced three experimental test conditions (within-subject) termed as control-condition (without any peripheral information systems), visual-condition (with the visual peripheral information system, VPIS), and haptic-condition (with the haptic peripheral information system, HPIS). A fully counterbalanced order of test conditions was applied to mitigate any learning effects ($3! = 6$ orders). In addition, a minimum gap of three days between each condition should prevent carry-over effects. The test condition was the independent variable. The dependent variables were the evaluation of SA, mental workload, and the assessment of reading performance. The experiment was conducted on the Eindhoven University of Technology (TU/e) campus, where the Dutch traffic laws apply. The TU/e security was informed about the study for additional safety precautions, and permission to use the designated route was granted. Thirty-eight corners (16 to the left, 22 to the right) with an average radius of 9.2 m (SD = 3.3 m) were used in this study. This research is compliant with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) [23].

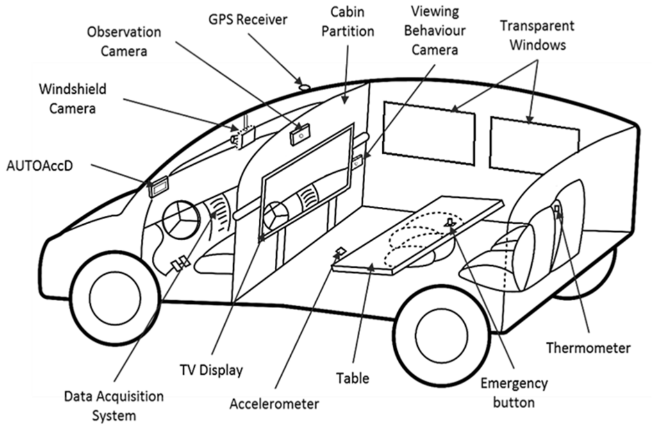


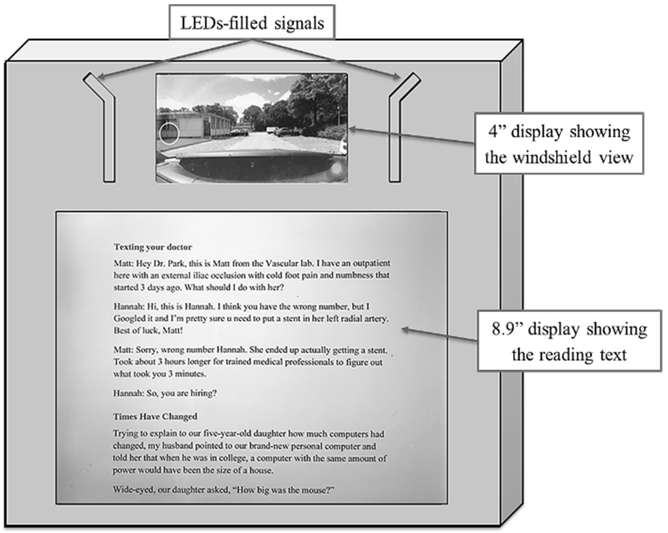
Fig. 1. Mobility Lab interior layout with a viewing behaviour camera. Adapted from [24].

B. Equipment

1) Mobility Lab and Wizard: A multi-purpose vehicle was modified into a FAV named Mobility Lab for human factor studies (Fig. 1) [24]. The Mobility Lab consists of two separate cabins, a rear cabin for passengers (the participants) and a front cabin for experimenters. The rear cabin of the Mobility Lab can have a transparent or opaque window setup. For the current study, the windows were transparent to let participants have a normal outside view. The mounted 40-inch TV display in the rear cabin was used to display or project a live feed from the windshield camera. An additional camera was mounted on the right-hand side of the TV display on the cabin partition to capture the participants' viewing behaviour during the experiment. The camera was mounted at about the same height as the participants' eye level when sitting in the right-back seat. An emergency button was available on the table for safety if the passengers could not continue the experiment. This alarm buzzer could be triggered to notify the driver to stop the car immediately if road conditions allow.

