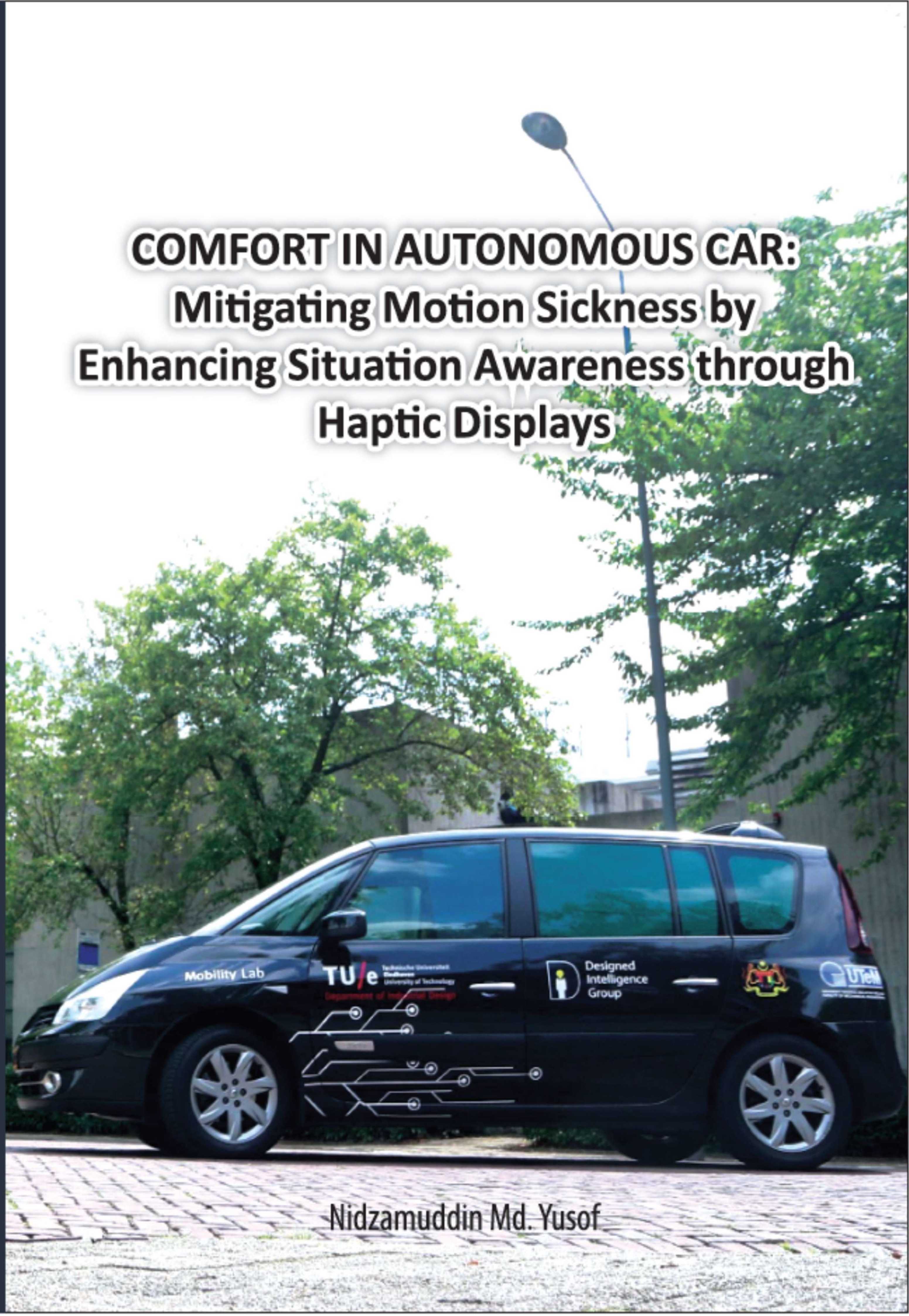
COMFORT IN AUTONOMOUS CAR: Mitigating Motion Sickness by Enhancing Situation Awareness through Haptic Displays



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MINISTRY OF EDUCATION MALAYSIA

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PROEFSCHRIFT

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door

Nidzamuddin bin Md. Yusof

geboren te Johor, Maleisië

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Lists of Abbreviations

ADAS	Advanced driver assistance system
AUTOAccD	Automatic Acceleration and Data controller
BPM	Beats per minute
CI	Confidence interval
DAQ	Data acquisition
DBI	Driving behaviour inventory
DSQ	Driving style questionnaire
ECG	Electrocardiography
EGG	Electrogastrography
FFT	Fast Fourier transform
GIF	Gravito-inertial force
GPS	Global positioning system
GSR	Galvanic skin response
HF	High-frequency
HRV	Heart rate variability
ImpSS	Impulsive sensation seeking
IQR	Interquartile range
JND	Just noticeable difference
LED	Light-emitting diode
LF	Low frequency
LRT	Light rail transit
MDSI	Multidimensional driving style inventory
MEMS	Micro-electro-mechanical systems
MPV	Multi-purpose vehicle
MSAQ	Motion sickness assessment questionnaire
MSDV	Motion sickness dose value
MSI	Motion sickness incidence
MSQ	Pensacola motion sickness questionnaire
MSSQ	Motion sickness susceptibility questionnaire
OBD-II	On-board diagnostic type II
PDI	Pensacola diagnostic index
pNN50	Percentage of successive normal sinus RR-intervals more than 50 ms
POI	Points of interest
PPG	Photoplethysmography
PSD	Power spectral density

r.m.s	Root mean square
RMSSD	Root-mean-square of successive differences
RTH	Risk homeostasis theory
SAGAT	Situation awareness global assessment technique
SART	Situational awareness rating techniques
SASHA	Situation awareness for solutions for human-automation partnerships in the European air traffic management system
SSQ	Simulator sickness questionnaire
SSS-V	Form V of the sensation seeking scale
SWORD	Situation awareness subjective workload dominance
TU/e	Eindhoven University of Technology
VLF	Very-low-frequency
ZKPQ	Zuckerman-Kuhlman personality questionnaire

Chapter 1. Introduction

The rapid development of current technologies, especially in the area of Advanced Driver Assistance Systems (ADAS), will make an autonomous vehicle a reality in the future. The benefits of the autonomous vehicle are potentially significant. In addition to greater safety and efficiency on the road, the autonomous vehicle is capable of driving by itself and perform all driving-related tasks. Thus, its users can comfortably shift their focus to other tasks to be more productive during a journey such as working on a laptop, watching a video or just relaxing while enjoying the scenery of the route. However, such tasks/activities usually will require the autonomous vehicle users' focus off the road, which leads to an inability to predict the future path of the vehicle. As a result, they might feel uncomfortable when getting motion sickness symptoms while riding in an autonomous vehicle (Diels, 2014).

One of the reasons is that the users may have a low situation awareness of what will happen in the immediate future. Although situation awareness, in lower levels of the level of automation from the Society of Automotive Engineers (SAE, 2016), is crucially important to keep the users in the control loop of driving tasks, situation awareness at a higher level of automation (i.e. in an autonomous vehicle) is also vital to the users (Terken et al., 2017), especially on the manoeuvring behaviour of the autonomous vehicle when they are engaging in non-driving related tasks (Diels & Bos, 2016). The users who are focusing on non-driving related tasks may be exposed to acceleration forces that exert on the body by unexpected manoeuvers such as accelerating, braking or cornering of the autonomous vehicle. Repetition of this situation, especially at low frequencies (below 0.5 Hz), can induce motion sickness (Griffin & Newman, 2004a; Turner & Griffin, 1999b).

Currently, passengers are regularly looking outside of the window at the horizon for a few minutes before continuing the non-driving related tasks to anticipate the vehicle's trajectory. Visual information about an artificial earth-reference has been shown to increase anticipation and reduce carsickness (Bos, Houben, & Lindenberg, 2012; Tal et al., 2012). Furthermore, building situation awareness (by looking outside of the vehicle to gain information of the surrounding) is a coping mechanism that passengers normally apply to prevent motion sickness (Terken et al., 2017). Hence, even though the users of an autonomous vehicle might have the luxury of not manually driving the vehicle, the non-driving related tasks will be interrupted to gain situational awareness.

In this study, we explore ways to increase situation awareness regarding the immediate future manoeuvre of the autonomous vehicle while performing non-driving related task, and its effect in mitigating motion sickness. Based on literature reviews, an ambient display with haptics as a means was selected in providing necessary information peripherally.

1.1. Purpose of this study

The goal of this study is:

> *To mitigate motion sickness by enhancing the situation awareness of the autonomous vehicle users while engaging in non-driving related tasks.*

In this dissertation, we aim to improve riding comfort conditions of the autonomous vehicles. In regard to our motivation, enhancing situation awareness and mitigating motion sickness, we propose two main research questions that address our goal:

a) *Do information displays help to enhance situation awareness while engaging in non-driving related tasks?*

   A wide range of applications that deliver information in a peripheral manner is being explored by designers or researches (Pousman & Stasko, 2006). In driving contexts with a conventional vehicle, most of the conveyed information is related to either warning signals, spatial information or navigation tools for a driver. However, there is no information regarding the manoeuvre intention of the vehicle for a passenger as the driver is the one who is controlling the manoeuvers. In addition, the driver already has a good situation awareness as he/she is required to focus on the road for the whole journey. Hence, the driver can easily predict what will happen in the immediate future, and can easily perform a suitable immediate reaction.

   With autonomous vehicles, an active driver will turn into a passive driver or a passenger. The passenger is not required to focus on the road and can shift his/her attention to non-driving tasks. This situation leads to a lower situation awareness of the passenger compared to an active driver. A lower situation awareness before receiving any manoeuvring information of an autonomous vehicle from an information display can lead the passenger in confusion about the information. Furthermore, performing parallel processing of information is expected to increase the user's cognitive load. Thus, we further specified this main research question into two research sub-questions:

   i. How to convey the manoeuvring information to the users?
   ii. Does the information display affect the non-driving related task performance?

b) *Does increasing the situation awareness help to mitigate motion sickness in an autonomous vehicle?*

   Studies already found that exposing to low-frequency motions can induce motion sickness. In addition, a mismatch between visual, vestibular and somatosensory information can also lead to motion sickness symptoms (Reason & Brand, 1975). Therefore, the general idea of this study was to provide information concerning the immediate motion changes that will induce acceleration forces to the users, so that the users can prepare themselves to react to that motion appropriately.

However, how autonomous vehicles should behave on the road is still under discussion of the researchers (e.g. Meder, Fleischhut, Krumnau, & Waldmann, 2018). Moreover, engaging in a different type of non-driving task can lead to different severity of experienced motion sickness (e.g. Isu, Hasegawa, Takeuchi, & Morimoto, 2014). Thus, certain autonomous driving styles (that are based on acceleration forces) and the type of non-driving related tasks need to be specified first before answering the research question.

1.2. Research Approach

Autonomous vehicles are currently not available to consumers, and thus, almost no one has any real experience riding in it. Many studies use a driving simulator to study the autonomous vehicle riding experience. However, a study that involves physical comfort experiences, related to experiencing acceleration forces in a vehicle, requires at least a moveable-base driving simulator system. Each type of driving simulator is developed only for certain requirements and ignores other aspects of reality, which may affect the results (Reymond & Kemeny, 2000). Hence, a good test platform is needed for us to have a realistic data collection from a high ecological validity study. This brings us to a methodological research question:

c) *How to conduct our study in a real-world environment?*

Furthermore, the autonomous vehicles are not yet available yet in the market, and the technology itself is still in the development stage (Vincent, 2018). Therefore, the future users of an autonomous vehicle have not yet experienced being driven autonomously. It was argued that an autonomous vehicle should behave in an optimized manner that promotes safe, reliable and comfortable driving (KPMG, 2015). Conversely, drivers drive their cars based on emotions and motivations (Summala, 2007; Vaa, 2007). Hence, identifying people's preferred driving styles is important. As was highlighted in the previous paragraph, most researchers used a driving simulator to study automated driving, so that they managed to maintain the consistency in their experiments, although the driving simulator lacks the inertial forces experienced in real roads driving (Baltodano, Sibi, Martelaro, Gowda, & Ju, 2015). Thus, we further specified this main methodological research question into two research sub-questions:

i. What is the predicted and preferred driving style of an autonomous vehicle?
ii. How to maintain consistency of the conducted experiment in this study?

1.3. Structure of the Dissertation

The remainder of this dissertation is comprised of six further chapters as summarised below:

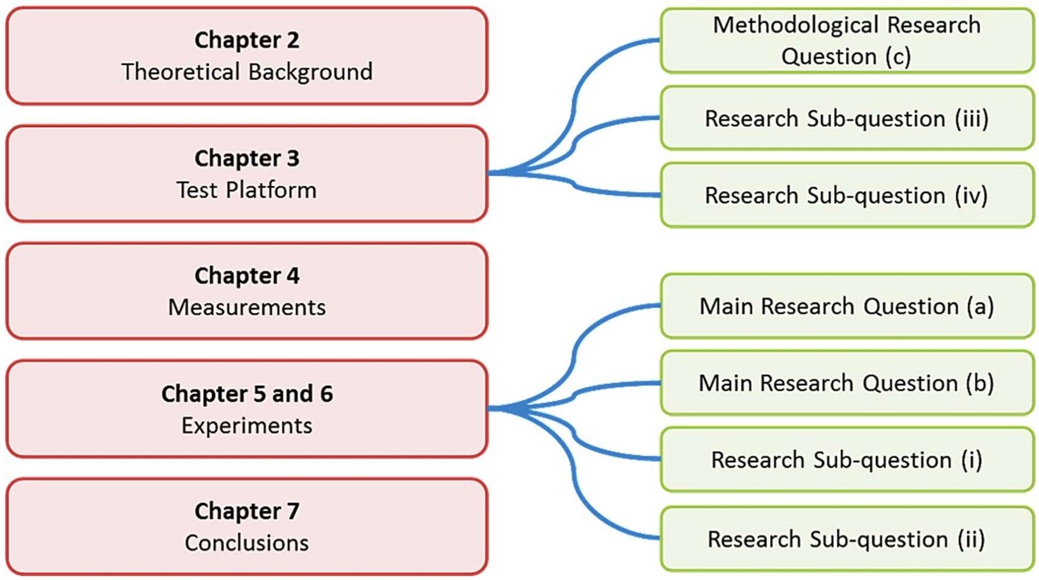


Figure 1-1: Relationship of Dissertation Structure to Research Questions

Chapter 2: This chapter aims to establish the theoretical basis of our study. First, we explain the autonomous vehicle in general. Next, we discuss the problem of motion sickness that may arise when users engage in non-driving related activities inside the autonomous vehicle. We explain the theories behind motion sickness, especially related to how users are getting motion sickness inside the vehicle, including motion sickness dosage. Then, we show possible solutions to mitigate motion sickness by enhancing situation awareness in vehicles through an ambient information system. We propose haptic cues as one of the modalities to increase situation awareness. In the end, we discuss possible implementations of haptic cues in an autonomous vehicle.

Chapter 3: In this chapter, we present the design and development of the test platform to be used for our study. First, we discuss the type of driving styles that human drivers normally exhibit and explain how these driving styles can be related to autonomous driving styles. Secondly, we introduce an overview of our test platform, including an explanation of the system architecture and its functions. At the end of this chapter, we evaluate our test platform with designated autonomous driving style on the real road.

Chapter 4: This chapter highlights three types of measurement that were used in the two experiments (Chapter 5 and 6). The first type of measurement consists of measurements to evaluate the consistency of the experimental manipulations. The second type of measurement consists of the participant measurements that assess the effect of haptic cues on the users by evaluating their motion sickness and situation awareness levels. The third type of measurement is the prototype measurement that evaluates the interaction between the participants and the haptic cues prototype.

Chapter 5 and 6: These two chapters focus on two experiments that attempt to enhance situation awareness by means of haptic cues. The first experiment (Chapter 5) involves a vibrotactile display that was designed, to be used on the forearm, to provide information about the vehicle's immediate manoeuvre (turning to the left or the right). Watching a video was selected as the non-driving related task in this experiment. The second experiment (Chapter 6) involves an iteration of the vibrotactile display with an extension of movable plates that actively move or push the users' upper body to the sides when the vehicle is turning to any direction, either to the left or the right. Reading from a tablet was selected as the non-driving related task in this experiment.

Chapter 7: At the end of this dissertation, we concluded the contributions to our study. First, we contribute to the definition of preferred autonomous driving style in terms of accelerations. Next, we contribute an alternative to consistently simulate autonomous driving style, on the real road, by developing our own test platform. Then, we contribute an exploration of how to mitigate motion sickness while engaging in non-driving related tasks. On the basis of the results of this research, it can be concluded that the haptic cue alone is effective to enhance the situation awareness level but not sufficient to reduce motion sickness symptoms. Although the motion sickness level is indeed lower with the implementation of the active mechanism, no statistically significant difference was found in terms of physiological parameters. Finally, we include the limitations of the current study and provide options for future work.

Chapter 2. Theoretical Background

2.1. Introduction

In this chapter, we describe six core elements that form the theoretical basis of our study (Figure 2-1). First, we explain the autonomous vehicle in general, including automation and the benefits of the autonomous vehicle, and activities inside the autonomous vehicle. Next, we discuss the problem of motion sickness that may arise when occupants engage in non-driving related activities inside the autonomous vehicle. We explain the theories behind motion sickness, how people are getting motion sickness inside the vehicle, and the calculation of the motion sickness dose value. Then, we show possible solutions to mitigate motion sickness by enhancing situation awareness in vehicles through an ambient information system. We propose haptic cues as a modality for increasing situation awareness. In the end, we discuss possible implementations of haptic cues in an autonomous vehicle.

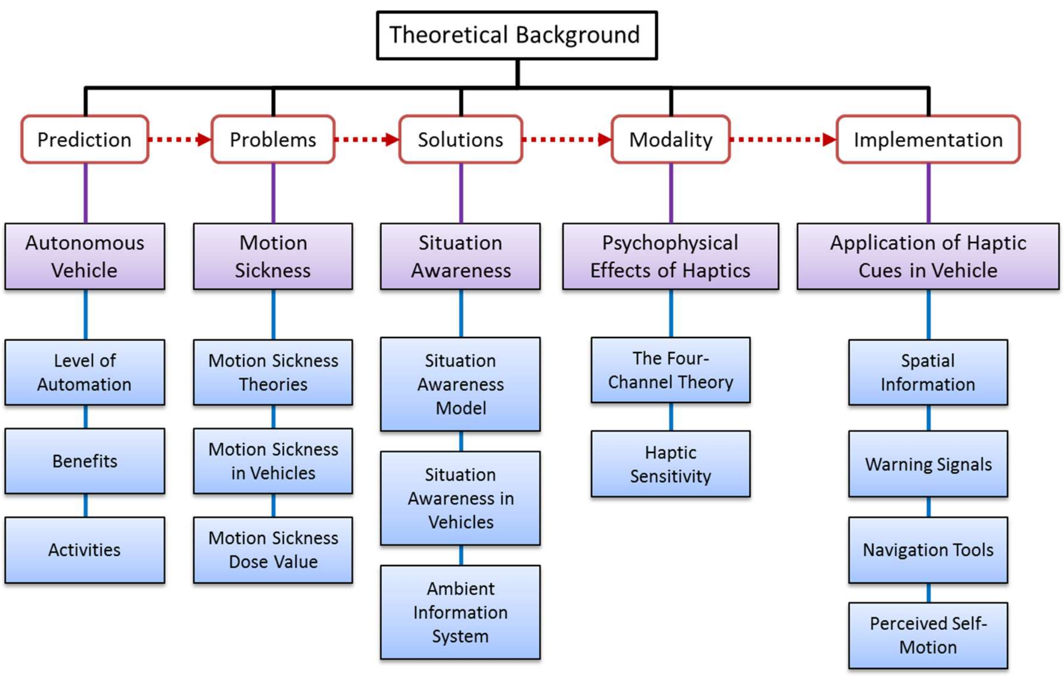


Figure 2-1: Six core elements of the theoretical background

2.2. Autonomous Vehicle

The vision of autonomous vehicles, also called fully-automated, driverless, self-driving or robotic vehicles, arose as early as the 1920s with a dream of a modern freeway system (M. Weber, 2014). The Stanford Cart was the first platform that successfully crossed a room filled with a chair and other obstacles autonomously in about five hours (Moravec, 1983). Around the same time, studies of autonomous technology and transportation became one of the main topics in universities, transportation agencies and automotive companies (Anderson et al., 2014), and the development of autonomous vehicle has progressed at a fast growth rate in recent years (Yang & Coughlin, 2014).

There are many predictions about when the autonomous vehicle will be available for consumers. The chipmaker Nvidia and the automaker Audi have announced at the CES 2017 that by 2020, their autonomous vehicle will be available on the road (Ross, 2017). In 2016, an MIT spin-off technology start-up company planned to deploy autonomous taxis commercially in Singapore by 2018 (Brown, 2016). At the 2016 New York International Auto Show in Manhattan, the automaker Ford announced to offer autonomous vehicles for commercial ride-sharing in 2021. The autonomous vehicle which does not have a steering wheel or pedals will only be available for consumers in 2025 or later (Sage & Lienert, 2016). The expert members of IEEE have concluded that the most practical form of intelligent transportation is the autonomous vehicle for which they anticipated that in the year 2040 autonomous vehicles would account up to 75 % of all vehicles (IEEE, 2012).

2.2.1. Level of automation

The difference between an autonomous vehicle and a conventional vehicle can be described in connection with the levels of control involved in the driving task. Michon (1985) defined these levels as strategic, tactical and operational levels. The strategic level is about the overall planning of a trip from one point to another including selections of the route and preferred arrival time. The tactical level is about the manoeuvring of the vehicle such as avoiding obstacles on the road or overtaking other vehicles. The operational level concerns how a driver is controlling the manoeuvers, for example, accelerating and braking. In an autonomous vehicle, the driver probably just needs to key in journey information at the strategic level, such as that the driver wants to arrive at a specific location in the shortest time. Then, the autonomous vehicle will take care of the other two levels of driving for the whole journey.

In addition, how the autonomous vehicle works is also based on the existing taxonomies of the levels of automation. According to the National Highway Traffic Safety Administration (NHTSA, 2013) and *Die Bundesanstalt für Straßenwesen* (BASt) of the German Federal Highway Institute (Gasser & Westhoff, 2012) taxonomies, there are five levels of automation whereas Society of Automotive Engineers (SAE, 2016) taxonomy, which is now the most commonly used in defining levels of automation, defined the levels of automation in six levels (Figure 2-2).

At the lowest level of automation (no automation, driver only, or level 0), the driver is responsible for all driving tasks without help from any advanced driver assistance systems (ADAS). At the second level (driver assistance, partially automated, or level 1), only one ADAS is activated at a time to assist either the steering or accelerating/decelerating tasks such as the adaptive cruise control or the lane keeping system. At the third level (partial automation, partially automated, or level 2), two ADAS can be activated to control both the steering and accelerating/ decelerating tasks. For example, the combination of adaptive cruise control and the lane keeping system releases the driver from the operational component of the driving task, but he/she is required to monitor the environment of the trip constantly. At the fourth level (conditional automation, highly automated, or level 3), the system can take over all driving tasks in a controlled environment such as on a highway. The driver will become the passenger without having to monitor the road but is expected to take over control when requested. For example, when the system is not capable of performing the driving tasks in an uncontrolled environment such as in heavy snow. At the fifth level (high automation, fully automated, or level 4) or at the highest level (full automation or level 5), the autonomous vehicle will drive by itself and perform all driving tasks. The role of the driver is changing into a passive driver or a passenger inside autonomous vehicles. The passenger does not have to respond appropriately to the system if requested.

Name	SAE Level	BASt Level	NHTSA Level	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	System capability (driving modes)
No Automation	0	Driver only	0	Human driver	Human driver	Human driver	n/a
Driver Assistance	1	Assisted	1	Human driver and system	Human driver	Human driver	Some driving modes
Partial Automation	2	Partially automated	2	System	Human driver	Human driver	Some driving modes
Conditional Automation	3	Highly automated	3	System	System	Human driver	Some driving modes
High Automation	4	Fully automated	3/4	System	System	System	Some driving modes
Full Automation	5	n/a		System	System	System	All driving modes

Figure 2-2: Summary of Levels of Driving Automation for On-Road Vehicles. (Adapted from Smith, 2013)

2.2.2. Benefits of Autonomous Vehicle

The benefits of the autonomous vehicle are potentially significant. One of the benefits of implementing the autonomous vehicle on the road is increased safety. According to NHTSA (2008), 90 % of accidents are caused by driver error. With the potential for driver error removed, the autonomous vehicle is expected to reduce instances of accidents caused by driver error such as distracted or fatigued drivers (Fagnant & Kockelman, 2015).

In addition, the autonomous vehicle is predicted to provide a greater efficiency on the road. Since an autonomous vehicle is predicted to provide more safety than a typical vehicle, this can lead to fewer accidents. Thus, it is estimated that congestion caused by traffic accidents can be reduced by up to 25 % (Anderson et al., 2014, p. 23). Furthermore, the sensory technology used inside autonomous vehicles could possibly identify the road situation better than human senses and react faster than drivers. This will increase the lane capacity by up to 500 % vehicles per lane per hour due to the expectation that an autonomous vehicle can be operated at higher speeds and closer together with another autonomous vehicle (Anderson et al., 2014, p.21). With the ability to communicate with each other (vehicle-to-vehicle, V2V) and their surroundings (vehicle-to-infrastructure, V2I) and to access real-time data such as live traffic updates and maps, an autonomous vehicle is capable of deciding the fastest, most efficient route possible.

Due to greater efficiency, an autonomous vehicle is likely to consume less fuel especially in terms of truck platooning, where two or more trucks are linked together in convoy by using connectivity technologies to reduce unnecessary stops and slowdowns during travelling. Also, an autonomous vehicle is expected to accelerate and decelerate more smoothly than a driver, and this leads to less fuel consumption between 4 and 10 % (Anderson et al., 2014, p. xvi).

Since an autonomous vehicle will drive by itself and perform all driving tasks, autonomous vehicle users can shift their focus to other tasks to be more productive during a journey such as working on a laptop, watching a video or just relaxing while enjoying the scenery of the route. Thus, other than the technology of autonomous vehicle itself, the interior design has also been the subject of design by many car manufacturers and designers to enable the passengers to do non-driving related tasks. Mostly, they already showed their autonomous vehicle prototypes to the public at the car show events, reimagining how passengers may actually ride in the cars in future. For example, XchangE (2014) from Rinspeed (Swiss), F015 Luxury in Motion (2015) from Mercedes-Benz (Germany), Tesla Model X, Witstar (2015) from GAC Group (China), Link & Go (2013) from AKKA Technologies (France) and GC-PHEV (2013) from Mitsubishi (Japan). Other companies in the market have also produced several concepts of autonomous vehicles, for instance, Trimaran from Volkswagen (Germany), Nuvu from Nissan (Japan), Boz from Zoux (Australia) and CARPet from Honda (Japan) to support the idea of how passengers want to spend their time inside the autonomous vehicles.