During the experiment, only the experimenter interacted with the participants. Similar to [25] and [15], an accomplice of the experimenter acted as a driving wizard. The primary task of the driving wizard was to simulate a FAV riding experience with the help of the Automatic Acceleration and Data controller (AUTOAccD) [26]. The AUTOAccD was developed to assist the driving wizard in simulating the intended longitudinal and lateral acceleration of the FAV. A defensive driving style was applied, which is generally preferred by drivers, as shown by previous studies [26], [27]. The lateral (cornering or turning) acceleration was maintained at around 0.29 g or 2.84 ms^{-2}. On the other hand, the longitudinal (fore-and-aft) acceleration was controlled to be kept to a minimum, as it was assumed that a FAV can always cross an intersection without stopping due to car-to-car communication [28].

2) Peripheral Information System: Two peripheral information systems were implemented in this experiment. One of the two peripheral information systems was the Visual Peripheral Information System (VPIS). The idea of the VPIS design was based on the outcome of a workshop about ambient peripheral displays [29]. The VPIS utilized the human peripheral field of view to convey navigational information of the FAV to the participants, and it was an iteration of another prototype used in a previous study [30]. The VPIS consisted of a 4.0" display (Fig. 2) and two LED-filled arrays at around an 8.9" tablet. Each array was equipped with 7 LEDs, with blue-emitting colour, that switched on 3 seconds before the Mobility Lab entered a corner/turning. The LEDs moved three times from the bottom to the top at each of the corners/turnings. The LEDs were diffused with a Perspex®acrylic sheet to ensure that the VPIS could grab the participants' attention while not interrupting their reading performance. The reading material was displayed on the 8.9" tablet display. The 4.0" display showed the live streaming of the front windshield camera during the entire session of the experiment. The idea was that the LED strips would provide information in the periphery of the visual field about upcoming manoeuvres while the occupant was reading, and that the occupant might then either continue reading or quickly shift their visual attention to the 4.0" display to collect additional information about the upcoming manoeuvre. The display was positioned relative to the tablet presenting the reading text such that inspection of the 4.0" display required a shift of visual attention across a minimal visual angle.



Texting your doctor

Matt: Hey Dr. Park, this is Matt from the Vascular lab. I have an outpatient here with an external iliac occlusion with cold foot pain and numbness that started 3 days ago. What should I do with her?

Hannah: Hi, this is Hannah. I think you have the wrong number, but I Googled it and I'm pretty sure u need to put a stent in her left radial artery. Best of luck, Matt!

Matt: Sorry, wrong number Hannah. She ended up actually getting a stent. Took about 3 hours longer for trained medical professionals to figure out what took you 3 minutes.

Hannah: So, you are hiring?

Times Have Changed

Trying to explain to our five-year-old daughter how much computers had changed, my husband pointed to our brand-new personal computer and told her that when he was in college, a computer with the same amount of power would have been the size of a house.

Wide-eyed, our daughter asked, "How big was the mouse?"

Fig. 2. Visual peripheral information system.

The other peripheral information system was the Haptic Peripheral Information System (HPIS). The idea of the HPIS design was based on conveying the navigational information through a vibrotactile display and inducing a movement, pushing the participant's body in the direction of the corner. The design of the vibrotactile display was based on a previous study that conveyed the information through vibration sensation on the forearms [31] (Fig. 3). In the HPIS condition, participants held the tablet in their hands.

The display consisted of two sets of vibration motors that were attached to two strips of hook-and-loop fasteners. The mechanism for the movement induction consisted of two movable plates fixed on the backrest of the car seat, covered with foam cushion and fabric. Three seconds before the car turned to the left or the 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.

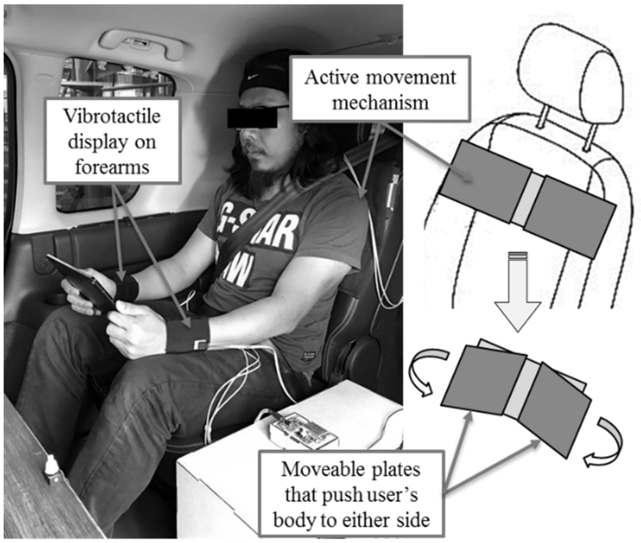


Fig. 3. Haptic peripheral information system.

Immediately after that cycle, the movable plate (the right plate if turning to the left, the left plate if turning to the right) was activated, turning forward through servo motors at about 40° as long as the cornering took place, countering the displacement of the body that usually occurs due to the centrifugal forces associated with left/right turns.

C. Participants

A total of 18 participants (9 males and 9 females) aged between 22 and 33 years old (Mean = 28.4 years, SD = 3.0 years) took part in the study. They were recruited through online social media as well as through flyers put up around the campus. They were paid €30 for their participation.

D. Data Collection

The data collection was grouped into two categories: Mobility Lab-based measurement (focused on evaluating the fully automated riding experience) and participant-based measurements (focused on the dependent variables that were tested).

1) Mobility Lab-Based Measurement: The *Automated Driving Test Ride Quality (ADTQ)* questionnaire asked how natural the FAV was when driven around inside the Mobility Lab, using a ten-point Likert scale (1 = very unrealistic, 10 = very realistic).

2) Participants-Based Measurements: Situation Awareness Rating Technique (SART), developed by [32], was used to evaluate the SA of the participants. It consists of 10 items using a seven-point rating scale (1 = low, 7 = high), divided into three constructs; understanding of the situation (U) – 3 items, attentional demand (D) – 3 items, and attentional supply (S) – 4 items. The obtained ratings are then combined into a single SA score, SA = total U - (total D – total S), ranging from -14 (lowest SA) to 46 (highest SA).

Rating Scale Mental Effort (RSME), developed by [33], was used to measure the mental workload of the participants. The scale consists of a 150 mm vertical line (1 mm is equal to 1 point) with nine anchor points indicating *"absolutely no effort"* at the minimum and *"maximum effort"* at the maximum. The participants rated the invested effort in getting the information in all three conditions.

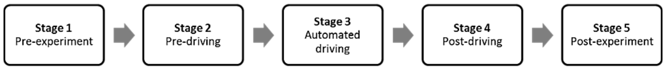


Fig. 4. The five stages of the experiment for the three conditions (control-, visual, and haptic-condition).

Viewing behaviour (VB) was assessed by combining information from the observation camera (Logitech HD c920 webcam) and the viewing behaviour camera (OMRON B5T-007001-010) (refer to Fig. 1). Both cameras were used to continuously record the participant's behaviour and viewing behaviour of the entire experiment. The recorded videos from the webcam were analyzed by advancing them at 1 s intervals, resulting in an average of 900 frames. From these data, it can be observed what exactly participants did during the experiment. At the same time, the data measured from the viewing behaviour camera were analyzed for gazing behaviour. Viewing behaviour was classified either as Head Down (looking at tablet/VPIS) or Head Up (looking at the TV screen or outside through windows). The percentage of the viewing behaviour (how long the participants' eyes were looking directly at the tablet/VPIS) was calculated over the total period of the automated driving period.