2.2.3. Activities inside Autonomous Vehicle

Since all the driving tasks will be performed by the autonomous vehicle, in a survey from CarInsurance.com (Vallet, 2013), they investigated what the drivers would do with the newly freed time in autonomous vehicles. Based on 2000 respondents, texting or talking with friends was the top desired activity (26 %), followed by "*other*" (21 %, mostly enjoying the scenery or just watching the road) and reading (21 %). On the other hand, watching movies (8 %), playing games (7 %) and working (7 %) were considered less preferred activities in autonomous vehicles.

Schoettle and Sivak (2014) did a survey of the public opinion about autonomous vehicles, and in the survey, they included a question of how people want to spend their time when riding in autonomous vehicles. Based on more than 3200 respondents from China, India, Japan, United States (U.S.), United Kingdom (U.K.) and Australia, they found that in average watching the road (43 %) was the most common response, followed by "*would not ride*" in autonomous vehicles (19 %). Regarding non-driving related activities, texting or talking with friends (11

%), reading (9 %), sleeping (9 %), watching movies (8 %) and working (6 %) were the most preferred non-driving related tasks inside autonomous vehicles.

A survey done by Cyganski, Fraedrich, and Lenz (2015) discovered that when travelling as passengers in a conventional car, observing the trip and route is the main activity in the car (95%), followed by listening to music (80 %, including reading, watching movies or surfing the internet). Around 60 % of the respondents prefer to talk with other passengers or to enjoy the trip and scenery. Less than 10 % of the respondents mentioned working or social networking when travelling by car. When the survey asked about what type of activities respondents would do in autonomous vehicles, enjoying the trip (71 %) and talking to other passengers (68 %) were frequently reported as main activities, followed by social networking (40 %) and surfing the internet (39 %). Around 31 % of respondents decided to watch movies or to work during the trip.

Kyriakidis, Happee, and de Winter (2015) conducted an Internet-based survey of public opinion about partially-, highly- and fully-automated vehicles. Based on 5000 responses across 109 countries, they found that the respondents would prefer to engage more in non-driving related tasks in higher levels of automation. More than half of respondents indicated that listening to a radio is the task which they would engage in when riding in any levels of automation of the vehicles. A little less than half of the respondents prefer to engage in phoning, mailing, eating, interacting with other passengers, and observing the road, while almost 40 % of the respondents pointed out that watching movies, reading and resting are the non-driving related tasks they would do when riding in autonomous vehicles.

Pfleging, Rang, and Broy (2016) have made a more detailed survey of expected activities when riding in autonomous vehicles. They obtained almost a similar result with previous studies in certain activities; the most frequent response was talking with other passengers (90 %), watching out of the window (82 %) and texting messages (71 %). They were followed by surfing the internet (61 %), reading (53 %), social networking (48 %), working (34 %), watching movies (26 %) and playing games (17 %). Other activities such as listening to music, eating and drinking, making phone calls, learn languages and performing activities related to personal hygiene also were reported in their survey. In addition, they found that smartphones (76 %) would be the most used device in autonomous vehicles, followed by the in-vehicle system (IVIS) (61 %), tablets (53 %) and laptop computers (43 %).

2.2.4. Synopsis

In summary, there are clear trends that the higher the level of automation, the more autonomous vehicle users will be engaging in non-driving related tasks. The transformation from active drivers to passive drivers or passengers will allow them to utilise more of their time during the journey to engage in non-driving related tasks. Talking with other passengers or watching the road is the preferable way to spend their time when riding in autonomous vehicles, similar to current situations when riding in lower levels of automation vehicles. Reading, watching movies and surfing the internet are some of the new non-driving related tasks that drivers prefer to do in autonomous vehicles. It should be kept in mind that these findings result from surveys with people who have almost no experience with autonomous driving. However, as highlighted by Diels (2014), autonomous vehicle passengers are likely to suffer from motion sickness because of the transformation from an active driver to a passive driver or a passenger, engaging in non-driving related tasks, and different seat orientations, especially facing backwards or side of the autonomous vehicle.

2.3. Motion Sickness

The first statement about motion sickness was recorded by Hippocrates as "*sailing on the sea shows that motion disorders the body*" (Förstberg, 2000b). Motion sickness can happen in many types of environments, either with motion (e.g. traveling inside vehicle (Förstberg, 2000b; Karlsson & Tjärnbro, 2012; Sivak & Schoettle, 2015)), or without motion (e.g. inside simulator (Karl, Berg, Ruger, & Farber, 2013; Keshavarz & Hecht, 2011) or watching a 3D movie (Obrist, Wurhofer, Meneweger, Grill, & Tscheligi, 2013)). Motion sickness is the uncomfortable feeling that people experience which could lead to symptoms such as dizziness, nausea, sweating, headaches, drowsiness, stomach awareness and vomiting due to disturbance of their sense of balance by constant motion. These symptoms can occur as soon as someone experiences motion or is exposed to a provocative stimulus and these symptoms generally disappear within minutes after exposure (Reason & Brand, 1975), or can last up to hours (Brainard & Gresham, 2014; Howarth & Finch, 1999) or till even days (Benson, 1992).

Different people have different susceptibility to motion sickness. Various factors or variables combined together modulate motion sickness susceptibility such as age and gender, and psychological state (e.g. effect of drugs and mental activity). In general, Reason and Brand (1975) suggested that very young children who are under two years old cannot get any motion sickness, while children under 12 years old are most susceptible to motion sickness. Turner (1999) discovered that age around 9 to 10 years old has peak susceptibility to motion sickness and that motion sickness susceptibility declines after 12 years old. However, some individuals may have a higher susceptibility in older age (Golding, 2006a). Furthermore, women have also been found to be more susceptible to motion sickness than men (Paillard et al., 2013; Turner & Griffin, 1999a) and a study by Javid and Naylor (1999) also confirmed that female animals have the same characteristics. Matchock et al. (2008) conclude that the instability of estrogen (a hormone that occurs naturally in women and plays an important role in the development of the female characteristics of a woman's body; Learner's Dictionary, 2015) levels during menstruation and pregnancy period may influence the susceptibility to motion sickness. Some prescriptions for the medication (antibiotics or medications related to the menstrual period) can worsen the symptoms of motion sickness. On the other hand, Zhang et al. (2015) reviewed that many types of drugs are used to alleviate motion sickness symptoms. In other aspects, the state of mental activity can affect the susceptibility to motion sickness. Migraine and anxiety are found as conditions that are commonly related to motion sickness symptom (dizziness and balance disorder) (Furman, Balaban, Jacob, & Marcus, 2005).

Overall, the motion environment is the key point that can provoke motion sickness. Regardless of any motion environments (either one is moving or being moved), Griffin (1990, p. 272) pointed out that the awareness of motion depends on three human senses; visual system, vestibular system and somatosensory system.

The visual system is based on the rate and the direction of the observer's sight through the surroundings, creating an optic flow. Gibson (1950) was the first who explained the concept of optic flow in detail. He described that when we are moving forward towards the point of aim, we see an expanding gradient motion of visual information moving away from the focus of expansion (Figure 2-3). This optic flow is important to create the perception of self-motion, including speed, travelled distance and direction, either translational or rotational.

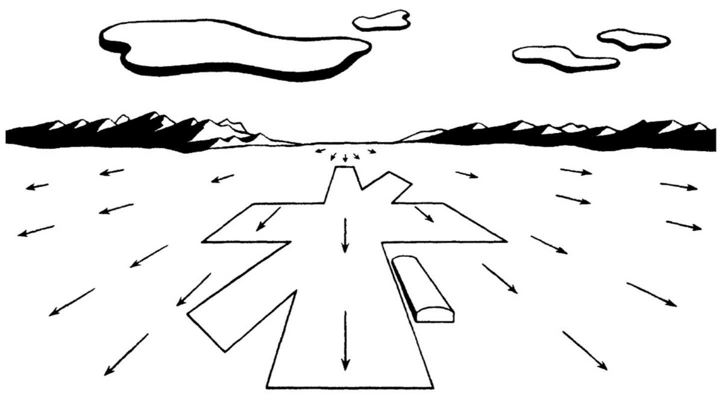


Figure 2-3: Motion perspective in the visual field ahead (Source: Gibson, 1950, p. 121)

The vestibular system consists of otoliths and three semicircular canals systems located inside the inner ear (Hawkins, 2017). The functions of both systems are to maintain the balance (posture and equilibrium) and stabilize the eyes relative to the surroundings. The otolith system consists of two sacs called utricle and saccule (see Figure 2-4). Inside of the sacs is a sensory cell called macula, sensitive hairs which detect linear acceleration. When there is a translational head movement, the hairs will be deflected and produce certain nerve impulses to the brain, generating a perception of acceleration. In addition, the hairs also are affected by gravity, which can sense head tilting. On the other hand, the almost horizontal canal is a lateral semicircular canal, and another two are the posterior semicircular canal and superior semicircular canal. These semicircular canals are perpendicular to each other. This system produces a perception of angular acceleration which tells us that our head is moving in yaw, roll or pitch direction and not affected by the gravity.

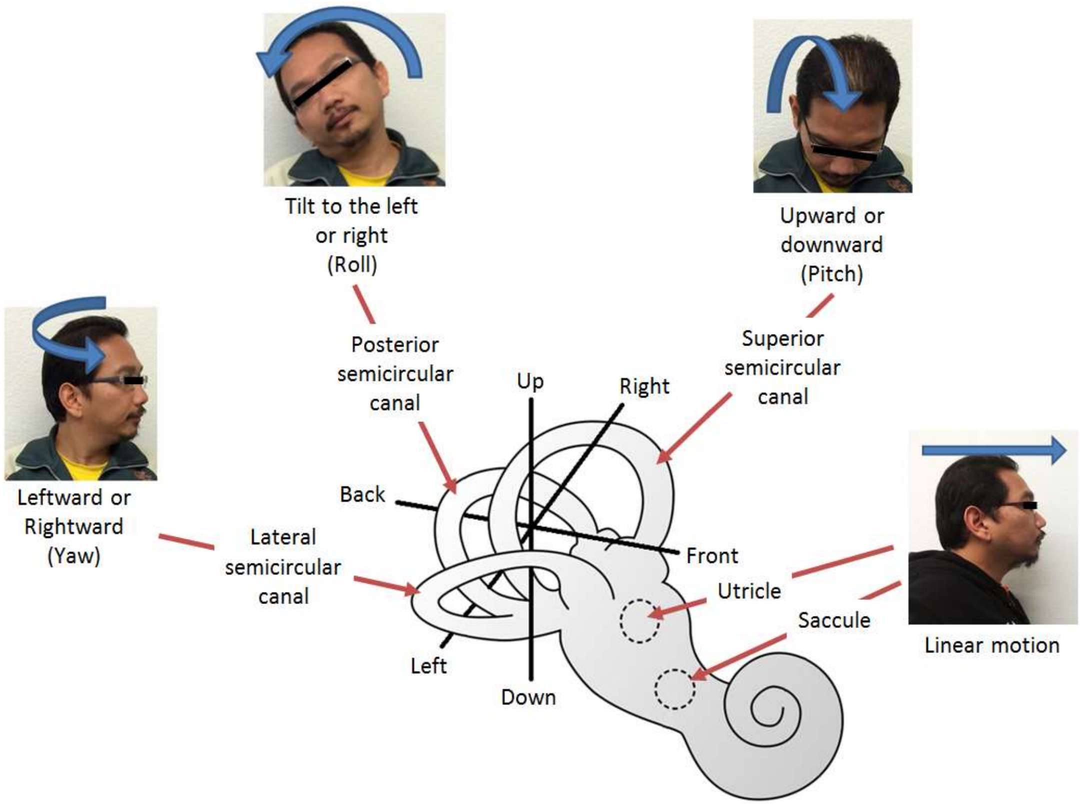


Figure 2-4: The semicircular canals and otolith systems in the inner ear (Adapted from Mouagip, 2011)

The somatosensory system is a system that obtains information, either external or internal, about the condition of the human body such as position and movement of our body parts or temperature of the body (Dougherty, 2012). The senses are mainly divided into three sub-systems; exteroception, proprioception and interoception (Figure 2-5). Exteroception includes the sense of external stimuli or objects that contact with the skin. For instance, the sensations of pressure and vibration (taction), hot and cold (thermoception), and pain (nociception). Interoception contains the sense of internal stimuli and provides information regarding internal organs and overall body condition such as the sensation of the heartbeat. Proprioception involves the sense of balance (one of the vestibular system), and the kinesthetic sense gives information about positions and movements of a body part from receptors in muscles, tendons, and joints. These are the senses that transmit all the information into the central nervous system, where it will be interpreted with the aim of handling the motions.

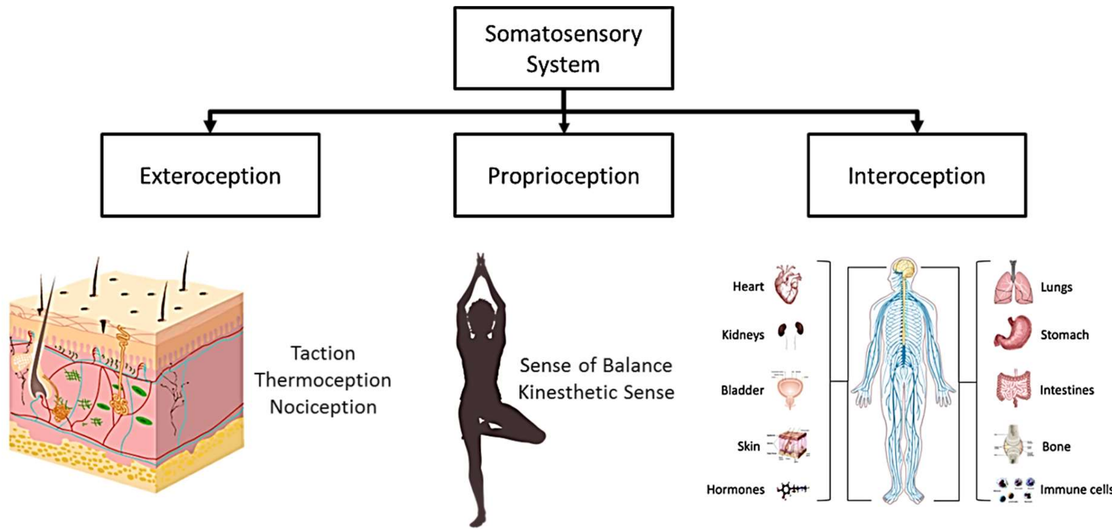


Figure 2-5: Somatosensory System (Source: Galderma, 2016; Hamsmith, n.d.)

2.3.1. Theories of Motion Sickness

The exact cause of motion sickness is still unknown. However, there are two major theories that try to describe how someone might get motion sickness. The theories are the sensory conflict theory and the postural instability theory.

2.3.1.1. Sensory Conflict Theory

The sensory conflict theory is the most prominent theory used to explain motion sickness and was proposed by Reason and Brand (1975). The theory describes that motion sickness results from a mismatch between visual, vestibular and somatosensory information compared to the anticipated and experienced movement, either with or without motion. Two main categories of motion cue mismatch were identified in this theory; (1) the visual-inertial (including both the vestibular and somatosensory senses) mismatch, and (2) the canal-otolith mismatch (when vision is absent) (see Table 2-1). In both categories, two types of mismatch can occur; type 1 mismatch, when both signals are contradictory or unrelated between each other simultaneously, and type 2 mismatch, when only one signal of information is received without the expected input from another system. For example, in a 'with motion' situation, a co-driver in a rally car will have a mismatch between what can be anticipated by the visual system and what actually is being felt by the vestibular and somatosensory systems when he/she is reading a book in the car or sitting in the rear passenger seat (Perrin, Lion, Bosser, Gauchard, & Meistelman, 2013). In a 'without motion' situation such as in fixed-based simulator, the visual system might sense and indicate self-motion of the body. On the other hand, the vestibular and somatosensory systems cannot register the corresponding motion that is typically experienced in the real world (Keshavarz, Riecke, Hettinger, & Campos, 2015). Both situations (with or without motion) may induce motion sickness. However, in a sleeping condition, even in extreme motions, the central nervous system does not analyse any sensory inputs to compare with earlier experienced. Thus no sensory conflict occurs that leads to motion sickness (Karlsson & Tjärnbro, 2012).

Table 2-1: Category of motion cue mismatch

Types of conflict	Categories of motion cue mismatch	
	Visual (A) - Inertial (B)	**Canal (A) - Otolith (B)**
Type 1 A and B simultaneously signal contradictory information	Moving around while wearing an optically distorting apparatus.	Performing a pirouette with a tilted head (Coriolis effect[1])
Type 2 (i) (A) responds without expected (B) signal	Driving a car in a fixed-base simulator with a moving visual display (simulator sickness).	Moving the head in a non-gravity area (space sickness).
Type 2 (ii) (B) responds without expected (A) signal	Reading a book or watching a movie inside a moving car.	Rotating the head about a non-vertical axis.

2.3.1.2. Postural Instability Theory

Riccio and Stoffregen (1991) introduced the postural instability theory, according to which postural instability can lead to developing motion sickness. This theory is the alternative theory to the sensory conflict theory. Compared to the sensory conflict theory which describes motion sickness in a perceptual way at the sensory level, the postural stability theory emphasizes the interaction between perception and action. Riccio and Stoffregen (1991) define postural stability as "*the state in which uncontrolled movements of the perception and action system are minimized*". Postural instability happens when people need to maintain their balance under conditions of modified visual and/or proprioceptive feedback. For instance, standing still and using a head-mounted display with a display virtual sway movement can enhance postural instability (Owen, Leadbetter, & Yardley, 1998). Hence, the cause of motion sickness is the prolonged postural instability, which also precedes the symptom of motion sickness. A study done by Stoffregen et al. (2010) supports this theory when they found that motion sickness symptoms can be significantly reduced by widening the participant's stance inside a moving room (passive stability).

2.3.2. Motion Sickness in Vehicles

Air, sea, and land vehicles are known to be examples of provocative stimuli that can provoke motion sickness (Golding, 2006a). In general, more than 45 % of student aircrew members experience nausea (or air sickness) during training compared to less than 10 % of passengers in civil aircraft (Benson, 1992). Benson (1992) also mentioned that the occurrence of motion

[1] Coriolis effect or cross-coupling effect is the vestibular effect of tilting the head during whole-body rotation (Guedry & Benson, 1978).

sickness on sea vehicles could be between 1 to 100 %, depending on the sea state, vehicle size, and sea-keeping properties. Turner and Griffin (1999) found that 12.8 % of coach passengers experience nausea symptoms during travelling. In addition, the reported illness in their study was three times higher when the view of the road ahead was blocked compared to an unblocked view.

When driving a conventional car, the driver is rarely susceptible to motion sickness although he/she is exposed to the same motion experienced by the passengers. This is because the driver is still in control of the car manoeuvres and can anticipate an immediate movement of the car. Once there is a movement (e.g. the car is turning), a copy of the movement signal called *"efference copy"* will be sent by the central nervous system to simulate the expected result (e.g. expected a feeling of forces), called *"reafference"* (see Figure 2-6) (Reason, 1969). This expected result will be compared with the actual sensed *"reafference"* from the sensory system (actual forces felt) within the internal model of the central nervous system. When a match is detected, the copy is deleted. On the other hand, when a mismatch is detected, further signals are sent back and forth, updating the internal model. The severity of motion sickness depends on the extent of the mismatch between these signals, and those in control of the movement (the drivers) are then less prone to motion sickness compared to passengers.

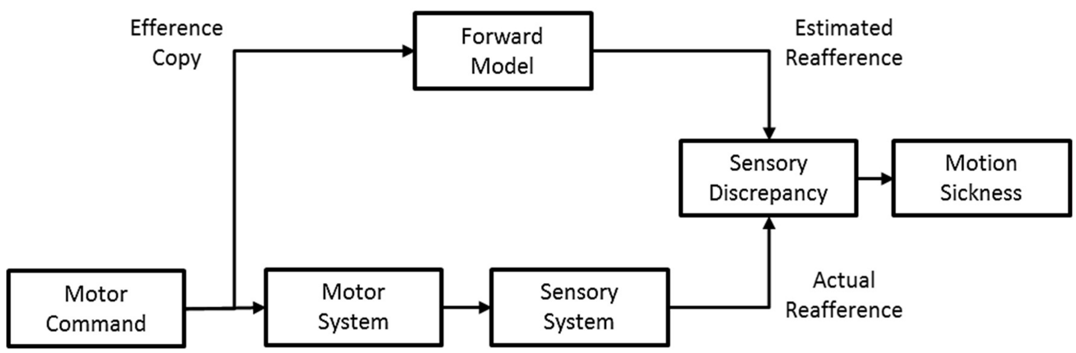


Figure 2-6: Basic internal model. The motor system is a part of the central nervous system involved with body movements

For example, while taking a corner, drivers usually do not just lean but also tilt their head toward the corner centre whereas the passengers' head usually is tilted in the opposite direction (Figure 2-7). This misalignment of head orientation relative to the gravity vector, also called gravito-inertial force (GIF), has been described to also provoke motion sickness (Bles, Bos, de Graaf, Groen, & Wertheim, 1998; Wada, Konno, Fujisawa, & Doi, 2012).

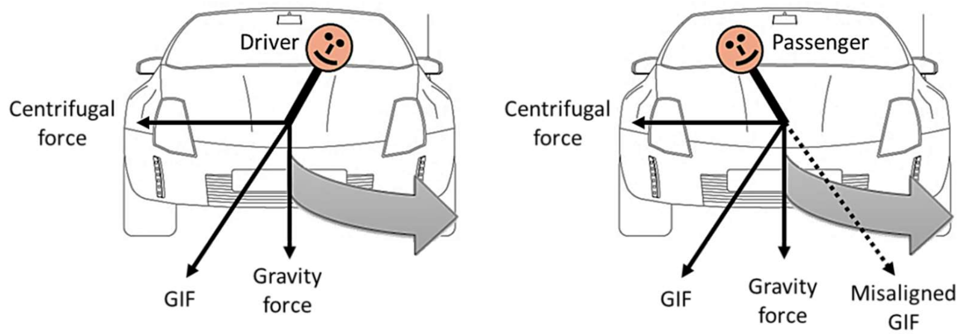


Figure 2-7: Typical head postures of the driver and passenger when taking a corner (Adapted from Wada et al., 2012)

Freedom to engage in non-driving related tasks while travelling is something that is currently being offered by car manufacturers and designers in their future autonomous vehicle concepts. However, these non-driving related tasks (such as reading, watching movies, playing games or working) usually will require passengers' focus off the road, which leads to the type 2 (ii) conflict in the sensory conflict theory, a conflict between vestibular (what passengers feel) and visual (what passengers see) sensors (Sivak & Schoettle, 2015), and also leads to an inability to predict the future path of the car (Diels, 2014). As a result, they might get motion sickness when riding in an autonomous vehicle. One of the coping mechanisms that passengers normally apply when starting to have motion sickness symptoms is looking outside of the window at the horizon for a few minutes before continuing the non-driving related tasks such as reading. This will help to correct the sensory mismatch between vestibular and visual cues. As mentioned by Diels, Bos, Hottelart, and Reilhac (2016), an autonomous vehicle should be designed to allow passengers to anticipate its motion trajectory.

A survey done by (Schoettle & Sivak, 2009) revealed the frequency (either often, usually, or always) of motion sickness experienced by passengers while watching a video (15 %) and while reading (26 %) inside a moving vehicle. They also discovered the severity (either moderate or severe) of both activities (watching a video - 15 %, reading - 32 %). By using these findings, Sivak and Schoettle (2015) calculated an estimate from their previous study (Schoettle & Sivak, 2014) of how engaging in non-driving related tasks in an autonomous vehicle would affect the frequency and severity of motion sickness. They estimated that 6 to 10 % of American adults would be expected to experience a certain level of motion sickness, compared to Indians (8 to 14 %) who had the highest expected range percentage. They also predicted that 6 to 12 % of American adults would be expected to experience moderate or severe motion sickness at one point, compared to Indians (8 to 17 %).

In addition, most of the concepts or prototypes of autonomous vehicles allow a face to face seat configuration, allowing the (passive) driver and front passenger to swivel around and make direct eye contact with the other passengers in the rear seats, enabling all passengers to have comfortably quality time together. This concept is well known from a long time ago with the horse-drawn carriage, which offered the vis-à-vis orientation (French words meaning face to face). And again, this flexibility of seat orientations contributes to the critical factor of motion sickness, the inability of passengers to predict the future path of the autonomous vehicle.

It is also known that motion sickness typically correlates with motions caused by accelerations. When travelling inside a car, the human body is exposed to linear accelerations from longitudinal (fore-and-aft acceleration), lateral (cornering) and vertical (road surface) directions (Figure 2-8). In a typical car, these motions vary depending on the magnitude and direction of the accelerations and lead to vibrations. Vibration is an oscillatory motion where the magnitude is the extent of the oscillation, and the frequency is the repetition of the oscillation cycle in a second. Normally, vertical vibration is caused by the profile of the road surface and the moving components inside the car, such as the engine (Sezgin & Arslan, 2012). Most researchers focus on optimizing the suspension of the car and designing new seat systems to minimize unwanted vertical vibration to increase the ride comfort and not because of motion sickness. This is because the frequency of the vertical vibration is peaked at 1 to 2 Hz due to suspensions' dynamics, such as the 40 % damping ratio in suspension which applies to most cars (Figure 2-9), and this frequency is not contributing to motion sickness (Cheung & Nakashima, 2006). The vertical vibration that is above this range of frequency (or high-frequency) is considered too severe for the car users and can cause discomfort or injury, for example, increased occurrence of low back pain. On the other hand, past studies showed that low-frequency vibration below 0.5 Hz is highly correlated with motion sickness (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999a). However, only low-frequency vibration in longitudinal and lateral directions is known to be the major cause of motion sickness (Turner & Griffin, 1999b, 1999a, 1999c), whereas the intensity of low-frequency motions in the vertical direction is not enough to evoke motion sickness (Griffin, 1990, p. 319).