Reading performance (RP) was assessed by three different sets of questions from three different texts. The reading materials were compilations of jokes taken from a magazine [34]. This type of reading material was chosen to encourage the participants to read the texts. Each set was designated for each condition, and each questionnaire consisted of 10 multiple-choice questions with four alternatives. Each correct answer scored 1 mark, and the reading performance was the total marks for each reading material between 0 (*no correct answer*) and 10 (*all answers are correct*). For control of reading performance, fourteen independent participants (students from Eindhoven University of Technology and other universities, 8 males and 6 females, aged between 22 and 36 years old, mean = 27.5 years, SD = 9.0 years) were asked to read two of the three texts from the same reading materials and answer the questions, and answer the questions for the third text without reading the text (rotating texts across participants). Without the reading material (chance performance), they scored an average of 5.5 (SD = 1.4), while, theoretically, the chance performance should be 2.5. In other words, some of the questions could be answered based on general problem-solving strategies and common sense. These participants scored an average of 8.7 (SD = 1.6) with text, which was considered sufficiently different from chance performance.

E. Procedure

In general, all experiment conditions consisted of five stages (Fig. 4). Stage 1 took place in a meeting room, while Stages 2 through 4 took place inside the Mobility Lab. Stage 5 was started inside the Mobility Lab and continued in the meeting room.

At the pre-experiment stage (Stage 1), the participant was briefed about the layout of the experiment, including the right to withdraw at any time. In addition, the participant was led to believe that the vehicle had no human driver during the driving stages (Stage 2, 3, and 4). After the briefing, the participant signed the informed consent form. Then, the experimenter ushered the participant to the right side rear door of the Mobility Lab from behind to make sure that the participant did not see the driving wizard who was already in the driver seat when entering the vehicle (Fig. 5). The participant was asked to wear the seat belt and was explained the use of the emergency button.

Concerning the task and the peripheral information system, the explanations were given depending on the session's condition. In all three conditions, the only task for the participant inside the Mobility Lab was reading the text. In the control condition, the participant was reading from a tablet. In the visual condition, the participant was reading from the VPIS (see Fig. 2). In the haptic condition, the participant was reading from a tablet with the implementation of the HPIS (the vibrotactile display on both forearms combined with the movement mechanism on the backrest of the car seat). The tablet and the VPIS have similar hand-held surfaces but are different in height dimensions.

At the pre-driving stage (Stage 2), the Mobility Lab was stationary with the engine turned on for about 5 minutes. At the automated driving stage (Stage 3), the driving wizard drove the Mobility Lab on the predefined route (Fig. 6) with the defensive driving style [26] for about 15 minutes, and the participants experienced one of the three conditions. At the post-driving stage (Stage 4), the Mobility Lab was stopped and idled for another 5 minutes with the engine turned on.

At the post-experiment stage (Stage 5), the participant was given a set of questionnaires consisting of ADTQ, SART, RSME, and reading performance to be immediately answered inside the Mobility Lab just after Stage 4 was finished. Then, the experimenter guided the participant back to the meeting room, where a debriefing was performed.

The same procedure was repeated at least three days later for one of the other conditions and at least three days later for the last remaining condition.

F. Statistical Analysis

Statistical analyses were performed using the IBM SPSS software [35] to compare the effects of the three conditions. The Shapiro-Wilks test was used for the normality test (to check if data is normally distributed), as this study had less than 50 participants. A parametric test was used if data were normally distributed, whereas if data were not normally distributed, a non-parametric test was used [36].

A one-way repeated-measures analysis of variance (ANOVA) was used for the parametric analysis to compare the means for the three conditions. Mauchly's test of sphericity was applied to check if the differences between the levels of the within-subjects factor (i.e., the conditions) have equal variances. If Mauchly's test of sphericity was met ($p > 0.05$), the sphericity assumed value was used to determine the one-way repeated measures ANOVA result. If a significant difference was found in the one-way repeated measures ANOVA, a post-hoc analysis using the paired samples t-test with Bonferroni correction ($p < 0.017$) was applied [36]. On the other hand, a paired samples t-test (if data were normally distributed) or Wilcoxon signed-rank test (if data were not normally distributed) was used for pairwise comparison of means of two conditions (either control-visual paired conditions or control-haptic paired conditions). 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 ($r = 0.5$) was conducted using the G*Power software [37]. This analysis was done to determine if the test contained a large enough sample size to reject the alternative hypothesis (i.e., failed to reject the null hypothesis) [36].

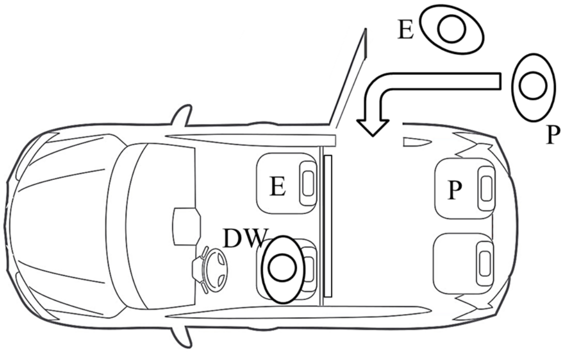


Fig. 5. The seating arrangement of the driving wizard (DW), the experimenter (E), and the participant (P), including the entering the vehicle procedure.

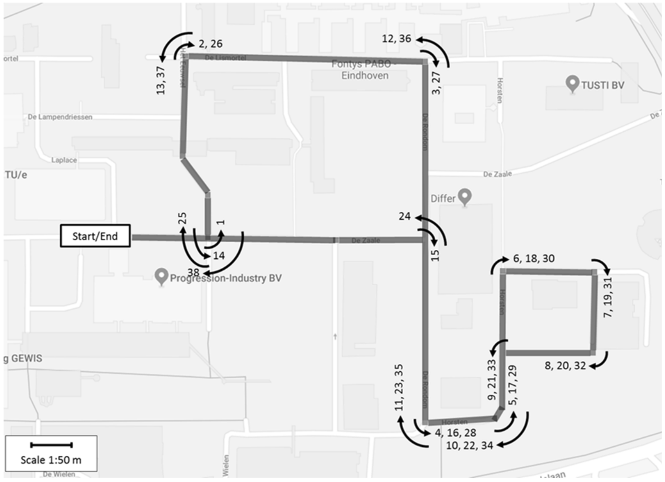


Fig. 6. The designated route. The numbers at the arrows represent the sequence of the corners starting from 1 to 38.

III. Results and Discussion

A. Evaluation of the Test Rides

For the ADTQ, one-way repeated measures ANOVA analysis was conducted to determine if there were statistically significant differences in the quality of the test rides experienced by the participants across the three conditions (see Table I). It was found that there was a statistically significant difference in the test ride quality across the conditions ($F_{2,34} = 3.704$, $p = 0.035$, $\eta^2 = 0.179$).

TABLE I

DESCRIPTIVE STATISTICS OF THE MEASURE OF THE ADTQ

Conditions	*n*	ADTQ Score	
		M	*SD*
Control	18	6.8	1.4
Visual	18	7.2	1.6
Haptic	18	7.8	1.7

Note:
The rating is a 10-point scale, 1 = very unrealistic, 10 = very realistic.

However, further posthoc analysis using a paired samples t-test with a Bonferroni adjustment revealed no statistically significant difference between any of the two paired conditions.

Participants were consistent in rating the automated driving using the 10 points rating scale. Although the ADTQ results showed a statistically significant difference between the three conditions, the differences between the means of the scores in each condition were modest. Furthermore, the average scores of 6.8 (out of 10) and higher indicated that the participants in this experiment also were optimistic about the defensive driving style as the fully automated driving style. This result was similar to the previous studies [26], [27]. However, these findings should be treated with caution since none of the participants had experience riding in a FAV prior to the experiment.