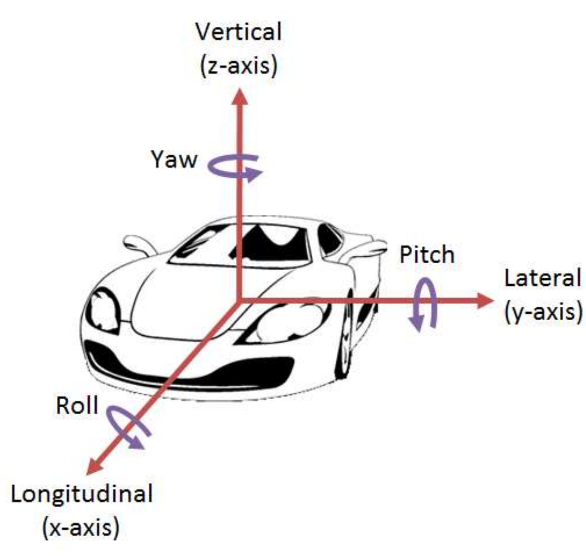


Figure 2-8: System of coordinates fixed to the car's centre of gravity according to ISO 8855 (International Organization for Standardization (ISO), 2011)

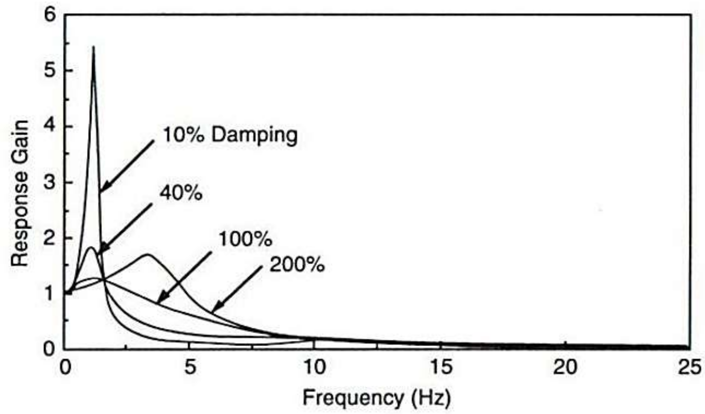


Figure 2-9: Effect of damping suspension isolation behaviour (Source: Gillespie, 1992, p. 156)

Furthermore, only 3.8 % of passengers reported suffering from motion sickness when travelling inside a train compared to car occupants (reported by 37.3 % travellers) (Turner & Griffin, 1999a). This because the rails were mostly in a straight line, and there were no sharp turns or corners that can induce jerking in the lateral direction. In addition, as mentioned by Le Vine, Zolfaghari, and Polak, (2015), train passengers experience smoother acceleration and deceleration compared to car occupants. These characteristics could be used as a way to mitigate motion sickness and enable train passengers to do any activities while travelling leisurely. However, longer routes are needed between junctions to enable smoother acceleration and deceleration of the autonomous vehicle. In the Le Vine et al. (2015) study, they found that the traffic congestion at the intersection worsened from 4 % to 50 % if the autonomous vehicle behaves like a tram and can go up to 2000 % if the autonomous vehicle behaves like a high-speed train.

2.3.3. Motion Sickness Dose Value

It has been shown that there is a relationship between the magnitude, duration, frequency, and waveform of the vibration (Mansfield, 2005). When riding in a car, the induced vibrations are in randomized forms due to many factors (driving styles, road, and such), and not in a constant sinusoidal form as in the simulator studies. By using fast Fourier transform (FFT) calculation that transforms the acceleration signal in the time domain into the frequency domain, a power spectral density (PSD) can be used to illustrate these random vibrations by showing the strength of the acceleration variations as a function of frequency, giving indications of which frequencies have substantial variations (dominance) and which frequencies have weak variations (non-dominance) (see Figure 2-10). Thus, it is important to verify at what frequency the acceleration dominates before further evaluation of its effect on motion sickness.

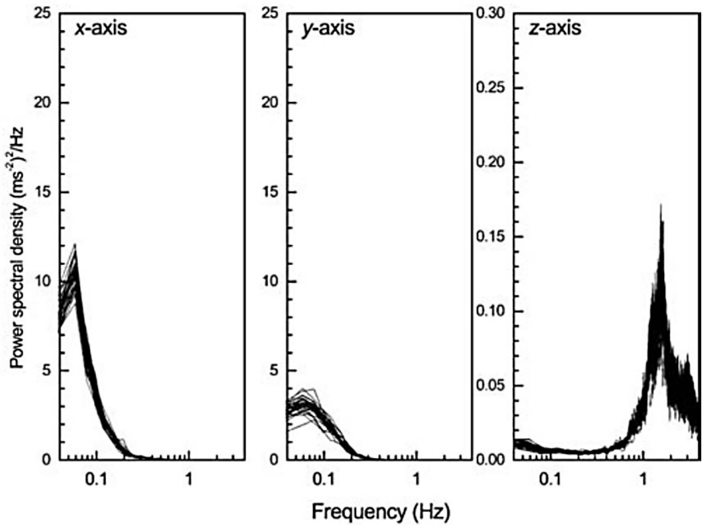


Figure 2-10: Example of PSD illustrating that accelerations are dominant below 0.1 Hz in x- and y-axis, and dominant between 1 and 2 Hz in the z-axis (Source: Griffin and Newman, 2004)

For the evaluation of whole-body vibration concerning health, the vibration is measured at all frequencies within the human sensitivity range. Then, the frequency weightings are used to reflect this sensitivity, where the most sensitive range is given a heavier weighting range than those with a less sensitive range (Basri & Griffin, 2013). Two main standards that relate to whole-body vibration are the BS 6841 (British Standards Institution, 1987) and the ISO 2631-1 (ISO, 1997). For the rest of the dissertation, only ISO 2631-1 will be used.

According to the ISO 2631-1 (ISO, 1997), frequency weighting that is known as W_f is used to predict motion sickness, especially any motion in a vertical direction at frequencies below 0.5 Hz (Figure 2-11).

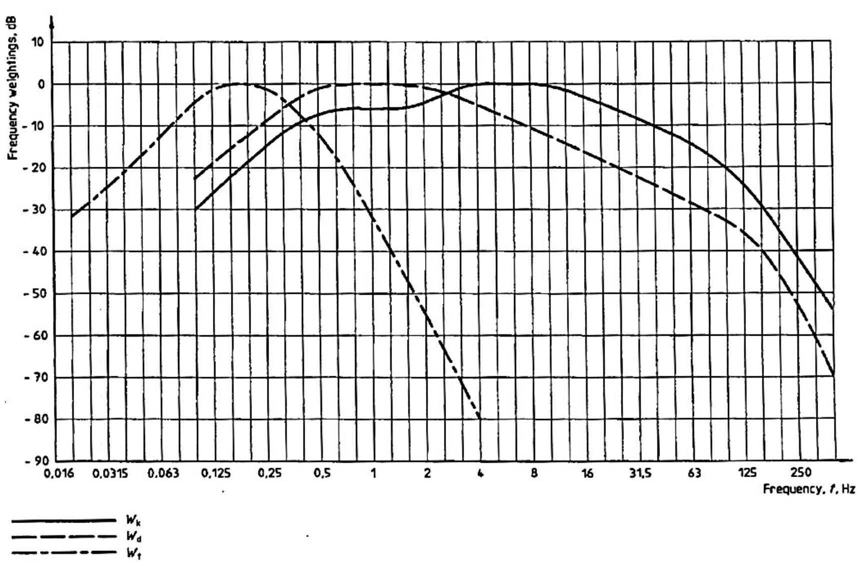


Figure 2-11: Frequency weighting W_f from ISO 2631-1, including W_k and W_d (Source: ISO, 1997)

Also, the chances of human getting motion sickness are higher when the duration of motion exposure is increasing. Hence, based on ISO 2631-1 (ISO, 1997), a measure of the probability of nausea called motion sickness dose value (MSDV) is implemented and calculated as:

$$MSDV = \sqrt{\int_0^T [a_w(t)]^2 dt} \tag{2-1}$$

where a_w is the weighted root mean square (r.m.s) of acceleration in the vertical direction with frequency weighting W_f while T is the period of the exposure. The MSDV unit is $ms^{-1.5}$. In addition, motion sickness incidence (MSI) is usually used to assess the percentage of people who may vomit and is defined as:

$$MSI = K_m * MSDV_z \tag{2-2}$$

where K_m = 1/3 for a mixed group of test subjects based on a study done by Lawther and Griffin (1987). As the frequency weighting W_f is for vertical acceleration only, Förstberg (2000) and Griffin and Newman (2004) pointed out that based on other researchers, the constant K_m in the formula should be replaced with 1.41 K_m (or $\sqrt{2}\ K_m$) when the formula is to be used for horizontal acceleration. Hence, a_w can be used as the weighted r.m.s of acceleration in the MSDV when evaluating the motions in longitudinal, lateral and vertical directions.

2.3.4. Synopsis

In summary, motion sickness is already one of the issues that negatively affect the ride comfort in the current transportation system. It becomes worse with the introduction of the autonomous vehicle especially when engaging in non-driving related tasks. Changing the behaviour of the autonomous vehicle to be like a train might not feasible especially at the junction that can worsen the traffic congestion. Based on the two theories of motion sickness, the information of the surrounding is important for the autonomous vehicle passengers to understand the situation and to react accordingly. Therefore, to reduce or correct the inconsistencies between the senses of motion awareness, there is a need for additional information that can enhance the awareness of the autonomous vehicle passengers. Accordingly, a more detailed understanding of situation awareness can give insight into how awareness can be enhanced in an autonomous vehicle.

2.4. Situation Awareness

Research on situational awareness or situation awareness (SA) can be traced back to military aviation researchers. Situation awareness is defined in various ways, depending on the theoretical and methodological approaches. Fracker (1988) mentioned that situation awareness should be defined based on what to measure, and Dominguez (1994) highlighted which elements should be in the situation awareness definition. Both authors reviewed a number of situation awareness definitions in their works. Endsley (2000) mentioned that simply said; situation awareness is "*knowing what is going on around you*". In driving contexts, situation awareness 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 (Sukthankar, 1997). Gugerty (1997) defined situation awareness as the activated knowledge that the driver has about the dynamic scene.

2.4.1. Situation Awareness Model

Models of situation awareness have many resemblances in their terms and elements (such as mental models, memory structures, goals, and attention), including the situated situation awareness theory (Chiappe, Strybel, & Vu, 2012) and the data/frame model of sensemaking (Klein, Moon, & Hoffman, 2006). However, the theoretical framework of situation awareness as described by Endsley (1995) has historically been widely cited and used (Golightly, Wilson, Lowe, & Sharples, 2010). This is because the model has been found to be applicable not just in the aviation field, but also in a wide variety of domains, such as maintenance, driving, education and rail operation.

Endsley's (1995) model of situation awareness is a dynamic decision-making model and describes situation awareness states. The model illustrates three stages or steps of situation awareness formation: perception, comprehension, and projection (see Figure 2-12).

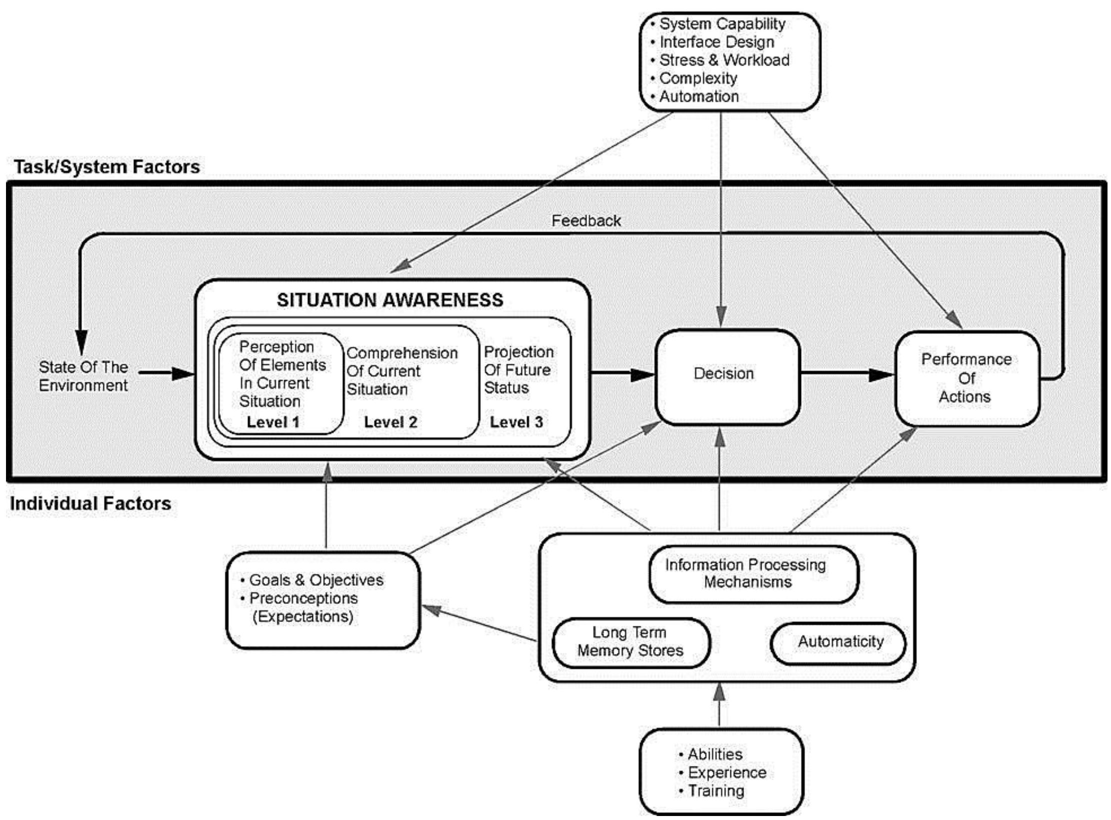


Figure 2-12: Framework of situation awareness model (Source: Endsley, 1995b)

The first level, the perception, is the first step in achieving situation awareness by getting relevant elements (information) from the environment. For instance, in terms of driving contexts, this first step can be accomplished by getting a simple recognition from the current speed of the car, the speed of the lead car and other road users' speed. From this information, the next level of SA, the comprehension, comes in the form of the processes of pattern recognition and evaluation to analyse unconnected information. After getting the knowledge of the current situation (from Levels 1 and 2), then the driver can predict the future situations and then decide whether it is safe to overtake another car or to keep a distance between each other. This process is influenced by two major factors. First, the ability to acquire situation awareness with the same input (situation awareness elements or information) is different between individuals, including any experience and training they had. From here, it builds up characteristics of how well individuals can process information, by using his/her long-term memory and any patterns that can be performed automatically. Furthermore, people may have certain goals and expectations that can act to filter the relevant information from the environment. Second, the task or system environment factors, such as system and interface (or display) complexity, stress and workload, may also affect SA.

2.4.2. Situation Awareness in Vehicles

Generally, situation awareness has been studied to evaluate the effects of using in-vehicle technologies such as adaptive cruise control, driver training programs, and driving experience (Salmon & Stanton, 2013). De Winter, Happee, Martens, and Stanton (2014) reviewed many published papers regarding the effects of different levels of automation used inside vehicles and summarized that drivers of highly-automated driving have lower workload and altered situation awareness compared to manual driving, and that situation awareness is degraded when the highly-automated driving drivers are engaging in non-driving related tasks.

Schömig and Metz (2013) proposed a three-level model of situation awareness in driving when interacting with secondary tasks (non-driving related tasks) based on Michon's (1985) levels of the driving tasks (the strategic, tactical and operational levels). As mentioned in Section 2.2, the strategic level (the highest level) concerns the general planning of a journey, the tactical level is defined as the manoeuvring control of the vehicle, and the operational level is defined as the control level (the lowest level). In the Schömig and Metz (2013) model, at the highest level, the planning level, drivers deliberately choose the most suitable situation to interact with a secondary task that will not degrade the driving task. This includes less risky situations such as on a highway with fewer cars or less traffic. At the second level, the decision level, drivers will decide whether any engagement with the secondary task will be appropriate or not, based on driving situations, including for how long the engagement should be before getting a risky situation. At the lowest level, the control level, drivers need to be capable of adapting to a new situation (i.e. engaging the secondary task while driving) by dividing the attention of both tasks. Schömig and Metz (2013) conclude that as long as drivers are aware of and can adapt to the situation, engaging in a secondary task while driving is possible.

As mentioned before, autonomous vehicle passengers are likely to be more exposed to motion sickness due to the transformation from an active driver to a passive driver, engagement in non-driving related tasks, and flexibility of seat orientations (Diels, 2014). Once more, all these aspects contribute to the critical factor of motion sickness, which is the inability to predict the future path of the autonomous vehicle (Golding & Gresty, 2013) and the conflict between vestibular and visual inputs (Sivak & Schoettle, 2015). When a passenger is reading a book in a typical car, the passenger will look out of the window for a few minutes before continue reading the book as a coping strategy for reducing motion sickness symptoms. Looking forward out of the window can provide a fixed external visual reference and has no conflict of the inputs (Murdin, Golding, & Bronstein, 2011). A study done by Bos, Houben, and Lindenberg (2012) found that an artificial 3D Earth-fixed visual reference with an anticipatory trajectory can enhance situation awareness and reduce MS. In addition, Golding et al. (2003) found in their study that "*if the test person is aligned with GIF and if he/she can control the alignment*", motion sickness can be reduced. However, Cohen et al. (2011) discovered that although the angle of tilt on the train can help passengers to reduce motion sickness, the delay in having the vertical axis of the train move toward the GIF is responsible for producing the motion sickness. They suggested that the timing to react on the acceleration force in the GIF direction should be sharp in onset, to enhance the effect of mitigating motion sickness. Thus, the information autonomous vehicle passengers need to know about future motions of the vehicle is important to enhance their situation awareness, and for them to react accordingly.

2.4.3. Synopsis

In summary, this dissertation considers mitigating motion sickness by enhancing situation awareness of autonomous vehicle passengers when engaging in non-driving related tasks. One of the ways to achieve that is by providing necessary information peripherally. Next, we discuss the ambient information briefly and their relation with peripheral displays.

2.5. Ambient Information Systems

Ambient information systems is a term used to describe a wide range of applications that deliver information in a peripheral manner. Weiser and Brown (1996) mentioned that calm technology involves both our focal and peripheral attentions, and described calm technology as a type of information technology to convey or deliver information to the users being mostly in the users' periphery. The users can remain focused on their primary tasks while being aware of additional information through calm technology which should not hinder the main tasks. Pousman and Stasko (2006) summarized that the most commonly used terms in ambient information systems researches are ambient display, peripheral display, and notification systems. In general, all ambient displays are peripheral displays, but not all notification systems are peripheral displays. This is because the notification systems are not always peripheral but rather address focal attention. Based on Pousman and Stasko's (2006) characterisation of the behaviours of the ambient information system, a peripheral display should publish important but not critical information and be able to provide subtle changes as an update in published information.

Pousman and Stasko (2006) presented four design dimensions when designing ambient information systems; the information capacity, the notification level, the representational fidelity, and the aesthetic emphasis. The information capacity is the number of distinct pieces of information that an ambient information system can deliver. It can be ranked as low capacity with a single information detail or ranked as high capacity with more than 10 information details. For our study, the information regarding the future motions of the autonomous vehicle is important especially the motions that can provoke motion sickness. According to (Matthews, Dey, Mankoff, Carter, & Rattenbury, 2004), the notification levels are the differences of information importance that are meant to grab a user's attention. Higher notification levels are meant to interrupt a user with critical information while lower notification levels are meant to provide information peripherally. The notification level should be enough to make the users aware of the information of the future motions of the autonomous vehicle and not to interrupt their non-driving related activities. The representational fidelity describes how the information is transformed into signs or symbols (e.g. pictures, patterns, etc.) according to the system's display elements. It can be ranked as low fidelity with abstract signs (e.g. red colour that can be assumed as danger) and ranked high with indexical signs (e.g. maps and photographs). In our study, the information should be easy to distinguish and to understand between signs/symbols to avoid higher mental workload that may interrupt the non-driving related activities. Usually, the ambient information systems are made to be visible for the users. Hence, the aesthetics of the display is important. In our study, although being visually pleasing can be a primary objective for the display, being comfortable when interacting with the display (or when receiving information) is more important, especially when the users' sight is already occupied with the non-driving related activities.

2.5.1. Synopsis

Ambient information systems provide information either in the periphery or in the focus of attention. Based on the four design dimensions when designing ambient information systems, we are focussing more on how to deliver the information peripherally. In view of that, a closer look into the psychophysical effects of the haptic cue will shed light on how the information could be delivered without interrupting the autonomous vehicle passenger engaging with non-driving related tasks.

2.6. Psychophysical Effects of Haptics

Pielot and Oliveira (2013) stated that the visual and auditory modalities are the modalities that have been studied mostly by researchers of peripheral displays. However, as mentioned before, most non-driving related 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 (Diels & Bos, 2016), compared to watching a movie on a big screen in the dashboard. In addition, 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 (Pielot & Oliveira, 2013). A survey done by Bazilinskyy and de Winter (2015) investigated drivers' opinion on auditory displays in fully- and highly-automated driving cars. One of the displays called future system aimed to provide comfort in the fully-automated 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 cues offer a promising direction to provide information peripherally to increase situation awareness inside the autonomous vehicle.

According to Lederman and Klatzky (2009), visual and audio systems are acknowledged to provide precise spatial and temporal information, while the haptic system is better in processing material characteristics and objects. Haptic comes from the Greek word "*haptomai*" meaning "*to touch*" (Salisbury, Conti, & Barbagli, 2004). Most authors use *haptic* and *tactile* terms as the same (e.g. Lederman & Jones 2011). Conversely, some authors consider haptic sensation as a combination of two groups of senses; *tactile* and *kinesthetic*. *Tactile* is the perception of information or feel from *cutaneous* inputs, the sensors from the skin and right underneath it. Perception of vibration, pressure, touch, and texture come from these sensors (*mechanoreceptors*). On the other hand, the perception of weight, stretch, or joints angles (such as an arm, hand, wrist, and fingers) are sensed by sensors (also called *mechanoreceptors*) from muscles, joints or tendons, derived as *kinesthetic* inputs. For example, the ability to touch eyes or nose with closed eyes due to the perception of limb position and movement, and the ability to estimate the weight of an object due to the perception of muscle tension (Tan, 2000). Usually, haptic feedback or perception comes from a combination of both tactile and kinesthetic inputs.

In 1962, Gibson observed the behaviour of touching, between passive (object pressed against skin) and active (explore object with skin) touch, and found that passive touch sensations "*tend to focus the observer's attention to his/her subjective bodily sensation"* while active touch sensations "*tend to guide the observer's attention to properties of external environment"*. Furthermore, passive touch studies positively confirm that tactile feedback (*cutaneous* inputs) alone is sufficient to generate subjective sensations (Amemiya, Hirota, & Ikei, 2013; Fitch, Hankey, Kleiner, & Dingus, 2011; S. J. Lederman & Klatzky, 2009). Hence, only the tactile perception will be discussed further.

2.6.1. The Four-Channel Theory

In general, the adult human skin has an area of 1.8 m^2, a density of 1250 kgm^{-3} and a weight of 5 kg. *Cutaneous* membrane or skin can be clustered into two categories; hairless skin (called *glabrous*) and hairy skin. Glabrous skin can usually be found at hand or fingertip while hairy skin covers most of the human body. However, most studies focus on *glabrous* based on receptor population under the skin types (Cholewiak & Cholewiak, 2010, p. 344). According to Hsiao (2010, p. 349), there are 13 types of afferent nerve fibres under the skin, nine of which provide perception or information about pain (2), temperature (2), itch (1) and position (4). Another four are known as mechanoreceptors, sensors that respond to tactile feedback. These mechanoreceptors were figured in the four-channel theory, one of the most established frameworks in vibrotactile perception (Gescheider, Wright, & Verrillo, 2008).

Figure 2-13 shows two sensors lying close to the epidermis (outer layer) known as *Merkel cell* and *Meissner's corpuscle*, and another two lie deep in the dermis (inner layer) area called *Ruffini corpuscle* and *Pacinian corpuscle*. These sensors are divided into two types of characteristics, size of its receptive field (small or large) and adaptation rate of frequency, either low (slow) or high (rapid) (Table 2-2).

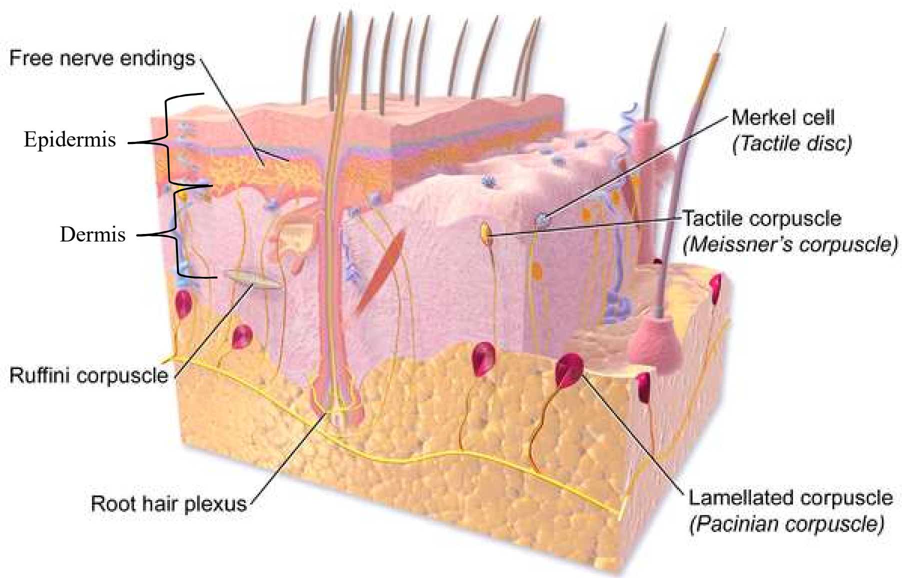


Figure 2-13: Tactile Receptors in the Skin (Source: Blausen.com staff, 2014)

Table 2-2: Characteristics of the Mechanoreceptor

Nerve Type/ Channel	SAI	SAII	RAI	RAII
Receptor Type	Merkel Cell	Ruffini corpuscle	Meissner's corpuscle	Pacinian corpuscle
Size of Receptive Field	Very small	Fairly large	Fairly small	Relatively large
Adaptation Rate	Very low	Low	High	Very high
Sensory Function	Form and texture	Motion direction	Motion detection	Vibrations

Merkel cell (known as Slow-Adapting type I or SAI) has a small receptive field and can detect very low-frequency vibration (above 0.4 Hz). It gives the perception of the fine detail of form and roughness. On the other hand, *Ruffini corpuscle* (known as Slow-Adapting type II or

SAII) has a large receptive field and gives the perception of skin stretching. Two of the sensors, *Meissner's corpuscle* and Pacinian *corpuscle*, are known as Rapid-Adapting type I and II (RAI and RAII) respectively. *Meissner's corpuscle* has a small receptive field, which can detect vibration between 5 to 60 Hz and give the perception of localized movements, such as handgrip control, whereas *Pacinian corpuscle* has a large receptive field and can detect high-frequency vibration (40 to 400 Hz). In addition, *Pacinian corpuscle* can give the perception of very fine texture and is primarily responsible for sensing vibration.

2.6.2. Haptic Sensitivity

Earlier research related to tactile sensory perception has been done by Weinstein (1968). He studied tactile sensitivity with respect to different genders and sides of the body (left and right) for various locations on the body, and used three measures of sensitivity; pressure sensitivity, two-point touch threshold, and point localization threshold.

In general, Weinstein (1968) found that women are more sensitive than men for pressures, especially at the forehead, trunk, and fingers. On the other hand, the pressure sensitivity is least felt at the lower limb including the thigh, calf, and sole (Figure 2-14). In addition, both sides of the body have the same pressure sensitivity.