B. Situation Awareness and Mental Workload Assessment

There was one outlier in the understanding-construct for the haptic condition. However, this outlier was kept in the analysis because it was considered genuine data. In addition, all data were normally distributed. Hence, paired-samples t-tests were performed to determine if there were statistically significant decreases in the mental workload and statistically significant increases in the experienced SA between the control condition and the conditions with the peripheral information systems (see Table II and Table III).

A statistically significant decrease was found in the mental workload score (RSME) with the HPIS but not with the VPIS. Power analysis with a probability of making a type II error ($\beta = 20\%$) was conducted with a large effect size (r = 0.5) to determine the smallest sample size suitable to detect the effect at the desired level of significance, which means that the observed differences would be significant with a sample size of at least 207.

TABLE II

DESCRIPTIVE STATISTICS OF THE SITUATION AWARENESS (SART) AND MENTAL WORKLOAD (RSME) DATA

Parameters	Conditions	*n*	*M*	*SD*
RSME	Control	18	77.9	34.3
	Visual	18	72.7	22.3
	Haptic	18	62.1	27.8
SART-D (Demand)	Control	18	11.0	4.5
	Visual	18	8.0	3.5
	Haptic	18	6.7	2.2
SART-S (Supply)	Control	18	13.5	2.9
	Visual	18	14.2	2.6
	Haptic	18	16.6	2.3
SART-U[!] (Understanding)	Control	18	10.2	3.7
	Visual	18	11.2	2.1
	Haptic	18	11.7	2.8
SART-Total	Control	18	12.7	5.9
	Visual	18	17.4	5.2
	Haptic	18	21.6	4.5

Note:
[!] Including one outlier
RSME scale ranging from 0 (no mental workload) to 150 (highest mental workload).
SART-D and SART-U = ranging from 3 (lowest) to 21 (highest).
SART-S = ranging from 4 (lowest) to 28(highest).
SART-Total = U-(D-S), ranging from -14 (lowest SA) to +46 (highest SA).

TABLE III

PAIRED SAMPLES T-TEST ON THE SITUATION AWARENESS (SART) AND MENTAL WORKLOAD (RSME) DATA

Parameter	Group	Paired Differences				*t*	*df*	p-value (one-tailed)
		M	SD	95% CI of Difference				
				Lower	*Upper*			
RSME	Control Visual	-5.2	28.8	-9.1	19.5	0.770	17	0.452
	Control Haptic	-15.9	35.8	-1.9	33.7	1.885	17	0.077*
SART-D	Control Visual	-3.0	4.8	0.6	5.4	2.657	17	0.017*
	Control Haptic	-4.3	5.2	1.8	6.9	3.565	17	0.002*
SART-S	Control Visual	0.7	3.6	-2.5	1.1	-0.841	17	0.412
	Control Haptic	3.1	3.3	-4.7	-1.4	-3.952	17	0.001*
SART-U[!]	Control Visual	1.0	3.1	-2.6	0.6	-1.350	17	0.195
	Control Haptic	1.4	4.7	-3.8	0.9	-1.302	17	0.210
SART-Total	Control Visual	4.7	6.9	-8.2	-1.3	-2.907	17	0.010*
	Control Haptic	8.8	7.1	-12.3	-5.3	-5.298	17	0.001*