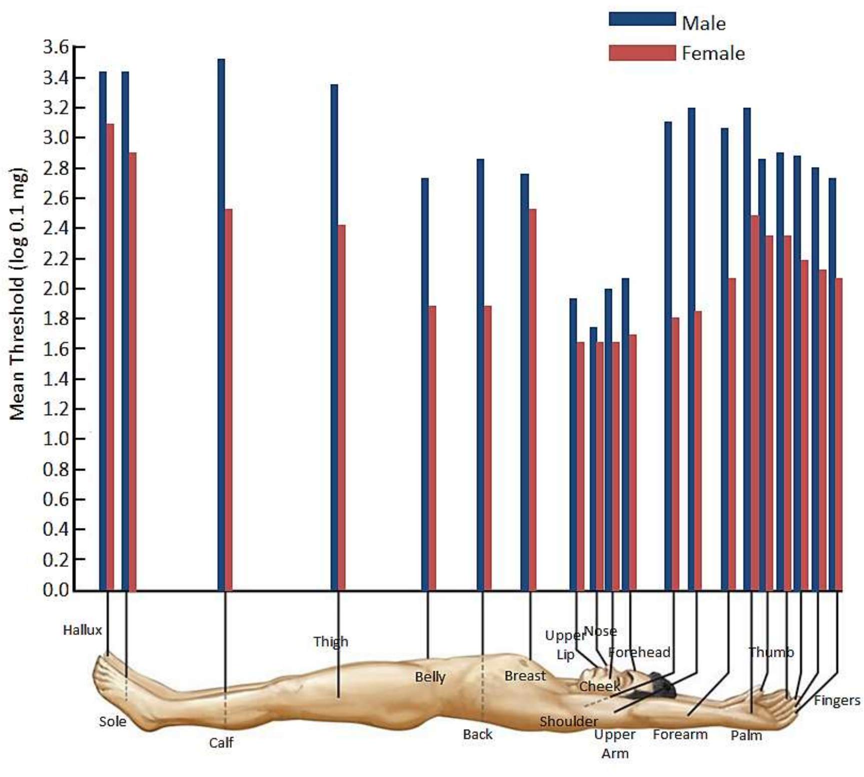


Figure 2-14: Pressure sensitivity threshold for male and female in different areas of the body (Adapted from Weinstein, 1968)

The other two measurements are to test the spatial acuity of the skin. The first method, the two-point touch threshold, is to represent the smallest spatial distance between two applied stimuli on the skin that can be detected. During an experiment, the participants need to determine either one or two points that can be felt when the stimuli are applied. The second method is the point-localization threshold where a stimulus will be applied on the skin, and then in time, another stimulus will be applied either on the same location or at a different location. The participants need to determine whether both stimuli occur at the same location or not. Weinstein (1968) found that both methods have shown that fingers, face, and hallux (the big toe) for both men and women were most sensitive and the results were almost parallel for both genders (Figure 2-15).

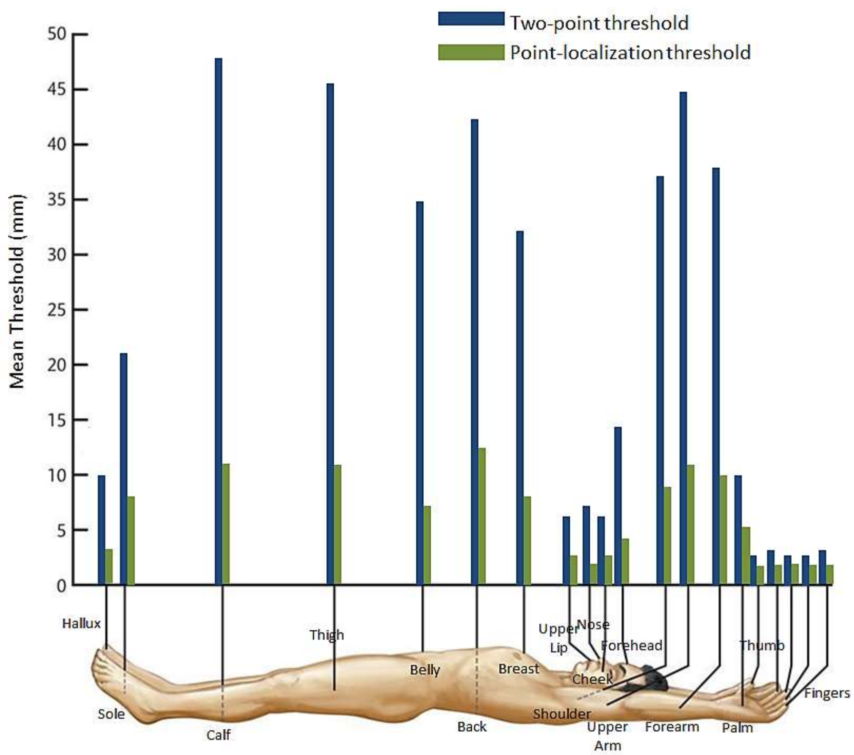


Figure 2-15: The two-point and the point-localization threshold for a male in different areas of the body (Adapted from Weinstein, 1968)

2.6.2.1. Can you feel it?

When using vibration as a stimulus to invoke the tactile sensation, many studies represent vibration sensitivity as the absolute threshold; the weakest stimulus intensity that can be sensed by a human. This threshold largely depends on the frequency, the amplitude, and the location of the contact area on the skin. In addition, the absolute threshold is affected by other factors, such as stimulus duration (Ternes & MacLean, 2008), stimulus waveform (Cholewiak & Reschke, 1997; Ternes & MacLean, 2008), contact force (Weinstein, 1968), skin temperature (Gescheider, Thorpe, Goodarz, & Bolanowski, 1997), presence of other vibration (Ryu, Chun, Park, Choi, & Han, 2010) and age (Kenshalo, 1986).

Study about vibration sensitivity related to different areas of the body has been extensively done by Wilska (1954). By using a vibrator device and placing it on various body regions skin, hands and soles are found to be the most sensitive to vibration, while the gluteus region is the least sensitive to vibration. According to Jones and Sarter (2008), frequencies between 150 and 300 Hz are considered ideal for vibration sensitivity for the whole human body. However, the amplitudes needed to detect vibration are different in different areas of the body. For example, at the most sensitive area, especially at the fingertip, the absolute threshold is about 0.07 μm of deflection (amplitude) with a frequency of 200 Hz, whereas the gluteus region can only detect vibrations of 200 Hz with minimally 14 μm of amplitude (Figure 2-16). Moreover, the vibration cues need to have a frequency higher than 60 Hz to avoid temporal masking from the ambient of vibration noise inside the vehicle, to convey in-vehicle information (Ryu et al., 2010).

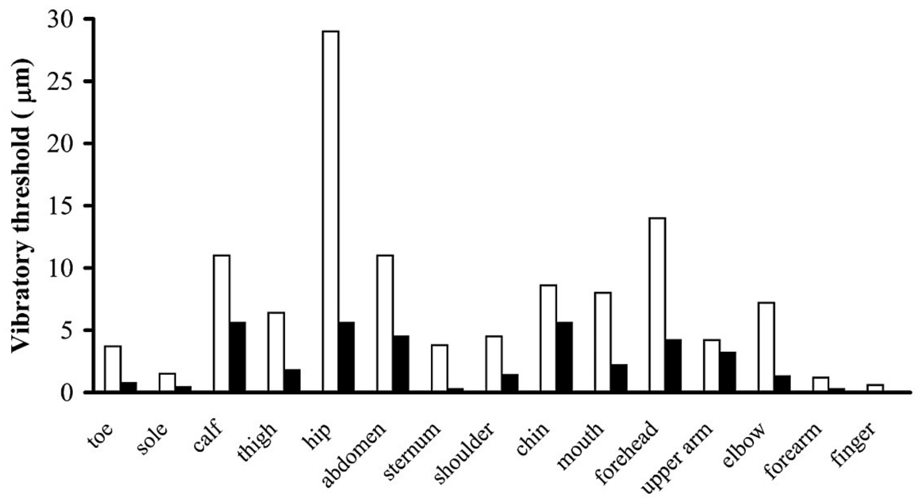


Figure 2-16: Amplitude thresholds for detecting vibration at 100 Hz (white bars) and 200 Hz (black bars) at various sites on the body from Wilska (1954) (Source: Jones & Sarter, 2008)

2.6.2.2. Can you guess the difference?

To distinguish between vibration cues, the capability to sense the differences or just noticeable difference (JND) is needed. JND is a measure of psychophysical acuity and is defined as the smallest difference between two stimuli by which observers report a noticeably different sensory experience in 50 % of the cases (Cannella, Scalise, Olivieri, Memeo, & Caldwell, 2013; Choi & Kuchenbecker, 2013). Generally, this discriminability is represented by the Weber fraction according to which the difference threshold depends on the strength of the initial stimulus.

Furthermore, according to Weber's Law, also called the Weber-Fechner Law (Gescheider et al., 1997; Jones & Sarter, 2008), these fractions tend to remain constant (C) regardless of the reference level (Figure 2-17). This can be expressed as:

$$\frac{\Delta I}{I} = C \quad (2\text{-}3)$$

where ΔI is the differences in intensity, I is the initial stimulus intensity, and C is the constant that may be expressed in a percentage. In a study done by Choi and Kuchenbecker (2013), at least 20 % to 30 % of the variance in amplitude or frequency in vibration intensities is necessary to distinguish between the differences. Another study done by Mansfield and Griffin (2000) found that the difference threshold is about 13 % for a variety of road stimuli measured in a simulated automobile seat vibration.

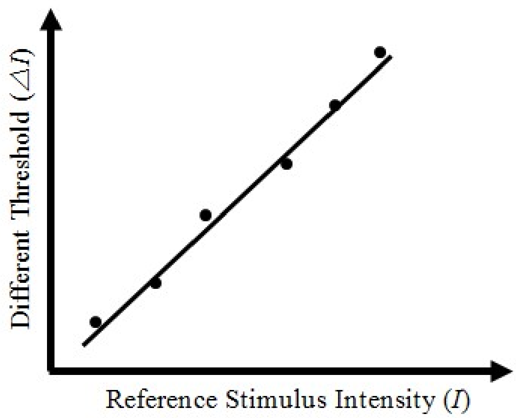


Figure 2-17: Weber's Law (Threshold versus Intensity)

2.6.2.3. Can you feel the groove?

In addition to frequency and amplitude, the rhythm of the vibration (Ternes & MacLean, 2008) and movement of the vibration, also called saltation phenomenon (Cholewiak & Reschke, 1997), are two important parameters when designing vibrotactile cues, the cues that provide the perception of vibration through touch, to convey different information. Saltation refers to a hopping, leaping or an abrupt movement or transition of the perception (Lockhead, Johnson, & Gold, 1980).

Ternes and MacLean (2008) investigated different types of rhythm on a single vibrotactile tactor as shown in Figure 2-18. Each row represents a duration of 500 ms, which will be repeated 4 times (total duration of 2 s). The note length, the on- and the off-time of vibration, is represented in grey and white colour respectively. According to Ternes and MacLean (2008), they found four distinguished groups of rhythm (short-even, short-uneven, long-even, and long-uneven) to deliver different information. Moreover, the difference of note lengths (from 1/8 to whole of the 500 ms) is more effective than unevenness of rhythm (mixed of short and long notes) in the overall duration of 2 seconds. However, they concluded that individuals have different sensations of frequency stimulation. Thus, the range of frequencies (high and low) present in both rhythm and amplitude still can be perceived, but with inconsistent results. On the other hand, they confirmed that by using only varied frequency as stimuli, different information could always be distinguished.

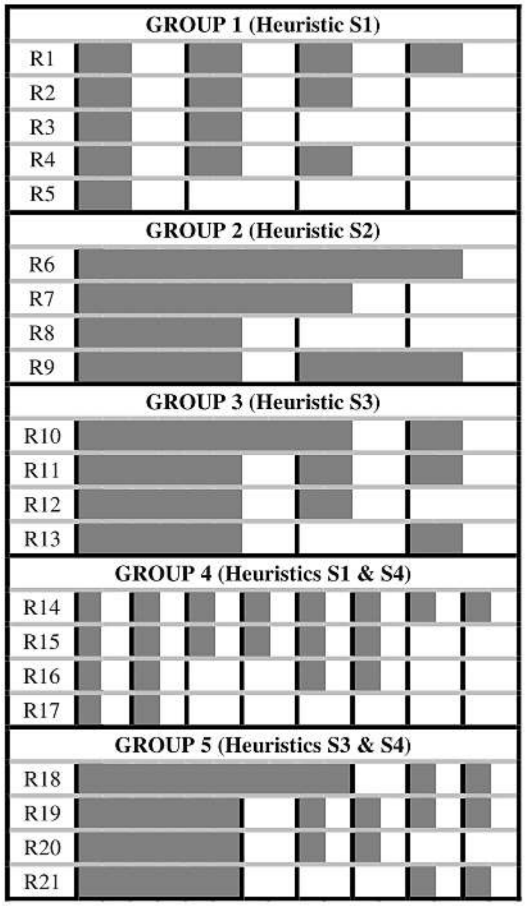


Figure 2-18: The rhythms setup in the Ternes and MacLean (2008) study

When using multiple vibrotactile tactors, either in linear or in an array arrangement, different information (vibration patterns) can be delivered to the observer by the saltation phenomenon. Usually, tactile saltation (pattern) can be generated by sequentially activating a line of tactors to invoke a sensation of moving point or line drawing on the skin, if the timing, spacing, and intensity are appropriate. Cholewiak and Reschke (1997) reported that by using an example of 7 x 4 array of tactors as in Ⓐ (refer to Figure 2-19), thin saltation (3 taps on single column as in Ⓒ) or thick saltation (3 taps on several columns as in Ⓓ) can provide the same sensation of seven distributed taps as in Ⓑ. However, the advantage of using the saltation phenomenon is that the sensation can be provided by using less actual stimulus locations than are felt.

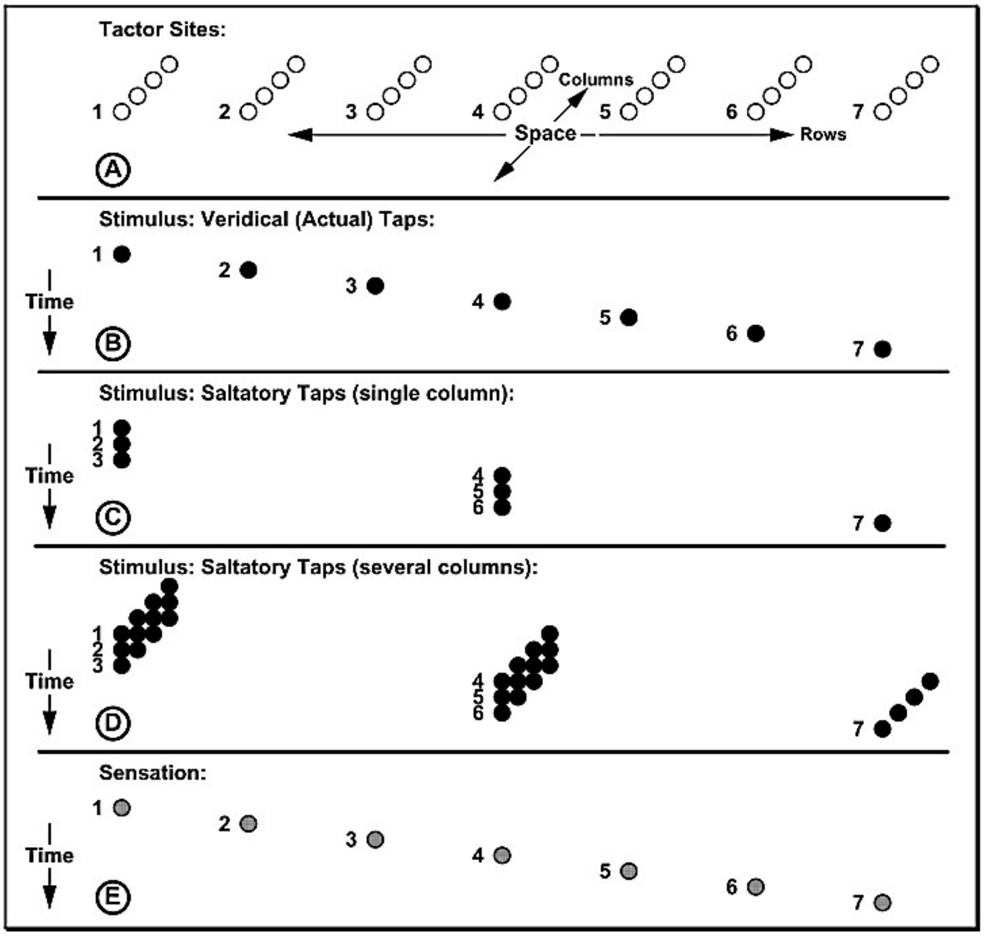


Figure 2-19: Saltation phenomenon (Source: Cholewiak & Reschke, 1997)

2.6.2.4. What was the feel?

Sometimes, the vibration itself can give impressions of other perceptions or sensations. According to Tan, Durlach, Reed, and Rabinowitz (1999), a human can sense different ranges of vibration, and they clustered these ranges into three distinct categories. Frequency up to 6 Hz can give a perception of slow motion (slow kinesthetic motion). From 10 Hz to 70 Hz, it can give a perception of rough or fluttering motion, while frequency above 150 Hz can be felt like a smooth vibration. Another study done by Hwang and Choi (2010) stated that vibrotactile stimuli could be divided into two distinct groups, low-frequency range (between 40 Hz and 100 Hz) and high-frequency range (between 100 Hz and 250 Hz). In addition, by modifying the frequency amplitude of vibration, the subjective quality of vibration can be controlled. However, the manipulation of vibration amplitude is only useful when the vibrotactile tactors have limited bandwidth to control the vibration frequency.

2.6.3. Synopsis

In summary, the sensitivity of human to sense any haptic cue is basically based on frequency, amplitude and the location of the tactile cue contact on the human body. Even though a human can sense the tactile cue on any part of the body, only certain parts of the body can be used to implement a vibrotactile device to avoid any distraction when engaging in any activities inside an autonomous vehicle. Hence, a better understanding of how to implement a vibrotactile cue to increase situation awareness in the autonomous vehicle is essential. Next, we identify exemplary vibrotactile cues in the vehicle application area.

2.7. Application of Haptic Cues in Vehicle

According to Erp and Veen (2001), haptic cues in a vehicle can convey different types of information related to driving. They clustered the types of information in five groups; the spatial information, the warning signals, the communication, the coded information, and the general information. The driver needs spatial information to perceive any object present in the surrounding when the driver's view is blocked (e.g. blind spot), and haptic cues also are suitable for warning signals due to their ability to draw the driver's attention. Furthermore, haptic cues can communicate with the driver in silent and private, without bothering other passengers with coded information that is intended only for the driver (e.g. speed and fuel level).

2.7.1. Spatial Information

Morrell and Wasilewski (2010) developed a vibrotactile seat to improve spatial awareness, especially to provide information about objects in the blind spot area while driving. They used 15 tactors, which were constructed from pager motors, and set as gradually activated to vibrate. The tactors were placed in the back seat (lumbar region) in a 3 x 5 array with 60 mm apart in a horizontal and vertical direction (see Figure 2-20). The array represented several zones behind the car and tactors vibrated at different intensities (vibration intensity and the number of active tactors) based on the distance of the nearby vehicle behind the driver's car. However, Morrell and Wasilewski (2010) mentioned that the experiment conducted was not focusing on quantifying any driver's parameters, but to test the suitable feedback strategies from the information given. Thus, no exact bandwidth parameters were stated in the report. Nevertheless, they conclude that vibrotactile feedback from the seat may help to improve awareness and safety.

Figure 2-20: The completed seat on the left and placement of the tactors on the right (inside the red rectangle box) (Source: Morrell & Wasilewski, 2010)

2.7.2. Warning Signals

In line with the rapid development of ADAS, most research attention is focused on vibrotactile usage in safety aspects, especially as an alerting or a warning signal. For example, awakening drowsy drivers (Arimitsu et al., 2007), notifying drivers to maintain lane position (Suzuki & Jansson, 2003) and alerting drivers for any possible imminent collision (Ho, Tan, & Spence, 2005; Lee, Hoffman, & Hayes, 2004). In addition, the tactors used were applied on various sites, for instance, on the seat (Fitch et al. 2011; Amemiya et al. 2013), on the seatbelt (Arimitsu et al., 2007), or directly on the drivers' torso (Ho et al., 2005).

Enriquez, Afonin, Yager, and Maclean (2001) conducted two experiments on 11 subjects to use a steering wheel fitted with a pneumatic pocket as a new method to generate haptic feedback. The first experiment was to determine whether a frequency of 5 Hz is enough to give an alert to the subjects and the second experiment was to explore haptic stimuli at different frequencies (2.5, 6 and 10 Hz) to provide different information. They found that through haptic feedback, the driver can get additional information, especially with different frequencies (at low frequency) to identify the information. However, it should be noted that the differences in low frequency can only be sensed by glabrous skin (and this study used palm skin to sense the changes in frequency).

On the other hand, Ho et al. (2005) used vibrotactile stimulation on the belt as a warning signal for the drivers. 16 subjects participated in the experiment using vibrotactile stimuli in the belt fastened around the participants' waist, where one tactor was positioned in the middle of the participant's stomach while the other was positioned in the middle of the participant's back. Both tactors vibrated with 290 Hz. The main objective of the experiment was to investigate vibrotactile usage to direct driver's attention to either front or back of the vehicle in the simulator. The findings show that a vibrotactile stimulus on the torso (waist) can direct the driver's visual attention to any possible imminent collisions. Furthermore, Arimitsu et al. (2007) studied seat belt vibration to alert drowsy drivers. Subjects who participate in the experiment were exposed to two tensions of seat belt forces (80 N and 130 N) on their upper torso for a period of 100 ms with a different number of pulses. The seatbelt vibration has shown its effectiveness to mitigate a driver's drowsiness and tension of 130 N with 100 ms duration for 3 times (pulses) is considered the most effective pattern.

Fitch et al. (2011) investigated whether a haptic seat can be used as the only method to deliver multiple and discreetly different types of alert (specifically: the forward collision warning, the curve speed warning, the intersection violation warning, the lane change/merge warning, and the lane departure warning). 24 subjects participated in several experiments using a haptic seat mounted with 6 tactors (see Figure 2-21); two mounted at the front edge of the driver seat, two mounted at the back-left and back-right corner of the seat pan (to stimulate side of the driver's thighs), and two mounted at the seat back. All tactors are setup with frequencies from 65 Hz to 73 Hz, and amplitudes from 137 μms^{-2} to 149 μms^{-2}. The study found that when the number of alerts increases, confusion and delayed responses may occur. However, this problem can be solved if the locations of the tactors are spaced far apart.

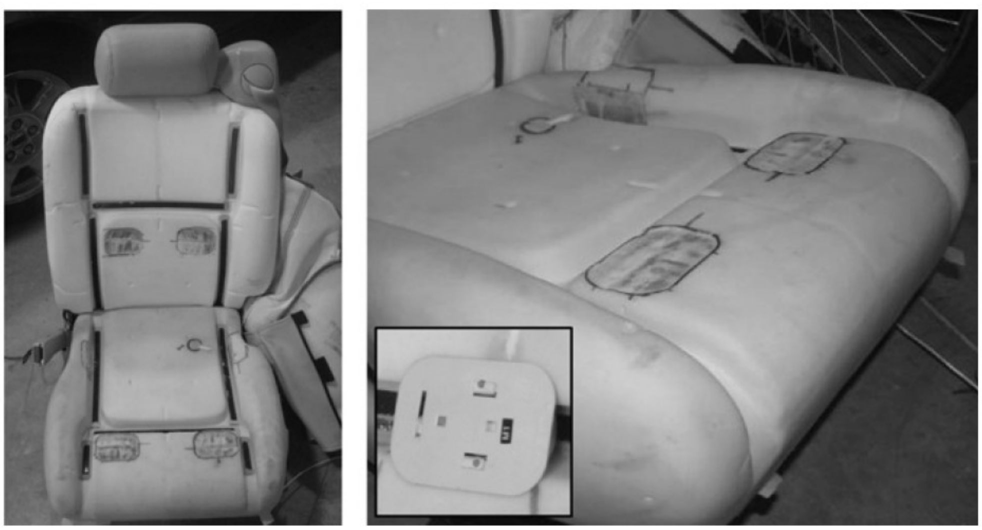


Figure 2-21: Haptic seat with 6 tactors at 3 different locations (Source: Fitch et al., 2011)

Dass Jr., Uyttendaele, and Terken (2013) explored the implementation of haptic in-seat feedback for lane departure warning for truck drivers. Two types of warning signal were tested in the study. These signals are defined based on situations where the outside of the truck's tire exceeded the outside of the visible lane marking; between 8 and 33 cm for Medium Criticality and over 33 cm for High Criticality. 8 vibration motors were mounted in the seat (Figure 2-22) where four motors vibrated with a 200 ms on-off rate for Medium Criticality or constantly vibrated for High Criticality on the side of the lane departure. They found that the haptic warning signal can be used in dealing with lane departures, either in normal driving situations or in driving with secondary task situations.

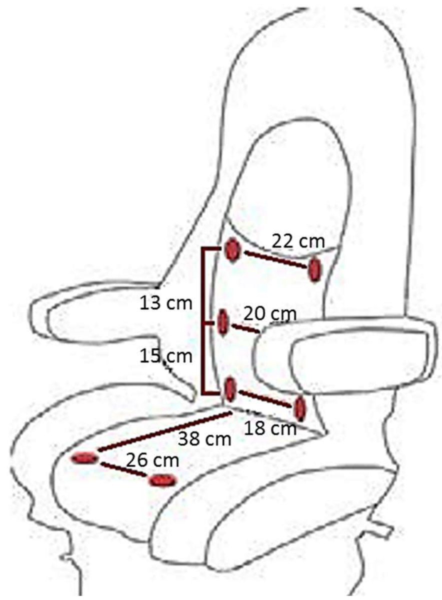


Figure 2-22: The position of the vibrators in the seat (Source: Dass Jr. et al., 2013)

2.7.3. Navigation Tools

Navigation tools, such as a global positioning system (GPS), are becoming common in many applications. However, the information on the visual display is inaccessible or undesirable in specific conditions. Tan et al. (2003) investigated the use of vibrotactile cues in the array for delivering attention- and direction-related information to its user. They chose the back of the human body to be equipped with the haptic device due to being easily accessible and mostly not being engaged by other displays. The tactors, modified from 40 mm diameter flat magnetic speaker, were in the form of 3 x 3 array with 8 cm equal inter-tactor spacing and vibrated at a frequency of 290 Hz (see Figure 2-23).

Figure 2-23: The haptic back display (Source: Tan et al., 2003)

In the first experiment, the device was used to draw attention to the participant about any changes in monitor display. They concluded that haptic feedback could reduce the response times of any changes in monitor display. In the second experiment, the device was used to give directional cues (east, west, south, north, southeast, southwest, northeast, and northwest directions) by different stimulation patterns (wave) using sensory saltation phenomenon (between *thin* and *thick* salutatory line). Their findings show that a small set of directional signals (the thin line) from haptic feedback can be easily understood by the participant compared to the thick line.

In a study by Van Erp and Van Veen (2004), 16 drivers were tested using a vibrotactile display as navigation tools of waypoints. Eight tactors, known as Special Instrument MiniVib 4 vibrators with a contact area of 18 mm x 22 mm and vibrating at 250 Hz, were mounted in the seat where four tactors were placed under each thigh in a straight line, at a distance of 4 cm between centres of the tactors. The general idea was to provide information concerning the direction of the oncoming change, such as turning left or right, and the remaining distance to this change. Depending on the oncoming direction (left or right), four tactors vibrated in a rhythmic manner with a 60 ms on-time length. At 250 m of the remaining distance, the tactors were activated three times separated by 270 ms. At 150 m of the remaining distance, the tactors were activated six times separated by decreasing intervals from 270 ms to 60 ms. At 50 m of the remaining distance, the tactors were activated five times separated by decreasing intervals from 60 ms to 100 ms. They concluded that the implementation of vibrotactile feedback in a car could reduce the driver's workload and reaction time towards the navigation messages.