Note:
** Indicates significance, $p < 0.10$*
[!] Including one outlier

In terms of the total score of SART, it was found that the conditions with the peripheral information systems (the visual- and the haptic-condition) were rated significantly better by the participants compared to the condition without the peripheral information system (control-condition). For the demand-construct of SART, it was found that the participants experienced statistically significant lower "demand" with the peripheral information systems compared to the control condition. For the supply-construct of SART, only the haptic condition resulted in a statistically significant increase in providing information to the participants. Regarding the t-test for the visual condition vs the control condition, a power analysis was conducted to evaluate the probability of making a type II error ($\beta = 20\%$) with a large effect size (r = 0.5) for the supply-construct. The total sample size needed for this paired samples t-test was found to be 93. For the understanding-construct of SART, there was no statistically significant difference found between conditions with and without the peripheral information systems. Power analyses were conducted to evaluate the probability of making a type II error ($\beta = 20\%$) with a large effect size ($r = 0.5$). The observed differences would be significant with a sample size of at least 53 (between the control and visual condition) and 29 (between the control- and the haptic condition), respectively.

In general, participants' SA level was higher with peripheral information than without any given information based on SART scores. However, there were no statistically significant differences between the three conditions for the understanding-construct. This result reveals that the SA level increase in the visual and haptic conditions was not due to better understanding prompted by the prototypes (VPIS and HPIS). One of the reasons could be that participants had to concentrate more on the situation in the control condition compared to the visual and haptic conditions. This interpretation is supported by the demand-construct results that showed statistically significant decreases from the control condition to the visual- and haptic-condition. This finding suggests that less attention is needed to the peripheral information systems when there are sudden changes in car motions.

The finding for the demand-construct is also in line with the supply-construct results. This construct represents the quality and quantity of the information. However, only the HPIS was found to have a significantly higher quality and quantity of information than the control condition. One possible explanation is that the relevant navigational information is first presented at the wrist, followed by the flap motions adjusting the participants' body to counteract the centrifugal force. Digesting the relevant information from the light movement generated by the VPIS and anticipating how to adjust one's body to counteract the centrifugal might be more challenging. However, in a previous study by [15], the peripheral visual feedforward system (PVFS) produced a statistically significant increase for the supply-construct compared to the control condition. The PVFS in that study was designed to provide peripheral information about the FAV's upcoming actions while the occupants watched a video, and the PVFS was mounted at the left and right sides of the TV. Possibly, the type of NDRT and the differences in prototype placement affect the effectiveness of the visual prototype. Finally, this interpretation is also supported by the RSME findings, showing that the haptic-condition mental effort was statistically significantly lower than the control condition.

C. Viewing Behaviour and Reading Task Assessment

There were no outliers in both viewing behaviour (VB) and reading performance (RP) data. For VB, data were not normally distributed, while for RP, data were normally distributed. Hence, paired-samples t-tests and Wilcoxon signed-rank tests were performed to determine statistically significant increases in the viewing behaviour and the participants' reading performance between the control condition and the conditions with the peripheral information systems (Table IV, Table V, and Table VI).

TABLE IV

DESCRIPTIVE STATISTICS OF THE VB AND RP DATA

Parameters	Conditions	*n*	*M*	*SD*
[1]Viewing behaviour (%)	Control	18	71.8	25.4
	Visual	18	74.1	24.3
	Haptic	18	79.0	23.9
[2]Reading performance	Control	18	5.9	2.7
	Visual	18	6.1	3.1
	Haptic	18	6.9	3.2
	[3]With Text	14	8.7	1.6
	[3]Without Text	14	5.5	1.4

Note:

[1] *Viewing behaviour ranges from 0.0 % (not looking at the tablet) to 100.0 % (looking at the tablet).*

[2] *Reading performance is a 10-point scale, 1 = cannot read, 10 = fully understand the text.*

[3] *Tested in a room with another 14 participants*

TABLE V

WILCOXON SIGN-RANK TEST ON THE VB DATA

Group	Median	*IQR*	*z*	Effect size (r)	p-value (one-tailed)
Control Visual	79.09 81.72	47.62 - 98.75 54.39 - 95.03	-0.719	0.120	0.472
Control Haptic	79.09 86.40	47.62 - 98.75 67.77 - 95.23	-1.590	0.265	0.112

TABLE VI

PAIRED SAMPLES T-TEST ON THE RP DATA

Group	Paired Differences				*t*	*df*	p-value (one-tailed)
	M	SD	95% CI of Difference				
			Lower	*Upper*			
Control Visual	-0.1	2.8	-1.5	1.3	-0.169	17	0.868
Control Haptic	-0.9	2.8	-2.3	0.4	-1.433	17	0.170

The VB assessment investigated how long the participants looked at the reading display during the fully automated driving (Stage 3 in Fig. 4). Pairwise comparisons indicated that differences in viewing behaviour between control and visual and between control and haptic were not significant ($p > .05$). Power analyses with a probability of making a type II error ($\beta = 20\%$) with a large effect size ($r = 0.5$) were conducted, and the observed differences would be significant with a sample size of at least 678 for the control-visual paired conditions and 140 for the control-haptic paired conditions, respectively.

The RP was measured to assess the participants' reading comprehension in the different conditions. Differences in reading performance between control and visual and between control and haptic were not significant. As can be seen from Table IV, reading performance in all test conditions was comparable to chance level (reading performance without text). Possibly, the mental workload is higher when reading inside a vehicle than reading in a room, affecting reading comprehension. Power analyses with a probability of making a type II error ($\beta = 20\%$) with a large effect size (r = 0.5) were conducted, and the total sample sizes needed for these paired samples t-tests would be significant were found to be 3615 for the control-visual paired conditions and 62 for the control-haptic paired conditions.

Based on the finding of these power analyses, the study setup is not sensitive enough to compare between the control and the visual condition and to compare between the haptic condition of VB and RB results.

IV. CONCLUSION

In this study, two peripheral information systems that involved the visual (VPIS) and haptic (HPIS) modalities were tested to evaluate their effects on situation awareness (SA), mental workload, viewing behaviour, and reading performance. The study was conducted when engaging in a non-driving related task (NDRT), reading, in a fully automated vehicle (FAV). The results were mixed. The finding was that both peripheral information systems were effective in enhancing SA. The mental workload was found to decrease only for HPIS. There was no evidence that the peripheral information systems positively affected reading performance compared to the control condition.

While most existing studies evaluated the application of the auditory and visual modalities as peripheral displays, the current study indicates that the haptic modality may be a good choice to provide information about driving to occupants of a FAV in silent and private ways.

Building good situational awareness is expected to increase the ride comfort of the FAV users. According to [6], knowing what is happening in a particular situation can lessen motion sickness symptoms while riding in a FAV. The current study indicates that peripheral displays may enable occupants of FAVs to collect the situational information that contributes to feeling comfortable while engaging in NDRTs. Hence, other than FAV technology itself, car manufacturers should consider increasing users' SA when designing the vehicle's interior to enable the passengers to engage in NDRTs.

Compared to any fixed-based simulator, the Mobility Lab is a test platform designed to be used in a real-road environment. Although the designated driving styles can be executed with the help of the Automatic Acceleration and Data controller (AUTOAccD), some of the road conditions and environments were beyond the driving wizard's control. For example, an unexpected pedestrian crossing the road could force the driving wizard to slow down or stop the Mobility Lab during the test. While the prototype information systems conveyed information about lateral manoeuvres, their effectiveness for conveying information about longitudinal manoeuvres, which may be harder to predict, still needs to be established.

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The authors declare that the contents of this article have not been published previously. They have contributed to the work described, read, and approved for publication in this journal. They have also been certified by their respective organizations for human subject research. This research is compliant with the Netherlands Code of Conduct for Scientific Practice.

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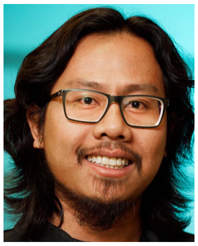

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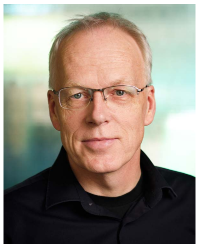

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