Van Erp, Van Veen, Jansen, and Dobbins (2005) investigated further the vibrotactile navigation with 12 subjects who were tested using a vibrotactile waist belt as navigation tools of waypoints. Eight tactors, modified from pager motors with a contact area of 1.5 cm x 2 cm and vibrating at 160 Hz, were placed at adjustable distances (roughly covering an area of 45° in angle) on a belt around the participant's waist. The general idea was that the algorithm used in their system calculated the direction and distance of the waypoint and rendered them into a tactile display. A tactor vibrated when the waypoint was within its range (45°), and the rhythm of vibration was faster when the distance to the checkpoint was smaller. Later, the authors tested the vibrotactile waist belt in a helicopter and in a speedboat. They concluded that the spatial information could be translated into a direction on the human's torso.

Asif and Boll (2010) also explored a tactile belt for drivers to provide turn-by-turn information. Eight tactors were sewed on a 90 cm long fabric tube at equal distances around the waist of the driver. The locations of the tactors represented the information of the direction while a number of pulses indicated the category of distance. The categories of distances were "*very far*" (between 200 m and 150 m with 4 pulses in 2.5 seconds), "*far*" (between 100 m and 80 m with 3 pulses in 2 seconds), "*near*" (between 50 m and 30 m with 2 pulses in 1.5 seconds), and "*turn now*" (10 m with 1 pulse in 1 second). After a pilot study, the authors chose the one tactor design to compare their tactile display with a typical car navigation system. In this design, only one tactor was activated representing the direction on that tactor position. Figure 2-24 illustrates an example of how the tactile belt works in a scenario. They found that the orientation performance of the drivers was better compared to the typical car navigation system.

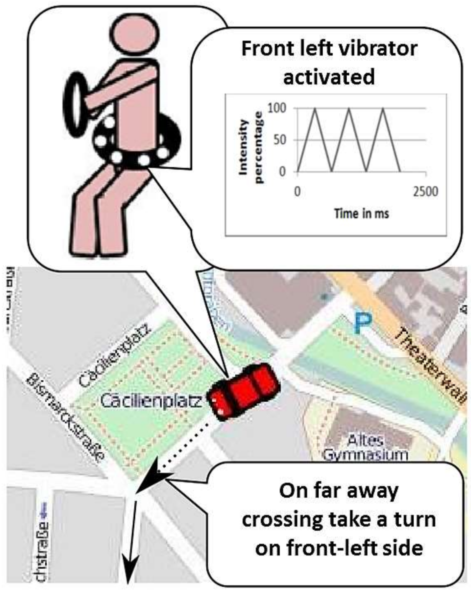


Figure 2-24: Example of a tactor is activated with 3 pulses on the front left side of the tactile belt before approaching a crossing (Source: Asif & Boll, 2010)

2.7.4. Perceived Forward Velocity/Self-Motion

Some researchers have studied the application of vibrotactile cues to induce a sense of self-motion, especially in a fixed-base driving simulator. Amemiya et al. (2013) conducted an experiment with seven subjects to study the effect of tactile flow on perceived forward velocity in the simulator. They designed and developed a tactile simulator, which was composed of voice-coil motors in a 4 x 5 array with 49 mm inter-distance and vibrating at 50 Hz (Figure 2-25). The voice-coil motors in each row vibrated for 200 ms of duration, and each row was sequentially activated with a constant interval to create the perception of motion (going forward) from front to back. During the experiment, subjects (participants) needed to estimate the velocity of self-motion from the tactile simulator compared to visual input from the monitor. The results showed that perceived forward speed increased as the visual speed and the tactile flow increased. Hence, the vibrotactile cue can enhance the perceived forward velocity in the simulator.

Figure 2-25: The tactile stimulator (Source: Amemiya et al., 2013)

2.7.5. Synopsis

Based on previous studies, haptic cues can convey different types of information that relates to driving. In an autonomous vehicle, this information can be used to increase awareness of the occupants especially for information that is associated with the change of vehicle movement that can lead to motion sickness. Although many haptic displays have been shown to be able to convey information, it should be kept in mind that almost all the haptic displays were designed for drivers and not for passengers who are riding in an autonomous vehicle. Hence, a new type of haptic display should convey the information without interrupting the passengers who are engaging in non-driving related tasks.

2.8. Chapter Summary

This chapter aimed to develop a theoretical basis for designing haptic peripheral technologies to mitigate motion sickness inside the autonomous vehicle. The level of motion sickness will be higher especially when there is a clear trend of how passengers want to spend their time during the autonomous vehicle ride. The literature review showed that by understanding the theories behind it, enhancing the awareness of autonomous vehicle passengers when engaging in non-driving related tasks could be one of the approaches that we can take in solving the issue. A new device or system that can provide essential information to the passengers in the periphery of the attention is expected to be available in the future without interrupting the engagement with non-driving related tasks. However, to evaluate such a system is not feasible in the current situation due to the non-existent commercial autonomous vehicle as a test platform. As a result, in the following chapter, we present our autonomous vehicle test platform car that was developed specifically to study human factors.

Chapter 3. Design and Development of an On-Road Autonomous Vehicle Simulator for Motion Sickness Studies

3.1. Introduction

One of the ways to study the autonomous vehicle experience is to use a driving simulator. Depending on the purpose of the study, a low-cost fixed-base driving simulator may suffice to induce an autonomous vehicle driving experience. However, as mentioned by Reymond and Kemeny (2000), an extended study that involves the physical comfort experience related to experiencing acceleration forces in a vehicle requires at least a moveable-base driving simulator system. However, most driving simulators are developed only for certain requirements and ignore other aspects of reality, which may affect the results (Molino, Opiela, Katz, & Moyer, 2005). Hence, we chose to execute our study in a real-road context with an instrumented car.

This chapter describes two phases in developing our own autonomous vehicle called Mobility Lab (Figure 3-1). The first part of this chapter is to determine how an autonomous vehicle should behave in terms of driving style. The second part of this chapter is the development of the instrumented car, specifically for our study.

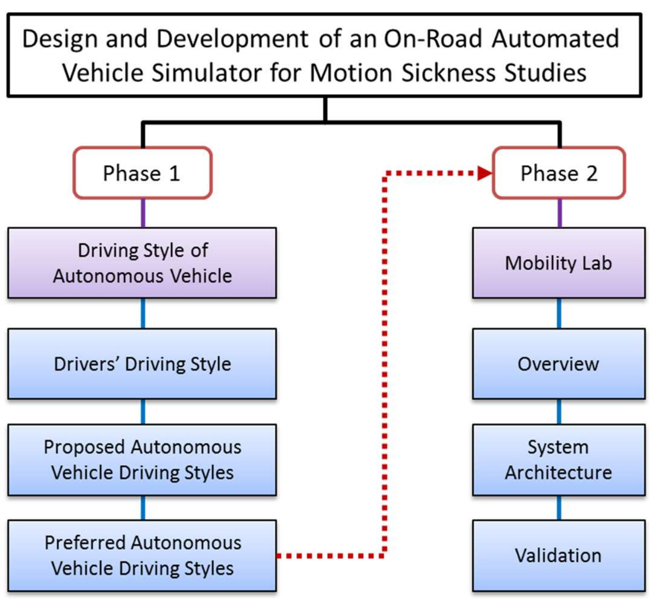


Figure 3-1: Two phases of designing and developing our Mobility Lab

3.2. Driving Style of Autonomous Vehicle

An autonomous vehicle is basically a robot, and the way it drives and decides is strictly based on optimized logic (based on algorithm outputs from sensors), which is expected to result in an optimized manner that promotes safe, reliable and comfortable driving. On the other hand, drivers drive their cars based on emotions and motivations (Summala, 2007; Vaa, 2007). Thus, the way an autonomous vehicle accelerates, decelerates, and takes a corner and a roundabout will be projected to be unfamiliar to different drivers. A conflict may arise in the driving style preferences for the different types of autonomous vehicle users such as concerning the selection of accelerations at different road profiles (e.g. intersections and corners). Thus, in order for autonomous vehicle users to feel comfortable, it might be expected that the preferences of autonomous vehicle users have to be matched with the autonomous vehicle driving style. Therefore, in this section, we will first consider differences between drivers, then design different candidate driving styles for autonomous vehicles, and then evaluate whether users of autonomous vehicles indeed prefer an autonomous vehicle driving style that matches their own driving style.

3.2.1. Drivers' Driving Style

The history of driver behaviour model development dated as far back as classic field theoretical study by Gibson and Crooks in 1938. They developed two theoretical concepts, the *field of safe travel* and the *field of minimum stopping zone*, which proposed that drivers have a *safety zone* where they detect threats (risk) and navigate the road environment by observing the impact of braking. Taylor (1964) proposed that driving is a self-paced task governed by the level of emotional tension or anxiety which the driver wishes to tolerate. Wilde (1982) described that this *level of anxiety* is a fear state coupled with subjective estimates of the probability of collision estimates, which are in turn linked to the objective probability. Hence, he developed risk homeostasis theory (RTH), representing that drivers will weigh the cost and benefits of alternative actions, in accepting a certain level of risk. As an example, the benefit of risky driving behaviour is gaining time by speeding. However, the driver may get a speeding ticket. Following the work of Taylor (1964), the first psychological theory was proposed by Näätänen and Summala (1974) as zero-risk theory, and eventually became multiple comfort zone model or safety margin model (Summala, 2007). The model describes that driving is largely driven by main motives (e.g. mobility and driving goals) and extra motives (e.g. hurry and social pressure). The comfort zone implies sufficient space and time margins around the driver, that is, to road edges, obstacles, other vehicles and, finally, to a crash.

Several self-report measures have been constructed to identify driver behaviour or driving style. However, most of the measurements only focus on certain aspects of driving. For example, the Driving Behaviour Inventory (DBI) developed by Gulian, Matthews, Glendon, Davies, and Debney (1989) studies the dimension of driver stress, and the Driving Style

Questionnaire (DSQ) developed by French, West, Elander, and Wilding (1993) studies accident involvement or risky driving behaviour.

Taubman-Ben-Ari, Mikulincer, and Gillath (2004) created the Multidimensional Driving Style Inventory (MDSI), which was modified from existing questionnaires (e.g. Gulian, Matthews, Glendon, Davies, & Debney, 1989; J. Reason, Manstead, Stradling, Baxter, & Campbell, 1990). The MDSI is a multidimensional measure that defines the driving styles of a group or population. Using a pilot sample in Israel, Taubman-Ben-Ari et al. (2004) revealed eight clear and meaningful driving styles (see Table 3-1). Hooft van Huysduynen, Terken, Martens, and Eggen (2015) further validated the developed MDSI by assessing the driving styles and driver profiles focussing on drivers in the Netherlands and Belgium. They identified six out of the original eight driving styles. In addition, Karjanto et al. (2017) used the MDSI to assess drivers in Malaysia and identified four significant driving styles.

Table 3-1: Comparison of driver's driving styles from three studies using the MDSI

Countries	Israel	Netherlands and Belgium	Malaysia
Driving Styles	Angry	Angry	Angry
	Anxious	Anxious	Anxious-Dissociative
	Dissociative	Dissociative	Careful
	Distress-Reduction	Distress-Reduction	Risky
	Careful	Careful	
	Risky	Risky	
	High-velocity		
	Patient		

The angry driving style is about expressing anger and irritation such as urging, honking and swearing, and relates to the treatment of fellow drivers. The anxious driving style is about feeling distressed and anxiety during driving. The dissociative driving style is about the driver's tendency to be easily distracted during driving that can lead to driving errors. The distress-reduction driving style is about engaging in relaxing activities during driving, aiming at reducing distress while driving. The careful driving style involves the element of planning and preparation in driving, to effectively control the trajectory of the car. The risky driving style is about seeking for thrill and sensation during driving, and drivers have a tendency to take risky and dangerous driving decisions such as driving too closely to other road users. The high-velocity driving style is about driving fast, displaying signs of time pressure while driving. The patient driving style is about being polite towards other drivers, displaying patient while driving. In Karjanto et al. (2017) work, the anxious and dissociative driving styles were combined as one driving style. This because drivers who show signs of anxiety and fear, might have less confidence in driving and might get easily distracted due to majorly focusing on the operational parts of the driving task, thus displaying dissociative driving behaviour.

According to most driving behaviour models, drivers are driving based on their own *personality traits* and *targeted feeling* (Summala, 2007; Vaa, 2013); meaning that different drivers have different driving styles. Personality traits can be regarded as dimensions of individual differences in the tendency to display consistent patterns of cognition, emotions, and behaviour. As mentioned by Vaa (2014) and Ulleberg (2002), the study of personality subtypes of young drivers provided the complete mapping of personality traits in drivers and suggested that any driver behaviour model should integrate an understanding of personality traits and how they influence behaviour in their model. Here, personality traits can be considered as driving styles as described by Elander, West, and French (1993). They define driving style as the approach of individuals manoeuvring their vehicles and something they accustom to over the years, including the selection of driving speeds in different circumstances, acceleration, distance to others, decision to overtake, and tendency to violate traffic laws.

Referring back to the literature in Section 2.3 that stated that motion sickness typically correlates with motions caused by accelerations (Donohew & Griffin, 2004; Griffin, 1990; Lawther & Griffin, 1987; Turner & Griffin, 1999b, 1999a, 1999c), choosing driving styles that relate to acceleration is our main focus.

Based on Zuckerman (1994, p. 27), the sensation-seeking trait is defined as "*seeking of varied, novel, complex, and intense sensations and experiences, and the willingness to take physical, social, legal, and financial risks for the sake of such an experience*". Arnett, Offer, and Fine (1997) found that sensation-seeking and aggressiveness traits were significantly related to reckless driving behaviour; driving over the speed limit, racing the car and overtaking other road users at no overtaking areas. However, they mentioned that the aggressive behaviour happened when a driver is in an angry mood. Delhomme, Chaurand, and Paran (2012) found that sensation-seeking is a stronger predictor of speeding than anger and that sensation-seeking is an important factor in driving behaviour. Jonah (1997) also explicitly mentioned that sensation-seeking is the main aspect that is influencing risky driving. They reviewed 40 published papers studying risky behaviour and found 10 to 15 % of the variance in risky driving correlated with the sensation-seeking trait. They highlighted that the percentage of explained variance appeared to be small due to different types of sensation-seeking measurement used in the 40 studies. Furthermore, Summala (2007) associated sensation-seeking with driving for pleasure in terms of high speed and acceleration, too close with other road users, and a tendency to be competitive on the road. Thus, sensation-seeking drivers show a more assertive driving style compared to other drivers who show a more careful or defensive driving style. Likewise, based on the questionnaire to measure sensation-seeking developed by Zuckerman, Kuhlman, Joireman, Teta, and et al. (1993), Taubman-Ben-Ari et al. (2004) found that drivers who score high in sensation-seeking were associated with risky and high-velocity driving styles, and drivers who score low in sensation-seeking were linked with a patient driving style. Karjanto et al. (2017) used the same questionnaire to investigate Malaysian drivers' driving style and found similar correlations between sensation-seeking and risky driving style. Lajunen and Summala (1997) also found a positive correlation between sensation-seeking and aggressive driving and a negative correlation between sensation-seeking and safety-oriented drivers. Both of these correlations were linked to the maximum speed and acceleration.

If we want to choose a driving style based on the acceleration forces, we define it based on the sensation-seeking trait as one-dimensional driving style. Thus, we name high sensation-seeking drivers as *assertive drivers*, who like to experience higher forces during cornering or braking. Conversely, drivers with the low sensation-seeking trait can be considered as *defensive drivers*, who show less risky driving behaviour and experience lower forces during cornering and braking.

3.2.1.1. Synopsis

In summary, driving styles differ across individuals. A driver may have several types of driving style based on his/her motives of why he/she drives in the first place (late for a meeting or an interview or relax while driving). Therefore more than one driving style for autonomous vehicle riding experience would be required (Kuderer, Gulati, & Burgard, 2015). In addition, the sensation-seeking trait was found to be associated with driving preference with regard to acceleration. Since this study focuses on motion sickness which is highly related to experiencing forces while riding in an autonomous vehicle, driving style that is based on the sensation-seeking trait or the preference on certain accelerations has been chosen for our autonomous vehicle driving style. Next, we propose specific autonomous vehicle driving styles based on the sensation-seeking dimension.

3.2.2. Proposed Autonomous Vehicle Driving Styles

In connection with the previous discussion, two types of driving styles were selected based on the sensation-seeking trait for the autonomous vehicle driving styles. We called them assertive and defensive driving styles. Thus, finding suitable ranges of acceleration is important to clearly separate both driving styles.

In terms of longitudinal acceleration, according to Bogdanović, Ruškić, Papić, and Simeunović (2013), drivers usually accelerate a car between 0.79 ms^{-2} and 4.86 ms^{-2} when leaving a signalized intersection, a junction with traffic lights. Based on their observation, they found that 45 % of 917 drivers that drove at a signalized intersection in Novi Sad, Serbia, accelerated in the range of 1.67 ms^{-2} and 2.47 ms^{-2}. Therefore, we defined the defensive driving style is lower than 2.47 ms^{-2}, and the assertive driving style is between 2.47 ms^{-2} and 4.86 ms^{-2} for the longitudinal acceleration.

Regarding the deceleration or braking, when approaching a signalized intersection, El-Shawarby, Rakha, Inman, and Davis (2007) found that drivers decelerate a car within a range from 1.51 ms^{-2} to 7.47 ms^{-2}. Based on the 821 deceleration events from 60 drivers, the mean value of deceleration is 3.27 ms^{-2}. Thus, we used the deceleration value of 3.27 ms^{-2} as a cut-off between the defensive and assertive driving styles.

As regards the lateral acceleration, the ranges are influenced by the radius of the corner *r* and also the speed of the car *v* (Hugemann & Nickel, 2003). 11 drivers participated in Hugemann and Nickel (2003) study and drove on a specific route. One part of the route consisted of 27 alternating corners between 10 m and 300 m radius. They found that the lateral acceleration was 3.10 ms^{-2} (10^{th} percentile), 4.10 ms^{-2} (50^{th} percentile) and 5.30 ms^{-2} (90^{th} percentile) for the corner with a radius from 20 m to 40 m. So, we separated the defensive and assertive driving styles based on the 50^{th} percentile value (4.10 ms-2) for the lateral acceleration.

For the vertical acceleration, it is usually measured as the peak vertical acceleration. The acceleration ranges are influenced by the size of a speed hump or speed bump and the speed of the car (P. A. Weber & Braaksma, 2000). The main difference between a speed hump and a speed bump is that the former is designed for a vehicle to traverse at a low speed (15-30 kmh^{-1}) without the need to slow down while the latter requires a vehicle to decelerate up to 8 kmh^{-1} when arriving at the tip of the bump (Fwa & Liaw, 1992; Institute of Transportation Engineers, 1999). According to Fwa and Liaw (1992), most drivers would avoid crossing a speed hump that induces a peak vertical acceleration above 6.86 ms^{-2} (or 0.70 g), and a mean value of 7.25 ms^{-2} (or 0.74 g) would be an acceptable choice when designing a speed hump. Although a peak vertical acceleration of 5.59 ms^{-2} (or 0.57 g) is acceptable for drivers (P. A. Weber & Braaksma, 2000), according to the ISO 2631-1 (ISO, 1997), acceleration below 0.32 ms^{-2} is considered acceptable for passengers doing non-driving related tasks (e.g. reading, eating, writing, etc.).

Furthermore, in order to enable the passengers to comfortably engage with non-driving related tasks (such as drinking and eating without spilling), the autonomous vehicle is predicted to have a smooth acceleration or deceleration and is suggested to accelerate and decelerate slower than a typical car or equal to a train (Le Vine et al., 2015). Le Vine et al. (2015) proposed that an autonomous vehicle should behave like a light rail transit (LRT), a form of urban rail transport similar to a tram. LRT has a typical maximum acceleration and deceleration at 1.34 ms^{-2} (Parsons Brinckerhoff Inc, 2012, p. 2-38) and LRT passengers can endure a lateral acceleration within a range of 0.1 g to 0.15 g (Parsons Brinckerhoff Inc, 2012, p. 2-40).

Hence, we added another driving style for autonomous vehicle and called it LRT driving style. All three types of driving style are defined based on ranges of acceleration (Table 3-2). There is no LRT driving style for vertical acceleration since there is no speed hump for the train track. In addition, the vertical acceleration of 1.60 ms^{-2} has been selected as a boundary between the defensive and assertive driving styles, in which this vertical acceleration is rated as "*uncomfortable*" in the ISO 2631-1 (ISO, 1997). For the high-end value of assertive driving style range in vertical acceleration, we are averaging the acceptable accelerations; when designing a speed hump (Fwa & Liaw, 1992) and when drivers cross the speed hump (P. A. Weber & Braaksma, 2000). However, it should be noted here that although we propose ranges of vertical acceleration for autonomous vehicle driving styles, we are not investigating any of the driving styles based on the vertical direction as it usually occurs when a vehicle is passing through a speed hump which is uncommon to have lots of speed hump on a road, and the speed hump itself is meant to urge drivers slowing down the vehicle.

Table 3-2: Ranges of acceleration for LRT, defensive and assertive driving style

Type of Acceleration	LRT Driving Style	Defensive Driving Style	Assertive Driving Style
Longitudinal Acceleration	0 g to 0.14 g ($0\ ms^{-2}$ to $1.34\ ms^{-2}$)	0.14 g to 0.25 g ($1.34\ ms^{-2}$ to $2.47\ ms^{-2}$)	0.25 g to 0.50 g ($2.47\ ms^{-2}$ to $4.86\ ms^{-2}$)
Longitudinal Deceleration	0 g to -0.14 g ($0\ ms^{-2}$ to $-1.34\ ms^{-2}$)	-0.14 g to -0.33 g ($-1.34\ ms^{-2}$ to $-3.27\ ms^{-2}$)	-0.33 g to -0.76 g ($-3.27\ ms^{-2}$ to $-7.47\ ms^{-2}$)
Lateral Acceleration	0 g to 0.15 g ($0\ ms^{-2}$ to $1.47\ ms^{-2}$)	0.15 g to 0.42 g ($1.47\ ms^{-2}$ to $4.10\ ms^{-2}$)	0.42 g to 0.54 g ($4.10\ ms^{-2}$ to $5.30\ ms^{-2}$)
Vertical Acceleration	n/a	0.00 g to 0.16 g ($0\ ms^{-2}$ to $1.60\ ms^{-2}$)	0.16 g to 0.66 g ($1.60\ ms^{-2}$ to $6.47\ ms^{-2}$)

3.2.3. Preferred Autonomous Vehicle Driving Styles

A study was carried out to explore preferences of autonomous vehicle users (the assertive and defensive drivers), especially for the selection of the accelerations in three directions (longitudinal, lateral and vertical directions) for three defined autonomous vehicle driving styles (LRT, defensive and assertive driving styles) (see Md. Yusof et al., 2016). However, since our study was aimed to be conducted on the real-road environment, another study was done first to investigate whether or not the selected ranges of acceleration in defining autonomous vehicle driving style could be executed consistently.

3.2.3.1. Validation of Consistency of Simulated Driving Style

Although we already defined the autonomous vehicle driving styles, we need to determine whether drivers can consistently execute that specific driving style. In this validation study, we present a device that can help and guide drivers to achieve defined accelerations while driving a car.

3.2.3.1.1. Methodology

Automatic Acceleration and Data controller (AUTOAccD). For realizing an autonomous vehicle driving style, a device was developed to assist a driver to drive according to the defined acceleration in the autonomous vehicle driving style. In addition, this device also measures and collects the vehicle dynamics data such as the speed of the vehicle for later analysis. Hence, we named the device Automatic Acceleration and Data controller (AUTOAccD).

The AUTOAccD was developed based on projects from Freematics (“Freematics,” 2014) as a data logger in a vehicle. The AUTOAccD consists of three main parts; a microcontroller board, an OBD-II adapter, and a GPS receiver (Figure 3-2). The microcontroller board is an Arduino MEGA 2560 R3 board with 3.2 inch TFT LCD touch display shield for a real-time data display and a micro secure digital (microSD) slot for data storage. The OBD (onboard diagnostics) is referring to a vehicle's self-diagnostic and reporting capability which is able to monitor real-time vehicle parameters such as the speed of the car, throttle position, and status of the engine. The OBD-II adapter also contains a triple-axis micro-electro-mechanical systems (MEMS) accelerometer and a gyroscope. The GPS receiver has the capability of a 5 Hz update rate.

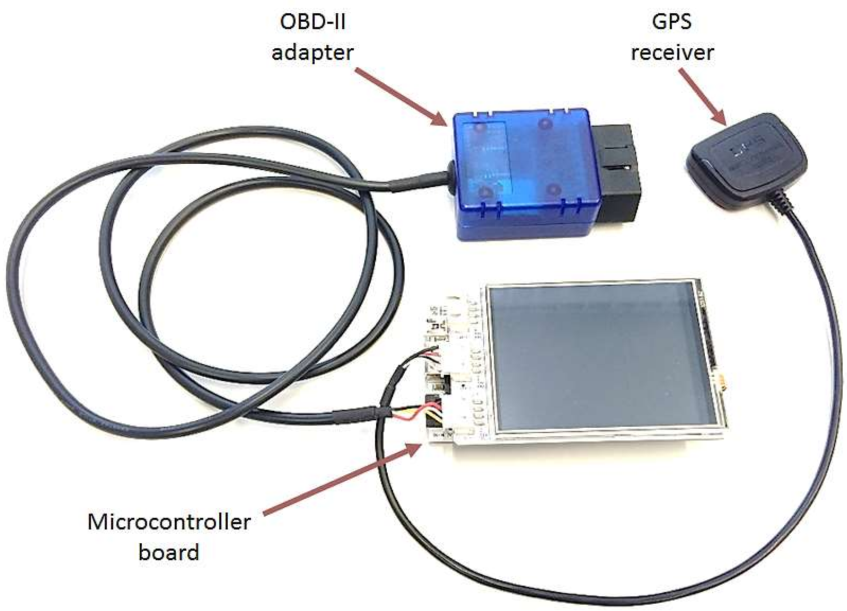
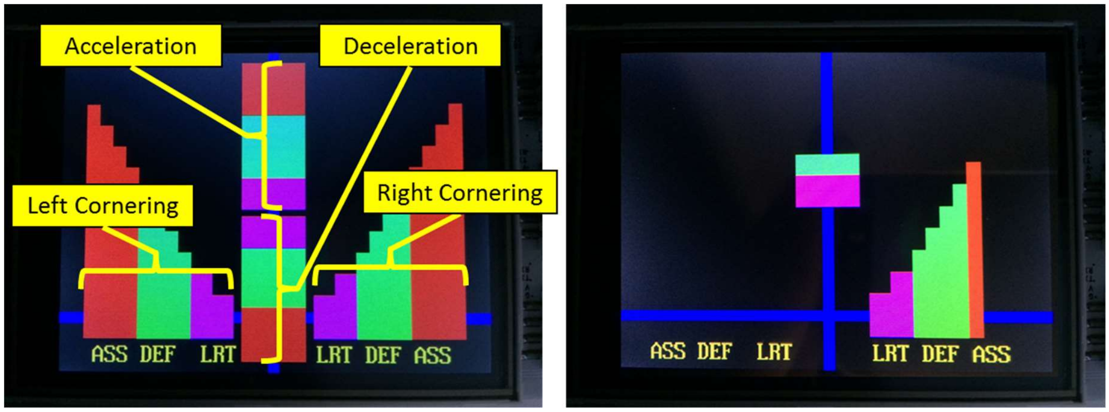


Figure 3-2: Automatic Acceleration and Data controller (AUTOAccD)

The display was designed to guide a driver in maintaining a certain autonomous vehicle driving style by displaying the defined ranges of lateral and longitudinal acceleration while driving a car. There is no indication of vertical acceleration due to the fact that the vertical acceleration in a vehicle usually happens due to the road surface in a very short time. The display is only showing the ranges of the acceleration in colours without numbers to reduce cognitive workload for the driver (Figure 3-3). Purple colour represents a set of range of an LRT driving style, green colour represents a set of range of a defensive driving style, and red colour represents a set of range of an assertive driving style. The two blue lines are perpendicular to each other representing the longitudinal direction (upward movement indicates acceleration and downward movement indicates deceleration of the car) and the lateral direction (rightward movements indicates cornering to the right and vice versa). See Figure 3-3 (b) for an example of the display during driving.



(a) (b)

Figure 3-3: AUTOAccD display. (a) All colours are shown on display representing ranges of driving styles (LRT = purple, defensive = green, and assertive = red) and directions of the accelerations. (b) Example of the display showing the defensive driving style in longitudinal acceleration with the assertive driving style when cornering to the right.

Experiment Setup. Two designated drivers (driver A and B), who are experienced drivers with a valid driving license, took part in the study. An Audi A3 (Figure 3-4), a family-sized car with a manual gearbox, was used as a testing vehicle for this experiment, provided by the Automotive Engineering Science (AES) Laboratory, Eindhoven University of Technology (TU/e), the Netherlands. The study was carried out based on two different urban road profiles consisting of a junction and a corner (Figure 3-5). The junction is used to assess acceleration and braking in the leaving- and approaching-a-junction scenarios. The corner is used to assess the lateral acceleration in the taking-a-corner scenario. The route is located within the TU/e. Each driver drove five times for every type of driving style in all four scenarios. The AUTOAccD was placed on the windshield of the car (Figure 3-6). The OBD-II adapter was coupled to an OBD connector in the car, located on the driver side underneath the steering wheel. The study was done during the weekend to avoid any other traffic that would impede the acceleration process and for safety purpose. For additional safety precaution, the TU/e security was informed about the study and permission to use the designated route was granted.

Figure 3-4: The Audi A3

Figure 3-5: A straight lane approaching a junction (left), and a corner turn to the right (right)

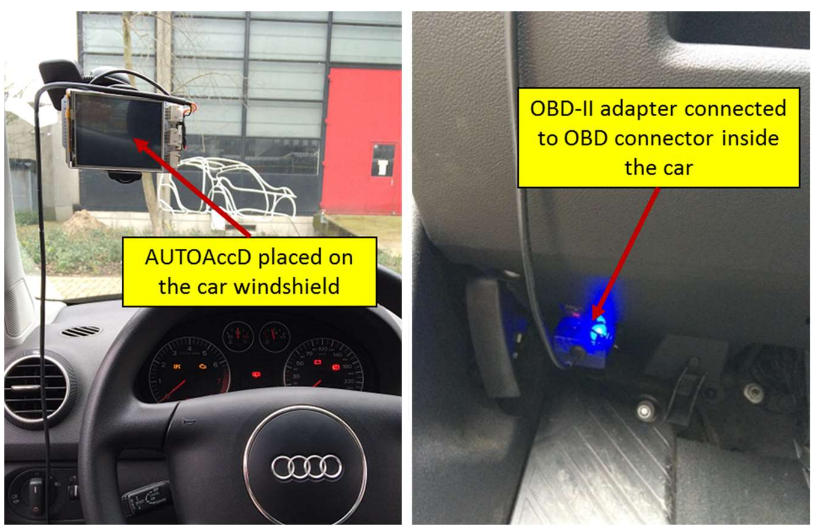


Figure 3-6: AUTOAccD placement inside the Audi A3 (Adapted from Karjanto et al., 2017)

Selected Accelerations. Based on the defined ranges of acceleration for autonomous vehicle driving style (refer to Table 3-2), the designated drivers were instructed to achieve specific accelerations in every autonomous vehicle driving style. In general, both drivers were instructed to drive with the LRT driving style in which the intended accelerations fall at the boundary between LRT and defensive driving style as shown on the AUTOAccD display (Figure 3-7). For the defensive and assertive driving styles, the drivers were instructed to drive with accelerations in the middle of both driving styles.

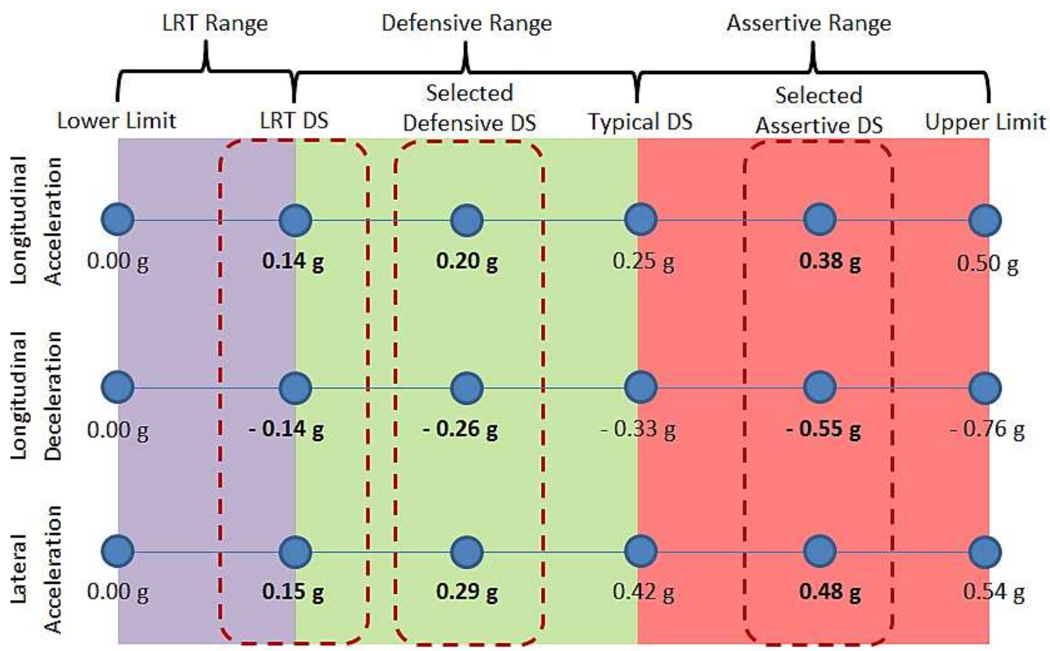


Figure 3-7: The range of selection for autonomous vehicle driving styles (DS) for longitudinal and lateral accelerations. The purple, green and red coloured areas represent the driving style ranges based on defined accelerations in Table 3-2. (Adapted from Karjanto et al., 2017)

Road Scenarios. In the leaving-a-junction scenario, the drivers were instructed to accelerate (with 0.14 g, 0.20 g, and 0.38 g) in a smooth motion without jerking (no gear changing except the first gear). The car was accelerated until a speed of 30 kmh^{-1} is achieved. In the approaching-a-junction scenario, the driver was instructed to drive the car with 30 kmh^{-1} speed, and then to decelerate (with -0.14 g, -0.26 g and -0.55 g) the car to a complete stop.

In the taking-a-corner scenario, it was important that the speed of the car and the radius of the corner were maintained as long as possible (Figure 3-8).

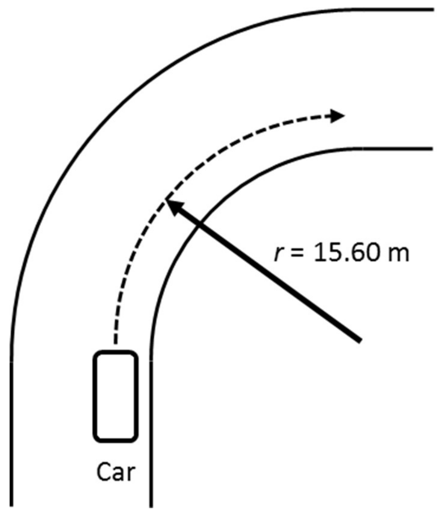


Figure 3-8: The taking-a-corner scenario

The drivers were instructed to stay in their lane when taking a corner to the right. Using the centrifugal acceleration a_c (the lateral acceleration), that was defined as:

$$a_c = \frac{v^2}{r} \tag{3-1}$$

where v is the speed in the corner and r is the radius of the corner (measured as 15.60 m), the drivers needed to maintain a certain speed in the corner to induce a specific autonomous vehicle driving style as an addition to the guide from AUTOAccD (about 17 kmh^{-1}, 24 kmh^{-1} and 31 kmh^{-1} for LRT, defensive and assertive driving style, respectively).

Data Collection and Analysis. Rather than using the traditional filters for de-noising such as time-frequency domain like Fourier transform, a time-scale domain filter known as Wavelet transform in a software called MATLAB (MathWorks Inc., 2015) was used. The Wavelet de-noising method was applied because of its ability to remove noises and retain the signal regardless of the frequency of the signal (Kang, Kang, & Park, 2010; Taswell, 2000). The Daubechies filter level three (Db3) was used in order to remove the high-frequency noise from the MEMS accelerometers (Hasan, Samsudin, Ramli, & Azmir, 2010).

The analyses started with the process of filtering or de-noising of the signal attained from the accelerometers. Wavemenu functions in Matlab were used for its simplicity and its elegant visual tools that enable the users to interactively de-noise a signal and instantaneously show the result on the screen (Misiti, Misiti, Oppenheim, & Poggi, 1996). After the de-noising process, the accelerations data (peak values) from the two designated drivers were compared to check the ability of the AUTOAccD in assisting the drivers in simulating the intended accelerations.

3.2.3.1.2. Results and Discussion

In the comparison of simulating autonomous vehicle driving styles between the two designated drivers, the means of the acceleration indicated that both drivers generally managed to induce accelerations within the designated ranges of an autonomous vehicle driving styles (Table 3-3, also see Table 3-2). Moreover, the low standard deviations in all scenarios (except in the taking-a-corner scenario with assertive driving style) showed that both drivers were very consistent in simulating the autonomous vehicle driving styles.

Table 3-3: Comparison of the mean (M) and standard deviation (SD) in g between the two designated drivers in simulating autonomous vehicle driving style and the targeted acceleration (TA)

Type of acceleration	LRT driving style			Defensive driving style			Assertive driving style		
	TA	Driver A Mean (SD)	Driver B Mean (SD)	TA	Driver A Mean (SD)	Driver B Mean (SD)	TA	Driver A Mean (SD)	Driver B Mean (SD)
Longitudinal acceleration	0.14	0.11 (0.01)	0.06 (0.03)	0.20	0.19 (0.06)	0.25 (0.05)	0.38	0.42 (0.08)	0.40 (0.06)
Longitudinal deceleration	-0.14	-0.13 (0.01)	-0.17 (0.02)	-0.26	-0.30 (0.04)	-0.33 (0.05)	-0.55	-0.47 (0.07)	-0.49 (0.06)
Lateral acceleration	0.15	0.12 (0.06)	0.12 (0.02)	0.29	0.30 (0.03)	0.32 (0.03)	0.48	0.47 (0.11)	0.46 (0.14)

For longitudinal acceleration and deceleration, both drivers had fluctuating accelerations and were less consistent in the defensive and assertive driving styles compared to the LRT driving style (Figure 3-9 and Figure 3-10). In both figures, the purple, green and red coloured areas represent the driving style ranges based on defined accelerations in Table 3-2, and the targeted driving styles were the selected accelerations that both drivers need to achieve in this validation study. Although a higher acceleration can successfully be achieved with a lower transmission, the maximum speed of 30 kmh^{-1} used in the study can be achieved in less than two seconds. This is also the same as in the approaching-a-junction scenario in which the car is coming to a complete stop in just a little over one second. Both drivers might have difficulty to achieve proper acceleration in a very short period.

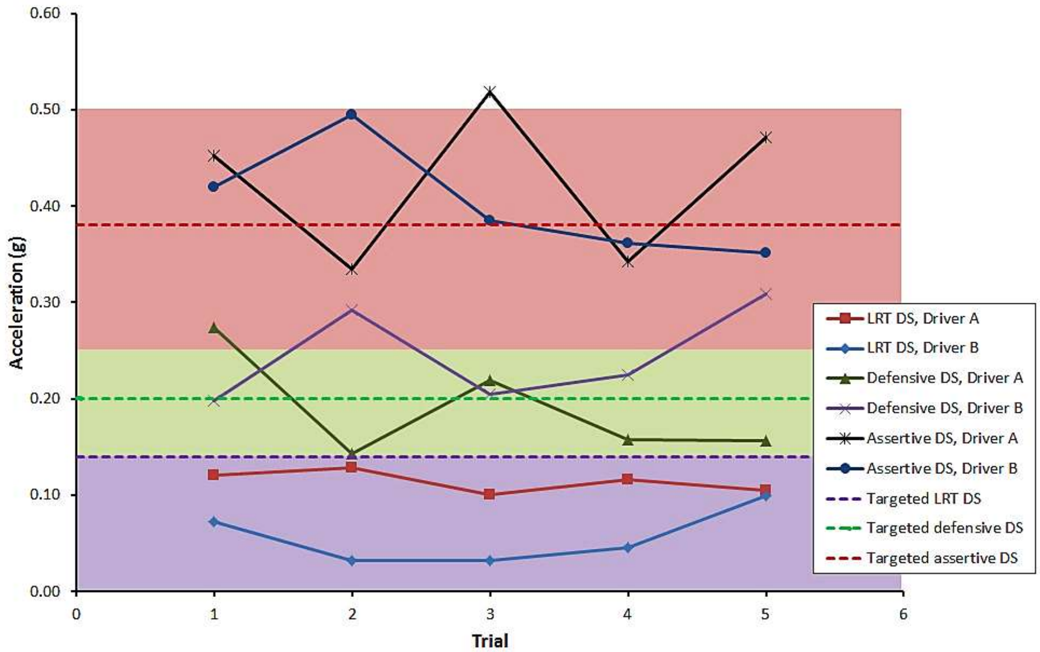


Figure 3-9: Tabulated longitudinal accelerations of the autonomous vehicle driving styles (DS) (Adapted from Karjanto et al., 2017)

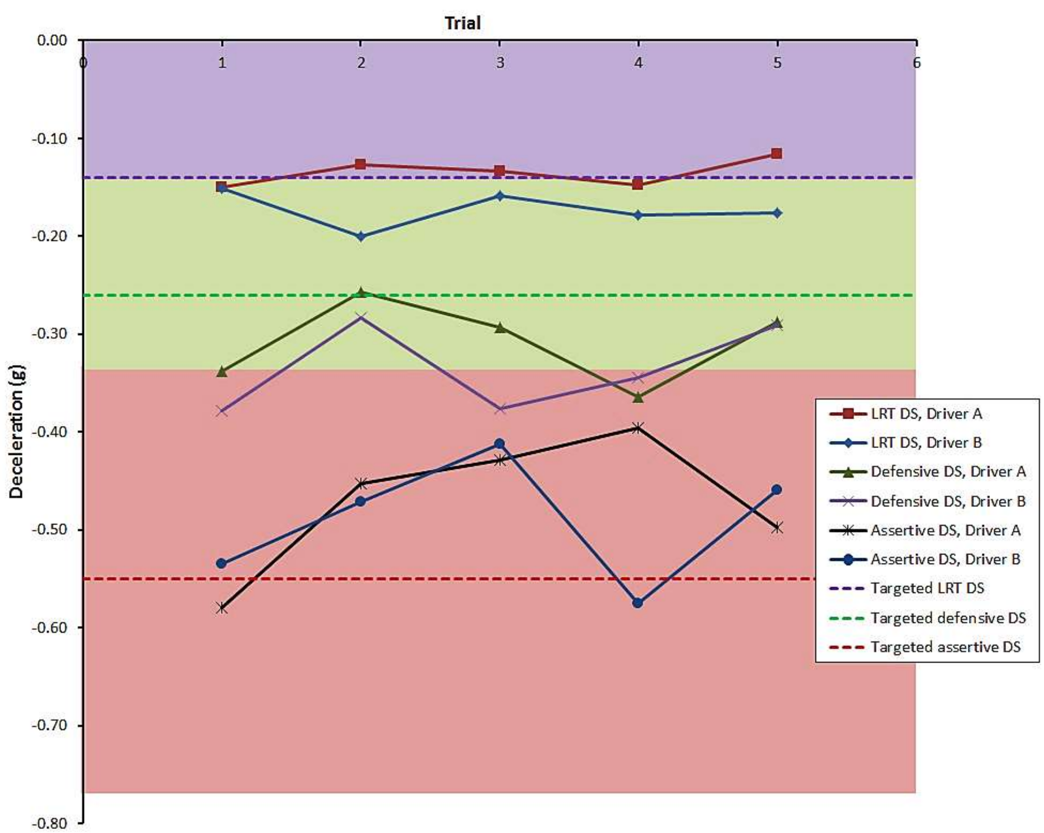


Figure 3-10: Tabulated longitudinal decelerations of the autonomous vehicle driving styles (DS) (Adapted from Karjanto et al., 2017)

For lateral acceleration, both drivers consistently managed to simulate the LRT and defensive driving styles, but not the assertive driving style (Figure 3-11). According to the centrifugal acceleration a_c formula in page 54, with the targeted acceleration at 0.48 g and the radius of the corner at 15.60 m, both drivers had about 2.8 s to maintain the assertive driving style in the corner. Although both drivers had more time to maintain the assertive driving style in the corner compared to longitudinal acceleration, maintaining the exact radius of travelling in the corner is quite difficult as the corner used in this study does not have any road markings on the surface. As mentioned by Charlton (2007), a clearer and more accurate guideline should be implemented, for example, line marking on the road surface where both drivers can align themselves for more accurate results in cornering.

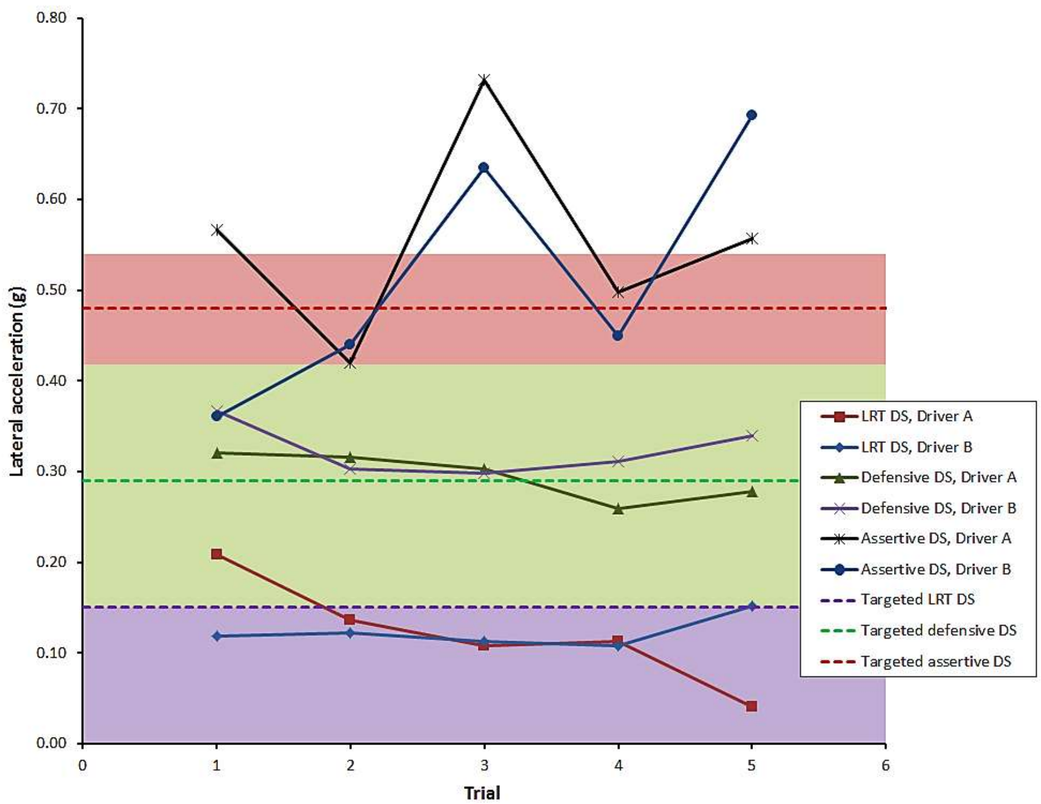


Figure 3-11: Tabulated lateral accelerations of the autonomous vehicle driving styles (DS) (Adapted from Karjanto et al., 2017)

3.2.3.1.3. Conclusion

In general, the display of the AUTOAccD that shows the real-time accelerations in terms of coloured bars manages to guide both drivers to easily understand how much higher or lower acceleration is needed to maintain the simulated autonomous vehicle driving styles. The differences in the mean of the acceleration between both designated drivers are not significant, and both drivers generally managed to induce accelerations within the designated ranges of autonomous vehicle driving style. However, when looking into each trial, we found that both drivers did not always manage to achieve good consistency, especially in the assertive driving style. One of the possible reasons might be that the validation study was conducted in a low-speed environment where it was difficult to maintain acceleration in assertive driving style in a very short period. The AUTOAccD implementation may be suitable for the high-speed environment for the assertive driving style. Nevertheless, a series of training exercises could be done for the driver who is designated for our study to simulate an assertive driving style in a low-speed environment.

3.2.3.2. Evaluation of Proposed Autonomous Driving Style

In line with the idea that drivers are primarily comfortable with their own driving styles, we hypothesized that drivers with assertive and defensive driving styles (known as assertive and defensive drivers) were expected to be only comfortable with the matching type of driving styles in the autonomous vehicle (Table 3-4). In addition, both types of drivers were expected to feel uncomfortable with the LRT driving style due to the very defensive driving style. This evaluation study is compliant with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) (Association of Universities in the Netherlands [VSNU], 2014).

Table 3-4: Hypothesized autonomous vehicle driving styles preferences

		Types of Driver	
		Assertive	**Defensive**
Type of Autonomous Vehicle Driving Style	**Assertive**	Comfortable	Uncomfortable
	Defensive	Uncomfortable	Comfortable
	LRT	Uncomfortable	Uncomfortable

3.2.3.2.1. Methodology

Equipment and Wizard Setup. The same Audi A3 from the previous validation study (Section 3.2.3.1) was used. The autonomous vehicle driving styles were simulated by a driving wizard, who was an experienced driver with a valid driving license. The Driving Wizard was implemented based on the method developed by Baltodano, Sibi, Martelaro, Gowda, and Ju (2015). The main role of the driving wizard was to consistently induce the corresponding accelerations based on the autonomous vehicle driving styles. Hence, the AUTOAccD (see Section 3.2.3.1.1) was used in the car to provide a continuous real-time induced acceleration at the desired locations. A series of training exercises were conducted before the study took place in order to make sure the driving wizard was able to maintain the desired accelerations at constant rates. In addition, the experimenter was in the car to complement the driving wizard. The primary role of the experimenter was to assist participants at any time and handling the questionnaires to participants during the experiment.

Road Scenarios. This study was conducted at the same locations as in the previous study within the TU/e compound (see Section 3.2.3.1). The selected locations will be known as points of interest (POI), where we probed participants' opinions about the simulated autonomous vehicle driving styles (see Figure 3-5). POI A and POI B were located on a straight road leaving or approaching a junction, where longitudinal acceleration and deceleration were simulated. POI C was located on a curved road with a radius of 15.60 m (see Figure 3-8) where lateral acceleration was simulated. All simulated accelerations were based on Figure 3-7. The total length of the track was around 440 meters. For additional safety precaution, the TU/e security was informed about the study and permission to use the designated route was granted.

Participants. Twelve participants (7 male and 5 female) who owned valid driving licenses participated voluntarily in this study. They were all employees or students at the TU/e and aged between 24 and 39 years old (mean = 29.6, SD = 4.0). Before participating, they answered the sensation-seeking questionnaire. Sensation-seeking is typically measured using Form V of the Sensation Seeking Scale (SSS-V; Zuckerman, 1996). The SSS-V consists of 40 items and uses a forced-choice format. However, several of the SSS-V items describe specific activities, and these render the SSS-V not fully relevant as a sensation-seeking measure for some studies. Thus, a new measure called the Zuckerman-Kuhlman Personality Questionnaire (ZKPQ; Zuckerman, 2002; Zuckerman, Kuhlman, Joireman, Teta, & et al., 1993) was developed based on the SSS-V. It consists of 99 true-false items which divided into 5 scales. The impulsive sensation seeking (ImpSS) scale describes a general need for thrills and excitement and consists of 19 true-false items (see Appendix 1). On the basis of the ImpSS questionnaire's score, the participants were classified as assertive (6 participants) or defensive (6 participants) drivers. Drivers with high sensation-seeking scores (between 10 and 19) were considered as assertive drivers, while drivers with low sensation-seeking scores (between 0 and 9) were considered as defensive drivers.

Ratings. A comfort rating survey was used to investigate participants' preferences on the autonomous vehicle driving styles by eliciting the participants' judgement at every POI (see Appendix 2). The survey is a 5-point Likert scale from 1 to 5 which a lower number is indicating a positive preference and vice versa. The survey consists of five items labelled as R1, R2, R3, R4, and R5. R1, R2, and R3 asked about the opinion of the autonomous vehicle driving behaviour with regard to comfort, pleasantness, and safety. R4 asked about participants' self-reflection on their own driving style when compared to the simulated autonomous vehicle driving style. R5 asked about participants' opinion on the magnitude of the simulated autonomous vehicle driving styles.

Procedure. Upon arrival, the participant was briefed about the nature of the experiment, especially the role of the participant during the experiment and was asked to sign the informed consent form (see Appendix 3). Then, the participant was brought to the car and once the participant was seated in the back seat, reminders of the safety measures such as fasten the seatbelt were given by the experimenter.

Then, the driving wizard drove the car to the first POI, POI A. Just before arriving at the POI A, the car was stopped, and the experimenter gave a short briefing to the participant about the induced force to be generated from the acceleration when the vehicle was passing through

POI A. Afterwards, the driving wizard drove through POI A with a defined autonomous vehicle driving style according to the selected acceleration based on Figure 3-7. Once the autonomous vehicle driving style had been simulated, the car was stopped again, and the experimenter handed out the comfort rating survey to the participant. The participant gave the ratings directly after experiencing the force, in order to minimize the washout effects. In addition, the car needed to be in a standstill position when the participants were engaged in the rating task to reduce any carsickness symptoms (Diels & Bos, 2016). After the participant completed the ratings for the current POI, the driving wizard drove the car to the next POI. This sequence was repeated at POI B and C.

To balance order effects, the order of simulated autonomous vehicle driving styles was counter-balanced for all participants, so that all orders occurred equally often (3! = 6 orders). Within a ride, always the same autonomous vehicle driving style was presented. After all three types of autonomous vehicle driving styles had been simulated, the participant was brought back to the starting point for a short debriefing and was given a small voucher as a token of appreciation. The total length of the session was around 45 minutes.

3.2.3.2.2. Results and Discussion

Statistical analysis was performed with IBM SPSS Statistics Version 23 (IBM Corp, 2015). The Friedman's test (Friedman, 1937) was used to compare the ratings for all three simulated autonomous vehicle driving styles at POI A, B, and C (leaving or approaching a junction and the corner). If there was a significant result from Friedman's test, post-hoc analyses with the Wilcoxon signed-ranks test (Wilcoxon, 1945) were conducted with Bonferroni correction (Bland & Altman, 1995) applied, setting $p_{crit} < 0.017$ (Field, 2009, p. 577).

In leaving a junction scenario at POI A, for assertive drivers, the ratings for comfort, pleasantness, and safety were lower (indicating better appreciation) for defensive and LRT driving styles than for assertive driving style, but none of the comparisons gave a significant effect (Table 3-5). The same direction of judgements (better appreciation of defensive and LRT driving styles) was obtained from defensive drivers with all comparisons being not significant if the Bonferroni adjustment of p_{crit} was applied. If the adjustment was not applied, most comparisons being significant, except for the differences between defensive and LRT defensive driving styles in all three ratings.

In approaching a junction scenario at POI B, the pattern was the same as in leaving a junction scenario, with a better appreciation of defensive and LRT driving styles, for both assertive and defensive drivers (Table 3-6). However, due to the Bonferroni adjustment of p_{crit} for multiple comparisons, there were no significant results in the post-hoc tests. Again, if the adjustment was not applied, most comparisons being significant, except for the differences between defensive and LRT defensive driving styles in all three ratings. In general, both types of drivers indicated uncomfortable, unpleasant and unsafe feelings with assertive driving style for the braking scenario. On the other hand, both types of drivers showed comfortable, pleasant and safe feelings with defensive and LRT driving styles.

Table 3-5: Rating analysis of autonomous vehicle driving style preferences at POI A (leaving a junction)

<table>
<tr><th></th><th>Types of Drivers</th><th>Autonomous Vehicle Driving Styles</th><th>Median</th><th>Friedman's Test Result</th><th>Group</th><th>Wilcoxon Signed-Rank Test</th></tr>
<tr><td rowspan="6">R1. Comfort</td><td rowspan="3">Assertive</td><td>Assertive</td><td>4.0</td><td rowspan="3">$\chi^2(2) = 2.21$, $p = 0.331$</td><td colspan="2" rowspan="3">n/a</td></tr>
<tr><td>Defensive</td><td>3.0</td></tr>
<tr><td>LRT</td><td>2.5</td></tr>
<tr><td rowspan="3">Defensive</td><td>Assertive</td><td>4.0</td><td rowspan="3">$\chi^2(2) = 10.18$, $p = 0.006$*</td><td>Assertive
Defensive</td><td>z = -2.22, p = 0.026*,
r = -0.64</td></tr>
<tr><td>Defensive</td><td>2.0</td><td>Assertive
LRT</td><td>z = -2.21, p = 0.027*,
r = -0.64</td></tr>
<tr><td>LRT</td><td>2.0</td><td>Defensive
LRT</td><td>z = -0.38, p = 0.705,
r = -0.11</td></tr>
<tr><td rowspan="6">R2. Pleasantness</td><td rowspan="3">Assertive</td><td>Assertive</td><td>4.0</td><td rowspan="3">$\chi^2(2) = 4.10$, $p = 0.129$</td><td colspan="2" rowspan="3">n/a</td></tr>
<tr><td>Defensive</td><td>1.5</td></tr>
<tr><td>LRT</td><td>2.5</td></tr>
<tr><td rowspan="3">Defensive</td><td>Assertive</td><td>4.0</td><td rowspan="3">$\chi^2(2) = 10.38$, $p = 0.006$*</td><td>Assertive
Defensive</td><td>z = -2.23, p = 0.026*,
r = -0.64</td></tr>
<tr><td>Defensive</td><td>2.0</td><td>Assertive
LRT</td><td>z = -2.26, p = 0.024*,
r = -0.65</td></tr>
<tr><td>LRT</td><td>2.0</td><td>Defensive
LRT</td><td>z = -0.58, p = 0.564,
r = -0.17</td></tr>
<tr><td rowspan="6">R3. Safety</td><td rowspan="3">Assertive</td><td>Assertive</td><td>3.5</td><td rowspan="3">$\chi^2(2) = 4.57$, $p = 0.102$</td><td colspan="2" rowspan="3">n/a</td></tr>
<tr><td>Defensive</td><td>2.0</td></tr>
<tr><td>LRT</td><td>1.5</td></tr>
<tr><td rowspan="3">Defensive</td><td>Assertive</td><td>4.0</td><td rowspan="3">$\chi^2(2) = 10.17$, $p = 0.006$*</td><td>Assertive
Defensive</td><td>z = -2.26, p = 0.024*,
r = - 0.65</td></tr>
<tr><td>Defensive</td><td>2.0</td><td>Assertive
LRT</td><td>z = -2.25, p = 0.024*,
r = - 0.65</td></tr>
<tr><td>LRT</td><td>1.5</td><td>Defensive
LRT</td><td>z = -1.34, p = 0.180,
r = -0.39</td></tr>
</table>

Note:
** Indicates significant effect (p < .05)*
The rating is a 5-point scale, 1= positive opinion, 5 = negative opinion.

In taking a corner scenario at POI C, the same trend emerged as for the other POIs, with a better appreciation of defensive and LRT driving styles than of assertive driving style, although the differences in ratings were smaller (Table 3-7). However, the ratings for the assertive driving style, in general, were less negative than for the other POIs. The effect of the autonomous vehicle driving styles was significant for ratings of comfort and safety, both for assertive and defensive drivers, but not for ratings of pleasantness. For comfort ratings, based on post-hoc analyses, both for assertive and defensive drivers, the differences between assertive and defensive driving styles and between assertive and LRT driving styles were only significant if the Bonferroni adjustment of p_{crit} was not applied. For safety ratings, the difference between assertive and defensive driving styles for both types of drivers gave significant results without the application of Bonferroni adjustment of p_{crit}.

Table 3-6: Rating analysis of autonomous vehicle driving style preferences at POI B (approaching a junction)

	Types of Drivers	Autonomous Vehicle Driving Styles	Median	Friedman's Test Result	Group	Wilcoxon Signed-Rank Test
R1. Comfort	Assertive	Assertive	4.0	$\chi^2(2) = 8.27$, $p = 0.016$*	Assertive Defensive	z = -2.22, p = 0.026*, r = -0.64
		Defensive	2.0		Assertive LRT	z = -2.12, p = 0.034*, r = -0.61
		LRT	1.0		Defensive LRT	z = -0.28, p = 0.783, r = -0.08
	Defensive	Assertive	4.0	$\chi^2(2) = 6.10$, $p = 0.047$*	Assertive Defensive	z = -2.07, p = 0.038*, r = -0.60
		Defensive	2.0		Assertive LRT	z = -1.83, p = 0.068, r = -0.53
		LRT	2.0		Defensive LRT	z = -0.41, p = 0.680, r = -0.12
R2. Pleasantness	Assertive	Assertive	4.0	$\chi^2(2) = 7.18$, $p = 0.028$*	Assertive Defensive	z = -2.12, p = 0.034*, r = -0.61
		Defensive	3.0		Assertive LRT	z = -2.06, p = 0.039*, r = -0.59
		LRT	1.0		Defensive LRT	z = -1.22, p = 0.222, r = -0.35
	Defensive	Assertive	4.0	$\chi^2(2) = 8.40$, $p = 0.015$*	Assertive Defensive	z = -2.00, p = 0.046*, r = -0.58
		Defensive	2.0		Assertive LRT	z = -2.32, p = 0.026*, r = -0.64
		LRT	2.0		Defensive LRT	z = -1.13, p = 0.257, r = -0.33
R3. Safety	Assertive	Assertive	3.5	$\chi^2(2) = 10.30$, $p = 0.006$**	Assertive Defensive	z = -2.04, p = 0.041*, r = -0.59
		Defensive	2.0		Assertive LRT	z = -2.23, p = 0.026*, r = -0.64
		LRT	1.0		Defensive LRT	z = -1.73, p = 0.083, r = -0.50
	Defensive	Assertive	3.5	$\chi^2(2) = 6.91$, $p = 0.032$*	Assertive Defensive	z = -2.27, p = 0.023*, r = -0.58
		Defensive	2.0		Assertive LRT	z = -1.84, p = 0.066, r = -0.53
		LRT	2.0		Defensive LRT	z = -0.33, p = 0.739, r = -0.10

Note:
** Indicates significant effect (p < .05)*
The rating is a 5-point scale, 1= positive opinion, 5 = negative opinion.

Table 3-7: Rating analysis of autonomous vehicle driving style preferences at POI C (taking a corner)

	Types of Drivers	Autonomous Vehicle Driving Styles	Median	Friedman's Test Result	Group	Wilcoxon Signed-Rank Test
R1. Comfort	Assertive	Assertive	3.5	$\chi^2(2) = 10.18$, p = 0.006*	Assertive Defensive	z = -2.33, p = 0.020*, r = -0.67
		Defensive	1.5		Assertive LRT	z = -2.23, p = 0.026*, r = -0.64
		LRT	1.0		Defensive LRT	z = -1.00, p = 0.317, r = -0.29
	Defensive	Assertive	3.0	$\chi^2(2) = 10.30$, p = 0.006*	Assertive Defensive	z = -2.07, p = 0.038*, r = -0.60
		Defensive	2.0		Assertive LRT	z = -2.27, p = 0.023*, r = -0.66
		LRT	2.0		Defensive LRT	z = -1.73, p = 0.083, r = -0.50
R2. Pleasantness	Assertive	Assertive	3.0	$\chi^2(2) = 4.67$, p = 0.097	n/a	
		Defensive	2.0			
		LRT	2.0			
	Defensive	Assertive	3.0	$\chi^2(2) = 4.11$, p = 0.128	n/a	
		Defensive	2.5			
		LRT	2.0			
R3. Safety	Assertive	Assertive	2.5	$\chi^2(2) = 7.63$, p = 0.022*	Assertive Defensive	z = -2.06, p = 0.039*, r = -0.59
		Defensive	2.0		Assertive LRT	z = -1.84, p = 0.066, r = -0.64
		LRT	2.0		Defensive LRT	z = -0.00, p = 1.000, r = -0.00
	Defensive	Assertive	3.0	$\chi^2(2) = 10.30$, p = 0.006*	Assertive Defensive	z = -2.07, p = 0.038*, r = 0.60
		Defensive	2.0		Assertive LRT	z = -2.23, p = 0.026*, r = -0.64
		LRT	1.5		Defensive LRT	z = -1.73 p = 0.083, r = -0.50

Note:
** Indicates significant effect (p < .05)*
The rating is a 5-point scale, 1= positive opinion, 5 = negative opinion.

Regarding the other two ratings, R4 (the participants' self-reflection on their own driving style when compared to the autonomous vehicle driving styles) and R5 (the participants' opinion on the magnitude of the autonomous vehicle driving styles), a general trend that can be deduced from Figure 3-12, Figure 3-13 and Figure 3-14 is that most of the participants agreed that the defensive driving style best reflected their own driving style. In addition, most participants indicated that the LRT driving style was too defensive and the assertive driving style was too assertive.

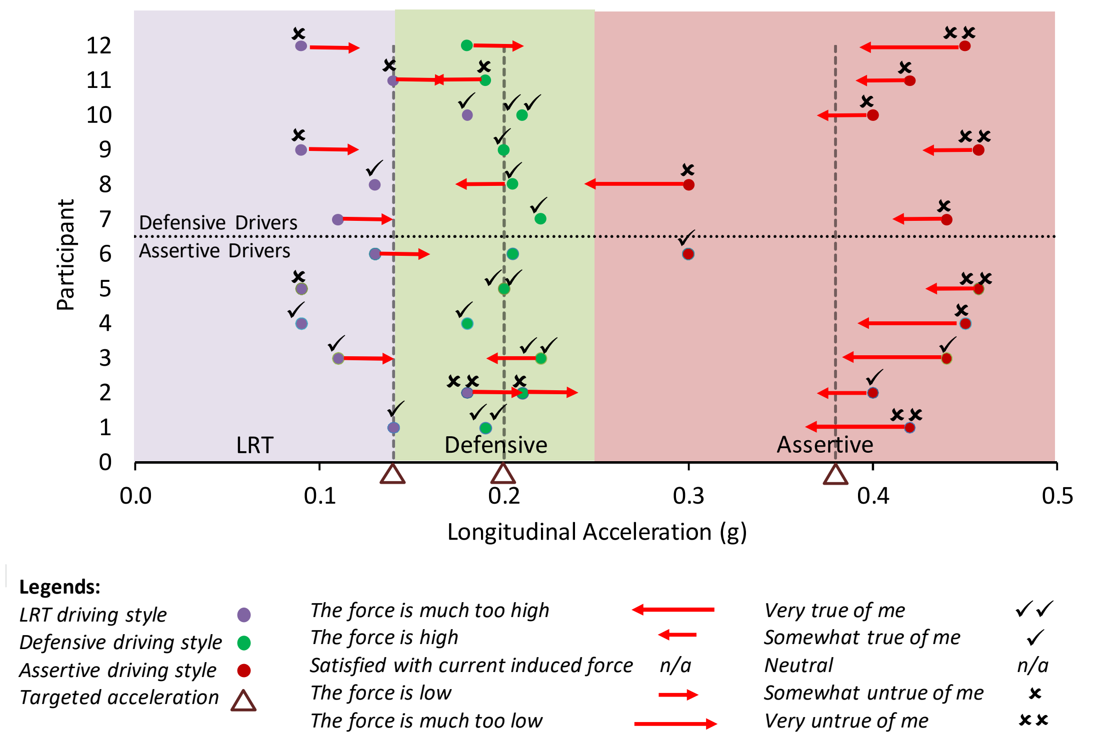


Figure 3-12: Comparison of the autonomous vehicle driving styles with participants' perception, and reflection of own driving style with the autonomous vehicle driving style at POI A (Adapted from Md. Yusof et al., 2016)

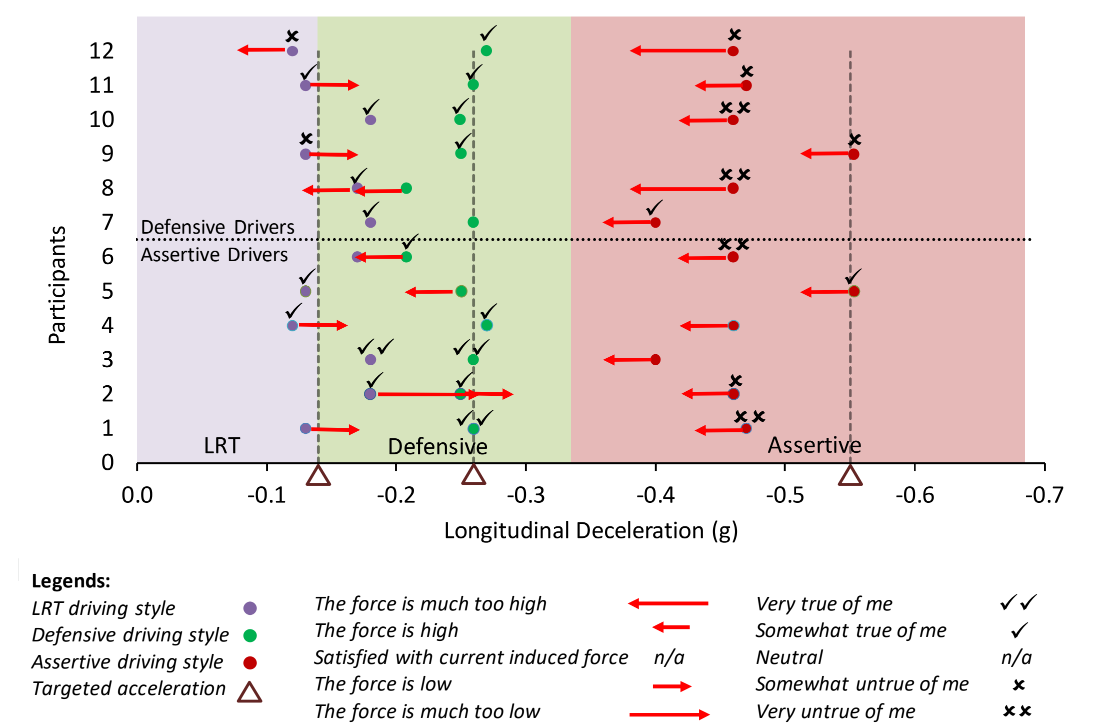


Figure 3-13: Comparison of the autonomous vehicle driving styles with participants' perception, and reflection of own driving style with the autonomous vehicle driving style at POI B (Adapted from Md. Yusof et al., 2016)

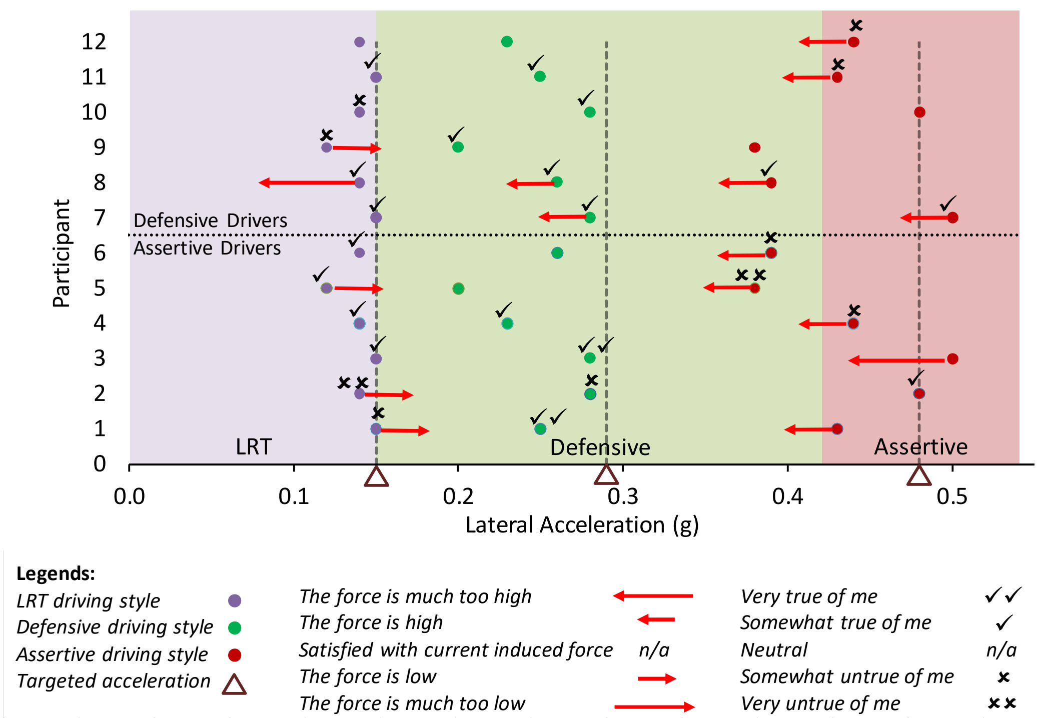


Figure 3-14: Comparison of the autonomous vehicle driving styles with participants' perception, and reflection of own driving style with the autonomous vehicle driving style at POI C (Adapted from Md. Yusof et al., 2016)

For longitudinal acceleration (Figure 3-12), nearly all participants reported that the assertive driving style was too aggressive. On the other hand, most participants felt the defensive driving style was just right, and half of the participants indicated that the LRT driving style was too defensive. Furthermore, participants reported having different opinions about the autonomous vehicle driving style depending on whether they were a driver or a passenger. For example, participants no. 2 and 3 stated that the acceleration for assertive driving style was similar to their actual driving style, but as a passenger (as in this study) they believed that the induced acceleration should be lowered.

A similar trend was found for longitudinal deceleration (Figure 3-13). All participants indicated that the assertive driving style was too assertive. The majority of the participants indicated that the defensive and LRT driving style were similar to their preferences. However, it should be noted that the LRT driving style was conducted at the border range between the high-end of the LRT driving style and the low-end of the defensive driving style because of the difficulties to simulate such small accelerations in a relatively short track available in the compound of TU/e (see Figure 3-7). Also, most participants reflected that their own driving style was similar to the defensive driving style, with an exception to the participant no. 8, who showed a preference for the LRT driving style when braking.

For lateral acceleration (Figure 3-14), most participants judged that the assertive driving style was too intense, although several experiment sessions were simulated at the higher-end of defensive driving style. Most participants reported that the defensive driving style was just right while half of the participants indicated that the LRT driving style was too defensive, although the LRT driving style was simulated at the lower end of the defensive driving style's range. In addition, most of the participants (except for participant no. 2 and 7) indicated that the defensive or LRT driving styles were a reflection of their own driving styles. Participant no. 8 demonstrated a strong preference towards the LRT driving style when taking a corner.

3.2.3.2.3. Conclusion

The evaluation study showed that both assertive and defensive drivers preferred the defensive and LRT driving styles compared to the assertive driving style for comfort (R1), pleasantness (R2), and safety (R3). However, all comparisons were found not significant due to Bonferroni correction used in this study which makes the test more strict ($p_{crit} < .017$). If the Bonferroni correction was not applied, significant results of the differences between assertive and defensives driving styles, and between assertive and LRT driving styles would be found. In addition, 12 drivers who participated in this evaluation study were enough to produce a large effect (Pearson's correlation coefficient, r, is equal to or larger than 0.5) results. Hence, no additional drivers are needed to participate in the study.

Most defensive drivers agreed that the defensive driving style was somewhat similar to their own driving styles, and they indicated that the assertive driving style should be slower. Interestingly, most assertive drivers also stated that the defensive driving style was a good reflection of their own driving style, and they also pointed out that the acceleration in assertive driving style should be lowered. There is a possibility that the assertive drivers were in fact not assertive drivers. This finding is contradicted with the previous finding that found correlations between sensation-seeking and acceleration (Lajunen & Summala, 1997). In this respect, it is worthwhile to note that Hooft van Huysduynen et al. (2015) mentioned that driving style might vary with the context. We may well imagine that an assertive driver will have different requirements and preferences when being driven by an autonomous vehicle than when driving himself. Based on our findings, the induced accelerations in the autonomous vehicle should be in the range of defensive and LRT driving styles, regardless of the type of driver.

3.2.3.3. Synopsis

In summary, we proposed three types of autonomous vehicle driving style, namely LRT, defensive and assertive driving styles. These autonomous vehicle driving styles are defined based on induced accelerations (in longitudinal, lateral and vertical directions) when travelling or riding in a train or a car. A device called AUTOAccD was developed to guide the driver in simulating the intended acceleration in autonomous vehicle driving style in a typical car. A validation study was done, and the results showed that drivers manage to simulate the LRT and defensive driving styles with assistance from AUTOAccD. On the other hand, based on our observation, the assertive driving style can only be consistently executed with a longer period of acceleration. Then, we investigated the preferences for the selected autonomous vehicle driving style. In general, there were no distinguishable differences between assertive and defensive drivers categorized by means of the sensation-seeking questionnaire. We found that both assertive and defensive drivers preferred the proposed defensive and LRT driving styles. Hence, we chose the defensive driving style as how autonomous vehicle should normally behave on the road and not the LRT driving style as its selected acceleration for the validation study was already at the lower-end of the defensive driving style's range. Next, in the second part of this chapter, we will describe the development of the instrumented car as the platform to conduct the tests for our study.

3.3. Mobility Lab: An On-Road Autonomous Vehicle Simulator

3.3.1. Introduction

The second part of this chapter describes the development of the Mobility Lab, an instrumented car that was developed to replicate an autonomous vehicle for research on comfort experience, especially in investigating the motion sickness and situation awareness in our study (Karjanto et al., 2018). First, we describe the overview of the appearance of the Mobility Lab and the reason or idea behind such a design concept. Next, we lay out the detail of the system architecture inside the Mobility Lab. In addition, a validation study was conducted to validate the capability of the Mobility Lab as the platform for our research.

3.3.2. Overview of the Mobility Lab

The design concept of the Mobility Lab is based on the existing prototypes and concepts of the autonomous vehicle by car manufacturers and designers. The idea was to devise a simulated autonomous vehicle by which various scenarios of passengers engaging in non-driving related tasks inside an autonomous vehicle could be realized. Thus, a spacious vehicle such as a minivan or a multi-purpose vehicle (MPV) is required. To maximize the non-driving related tasks, most of the current autonomous vehicles (either prototypes or concepts) have been designed in such a way that front passenger and/or driver can have a seat that faces backward, mainly for face to face interactions with other passengers, for example, the XchangE Concept from Rinspeed (Figure 3-15).

Figure 3-15: The envisioned autonomous vehicle called XchangE Concept (Source: McNabb, 2014)

Therefore, a 2011 Renault Espace IV was selected for our study platform as an instrumented car because of its railing system of the seat that provides safety for a rearward seating arrangement, and each seat is equipped with its own seatbelt (Figure 3-16).

Figure 3-16: The 2011 Renault Espace IV (top) and the possibility of the seat arrangement inside the car (bottom) (Source: Simona, 2006)

The envisioned interior layout of the Mobility Lab consists of two separate cabins for passengers (the participants) and experimenters (the driving wizard and the experimenter) (Figure 3-17). Based on this layout, a cabin partition was built between the first-row seats (the experimenter seats) and the second-row seats. A 40-inch TV display was mounted on the partition. Its function is to show the windshield-view taken from the windshield camera to the passengers inside the passenger cabin without seeing the experimenters or to play a video or movie, depending on the context of the tests. The second-row seats were modified into a table where devices such as a book, tablet and/or laptop can be placed. The third-row seats were maintained as is, to support up to two passengers simultaneously in future studies. The windows at the passenger cabin were covered with window blinds, to provide possibilities of opaque or transparent outside views. As a result, a variety of test setups is possible inside the Mobility Lab (Figure 3-18).

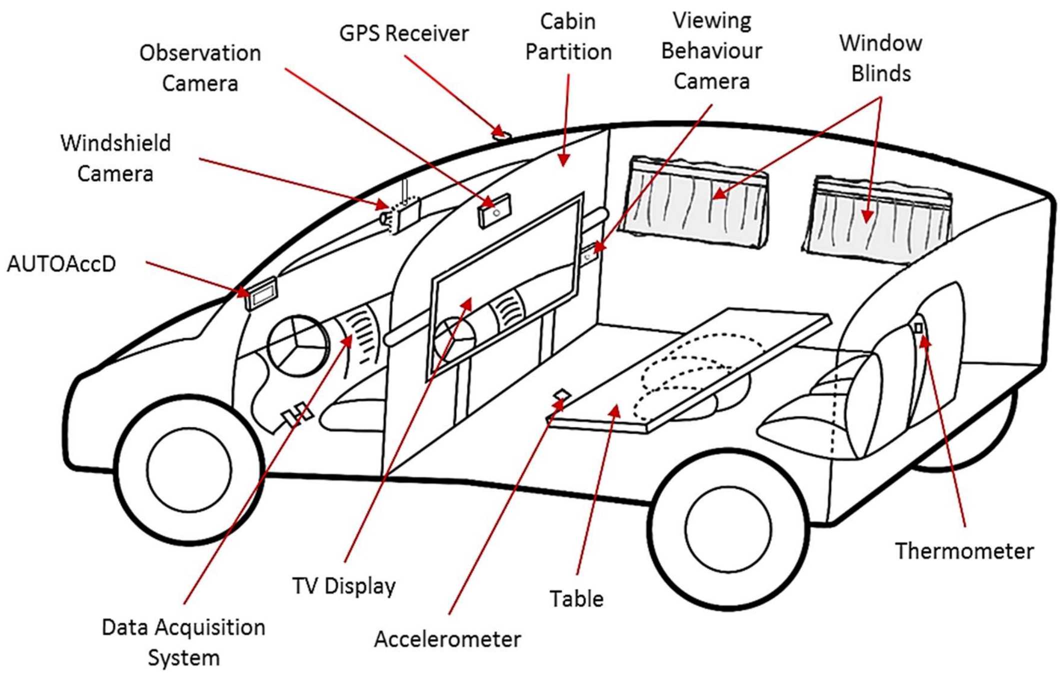


Figure 3-17: The envisioned interior layout of the Mobility Lab (Source: Karjanto et al., 2018)

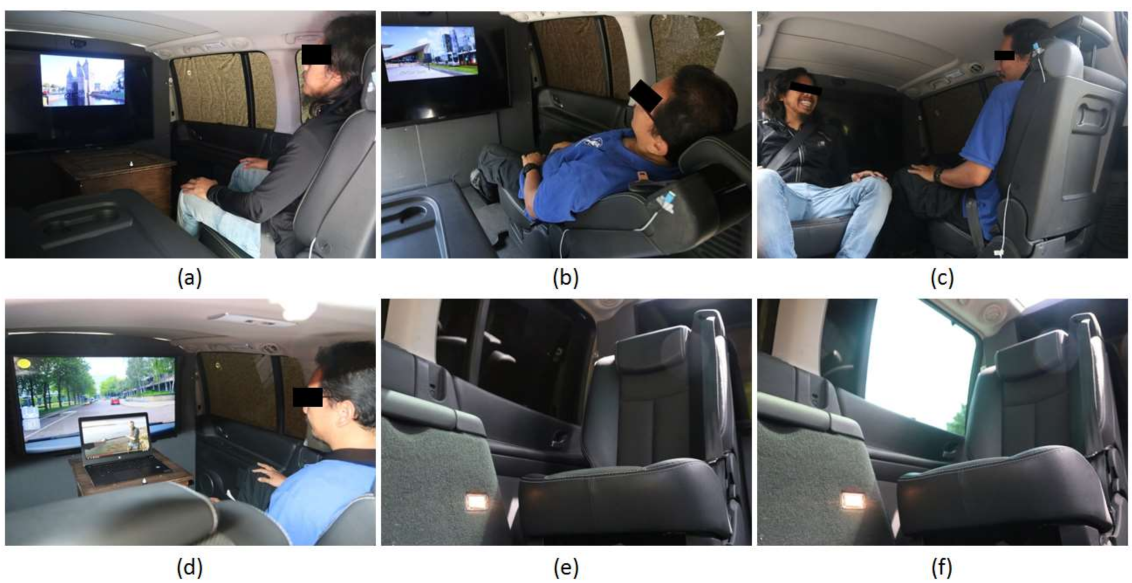


Figure 3-18: Several setup variations in Mobility Lab; (a) Upright sitting and (b) Supine position while watching a video; (c) Interaction face to face between passengers; (d) Watching a video on a laptop while the TV display is showing the windshield view; (e) Opaque windows (no outside view); and (f) Transparent windows (normal outside view) (Source: Karjanto et al., 2018)

A modified version of the AUTOAccD was placed inside the Mobility Lab where its display was mounted at the same place similar to the previous study (see Figure 3-6). The AUTOAccD was modified in such a way that the reading of raw data of accelerations is not taken from the OBD-II adapter but taken from an accelerometer that was fixed on the floor at the middle of the car. This is due to the idea that the accelerometer should be placed at the centre of mass of the car (M. E. Stanley, 2012). A thermometer was placed near to the passenger seat. Its function is to monitor temperatures that are experienced by the participants. The functions of the data acquisition system, the observation camera, the viewing behaviour camera and the GPS receiver will be described later in Section 3.3.3.1.

The exterior of the car was modified to increase the credibility of the Mobility Lab as an autonomous vehicle. The window at the driver side was covered with a darker polycarbonate sheet to hide the driving wizard from the participants view from the outside of the car but enable the driving wizard to see clearly outside through the window (Figure 3-19). In addition, a fake rotatable light detection and ranging (LiDAR) sensor was mounted on the car as the sensor is becoming common on the existing autonomous testing vehicle.

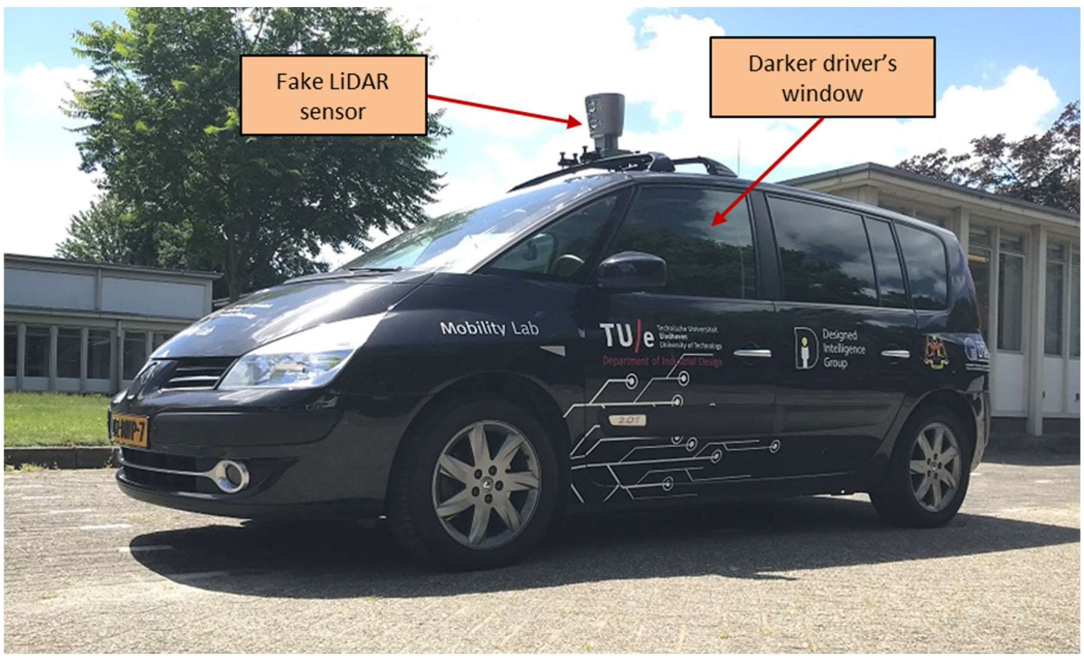


Figure 3-19: The Mobility Lab

3.3.3. System Architecture

There are two main systems that were implemented in the process of development of the Mobility Lab; the data measurement system and the power management system.

3.3.3.1. Data Measurement System

The data measurement system consists of four subsystems (Figure 3-20). A data acquisition (DAQ) system was developed to synchronize and record data from measurement sensors. A National Instrument compactRIO-9030 controller (NI cRIO-9030, National Instruments Inc. [NI], 2016a) was implemented as the DAQ device (Figure 3-21). It is a modular controller with a processor that is able to run a field-programmable gate array (FPGA) programs on a real-time (RT) module to provide real-time performance for data acquisition and control systems. The FPGA program and RT module were configured and controlled by a laptop through a software called LabVIEW (NI, 2016d) (Figure 3-22). See Appendix 4 and Appendix 5 for the block diagram view of the software.

Furthermore, the NI cRIO-9030 is capable of withstanding vibrations up to 5 g and temperatures up to 55 °C in operating conditions. It has 4 slots available to connect with any input and output (I/O) modules which mostly can be connected directly to various sensors. For now, only two modules were connected to the NI cRIO-9030, the NI 9041 (NI, 2016a) and NI 9205 (NI, 2016b). The NI 9041 is a digital I/O module that can interact with a variety of voltages and logic levels. The module has 8 I/O channels with a maximum of 10 MHz update rate. The NI 9205 is an analogue input module that measures voltage signals. The module has 32 single-ended or 16 differential analogue input channels with a maximum of 250 kHz sampling rate.

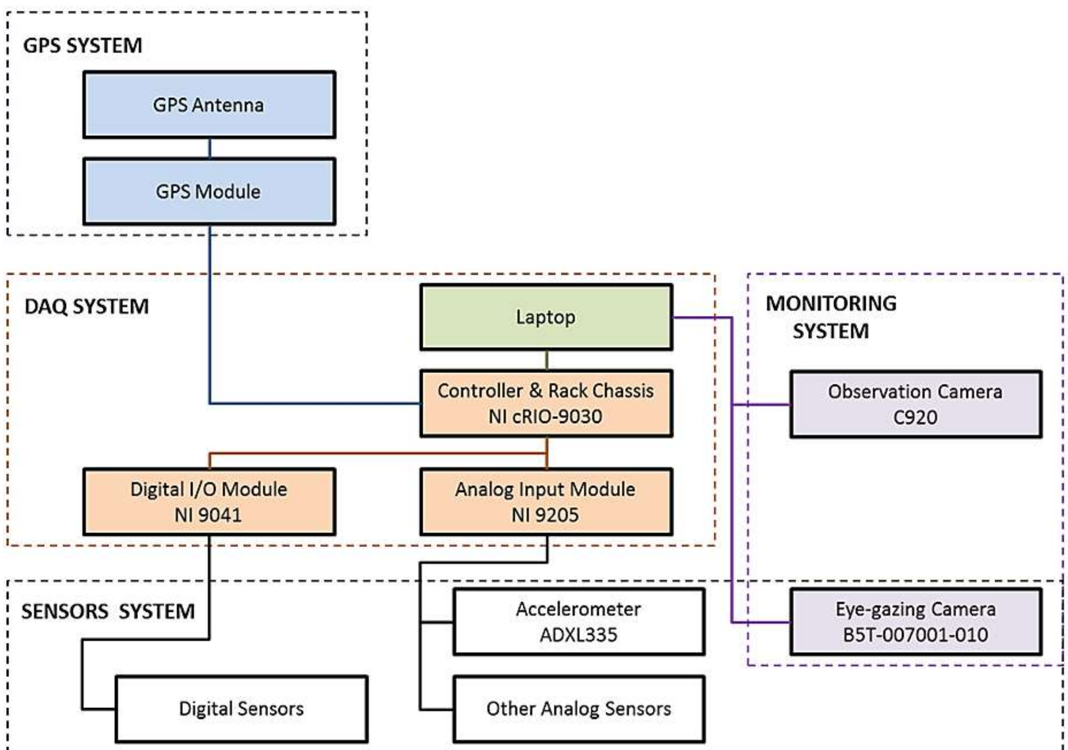


Figure 3-20: The structure of the data measurement system inside the Mobility Lab

Figure 3-21: NI cRIO-9030, coupled with NI 9041 and NI 9205, was mounted on the centre console of the Mobility Lab

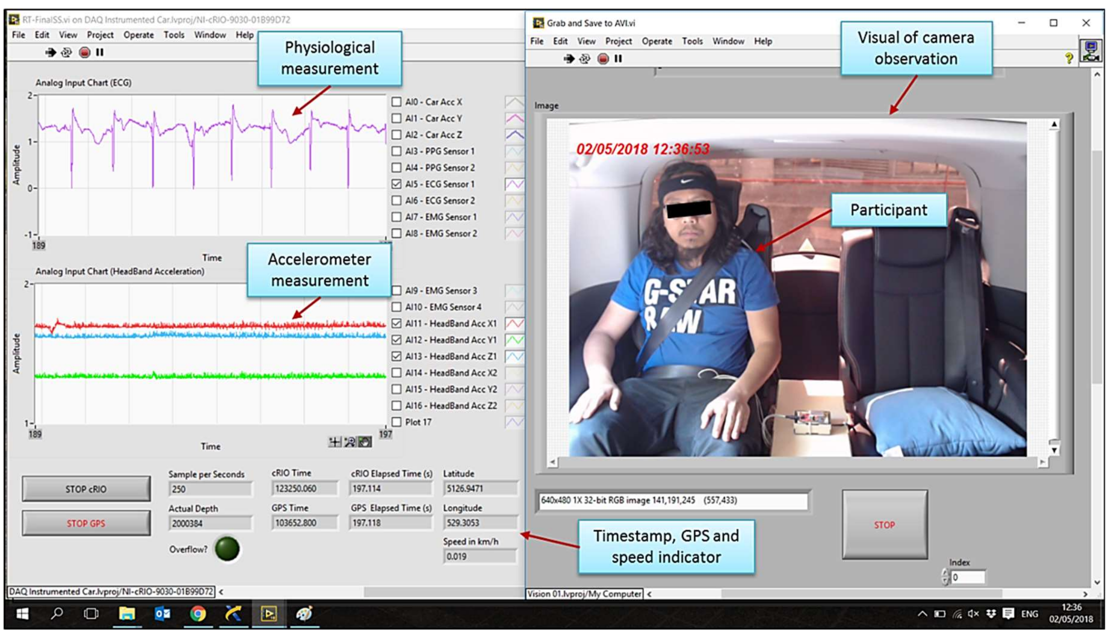


Figure 3-22: Example of real-time monitoring using LabVIEW software (front panel view)

The accelerometer that was placed on the floor inside Mobility Lab is one of the sensors connected to the NI 9205 (Figure 3-23). The accelerometer used is an ADXL335 from Adafruit (Earl, 2015) and has been used to measure acceleration forces in many studies (e.g. Chaudhuri & Dwivedi, 2015; Wu, Zwirello, Li, Reichardt, & Zwick, 2011). Here, its function is to measure acceleration on the body of the car. It is a small, low power, 3-axis MEMS accelerometer that generates ratiometric analogue voltage outputs. This accelerometer has a capability to measure up to +/- 3 g in x-, y- and z-axis in the static acceleration of gravity and dynamic acceleration of motion. In addition, it has a typical sensitivity of 300 mV/g with a bandwidth of 50 Hz.

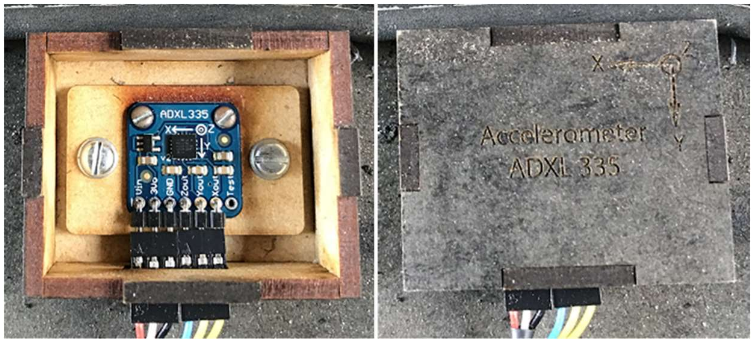


Figure 3-23: ADXL 335 accelerometer was fixed in a box on the floor inside the Mobility Lab

The GPS system consists of an Adafruit Ultimate GPS Breakout module (Figure 3-24), attached with an external active antenna. This system is used to provide an exact location of where an actual measurement is taken. The GPS module has a sensitivity of -165 dBm with the external antenna that can track up to 22 satellites at 10 Hz update rate (Fried, 2016). This system is connected to the NI cRIO-9030 synchronization with all other sensors.

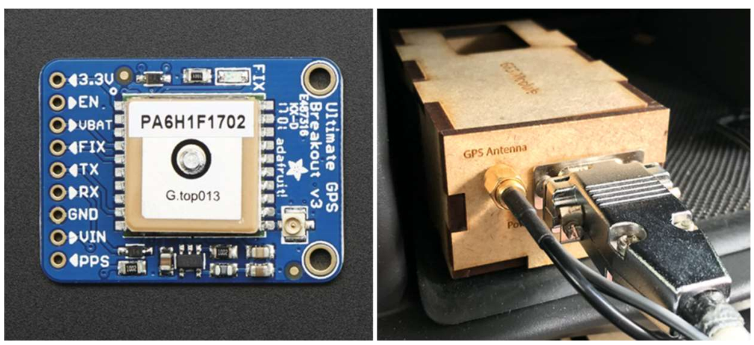


Figure 3-24: Adafruit Ultimate GPS Breakout module

The monitoring system consists of two cameras; both are mounted on the partition and are used to monitor conditions of the participants when conducting a test and to observe their behaviour (Figure 3-25). The observation camera is a Logitech C920, a high definition webcam camera. It is used to monitor (see Figure 3-22) and to capture all the behaviour of the participants. The camera also has an automatic light correction which it will automatically correct low-light settings when the car is in a darker or dimmer environment (e.g. the car is passing through a tunnel) to record a clear video. The other camera, or the behaviour camera, is an OMRON B5T-007001-010 (OMRON, 2016). This camera also is included in the sensors system in the system architecture due to the fact that it is also a sensor module. It can be used to detect hand, face, and body, or to estimate face direction, age, gender, and blink. The detection ranges are 54° in horizontal and 41° in vertical angle of views, and the maximum distance for detection is 3 m in front of the camera. Currently, this camera is only used to estimate and to record the eye-gazing of the participants.

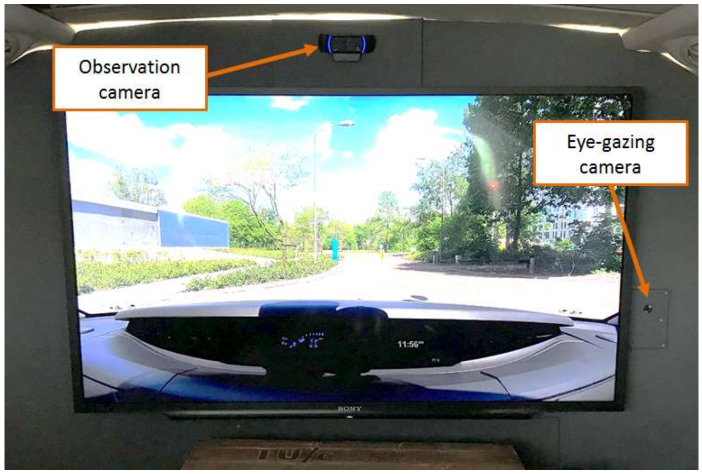


Figure 3-25: Location of two monitoring system cameras

3.3.3.2. Power Management System

The Mobility Lab is equipped with many devices that require continuous power supply such as the NI cRIO-9030 and the 40-inch TV display. Since the Mobility Lab was designed to be used on a real-road condition, it is impossible to have a power supply directly from a wall socket. Therefore, rather just than depending on the car battery which might drain the battery so fast, a secondary 12 volts battery was installed to supply the extra power (Figure 3-26). The secondary battery will automatically be charged by the alternator using a Samlex BS 140 Dual battery separator (Samlex Europe B.V., n.d.) when the car battery is fully charged. An inverter was connected to the secondary battery to convert 12 volts direct current into 240 volts alternating current.

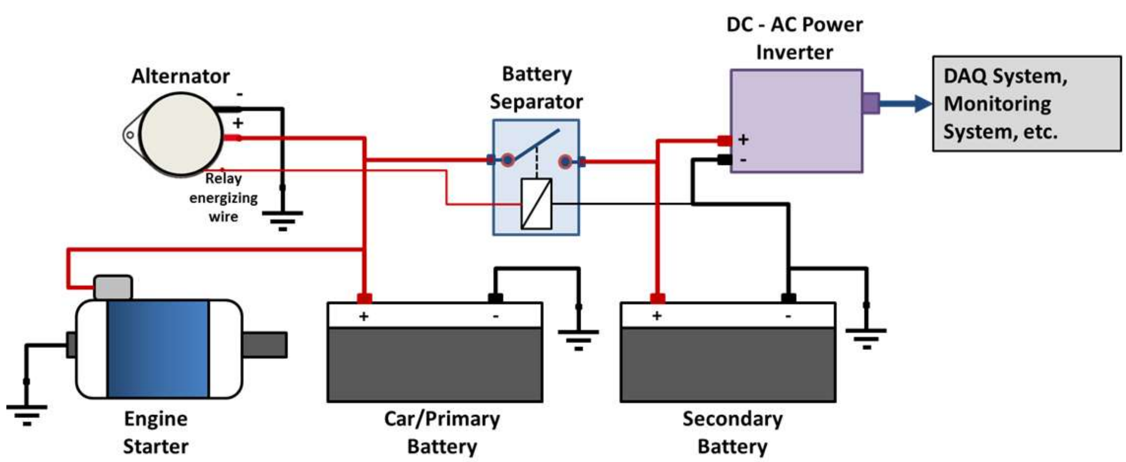


Figure 3-26: Power Management System

3.3.4. Validation Study

A validation study was done to validate the capability of the Mobility Lab to simulate an autonomous vehicle driving style consistently. In comparison to the validation study of consistently simulating the autonomous vehicle driving styles with the help of the AUTOAccD (see Section 3.2.3.1), this validation study quantified the autonomous vehicle driving style accelerations based on the whole ride rather than focus only at certain locations.

3.3.4.1. Methodology

Experiment Setup. Two designated drivers (driver A and B), who are experienced drivers with a valid driving license, took part in the study. The defensive driving style was selected as preferred autonomous vehicle driving style based on the findings from the previous study (see Section 3.2.3.2). The lateral acceleration was defined at around 0.29 g, while the longitudinal acceleration was controlled to be kept at a minimum, as it was predicted by Fajardo, Au, Waller, Stone, and Yang (2011) that an autonomous vehicle could cross a junction without stopping due to car-to-car communication. Each driver drove 23 times on the designated route inside the TU/e (Figure 3-27), where a speed restriction of 30 km/h was indicated.

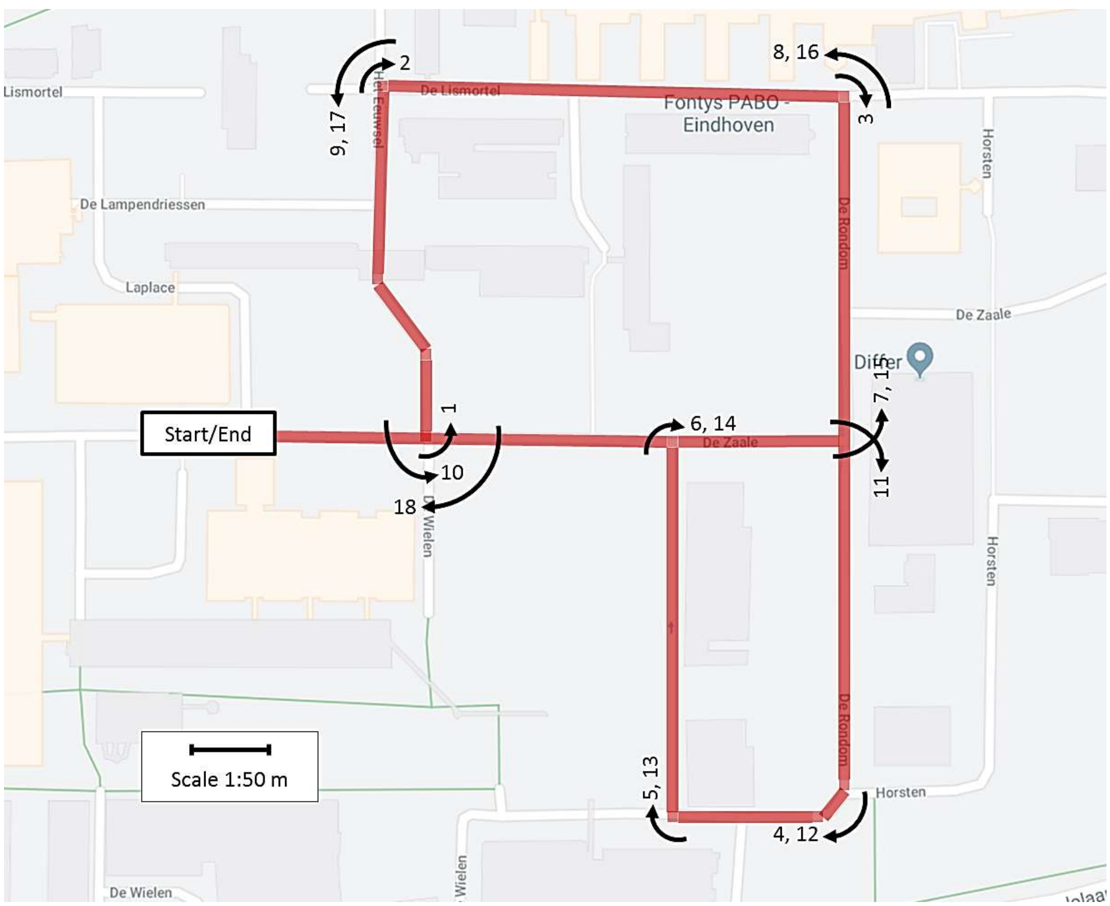


Figure 3-27: The designated route starting from corner 1 to 18

The route consists of 18 corners, either to the left (8 times) or right (10 times), with various radii ranging from 6.0 to 17.6 meters (mean = 11.1, SD = 4.1). The study was conducted outside office hours and on the weekend when there was no or only limited traffic present to minimize any encounters that would affect the longitudinal acceleration. For additional safety precaution, the TU/e security was informed about the study and permission to use the designated route was granted. This experiment is compliant with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) (Association of Universities in the Netherlands [VSNU], 2014).

Data Collection. The acceleration data that were recorded in the DAQ system were transferred into the National Instruments DIAdem (NI DIAdem) software, a software that can easily find, inspect, analyse, and report on measurement data (NI, 2015). The acceleration data were converted from analogue voltage input into acceleration value in g. This new acceleration value was filtered using the Savitzky-Golay filter (Savitzky & Golay, 1964) to denoise the acceleration signal while maintaining the height and shape of the waveform peaks (Schafer, 2011). The denoised acceleration data were then transformed into power spectral density (PSD) using FFT with the Hanning window function, and periodic correction setting was used to improve the accuracy of greatest amplitude (NI, n.d.). Later, the frequency weighting W_f was applied to the denoised acceleration data for the motion sickness dose value (MSDV) calculation. See Section 2.3.3 and Section 3.3.4 for detailed explanations of the PSD and the MSDV.

3.3.4.2. Results and Discussion

The means of all accelerations across the frequency spectrum for both drivers were presented in Figure 3-28 as a function of PSD. Both drivers showed almost identical distributions, where several peaks of acceleration were overlapped at different frequencies, especially in longitudinal (x-axis) and lateral (y-axis) accelerations. Thus, it can be deduced that all sessions have been consistently executed in a similar driving style. In other words, both drivers managed to drive at an about similar pace, entering and exiting the corners at almost the same time, and inducing almost the same accelerations for the whole driving.

Longitudinal and lateral accelerations were dominant at below 0.25 Hz while vertical (z-axis) acceleration peaked between 1 and 2 Hz. Past studies showed that low-frequency motions below 0.5 Hz are highly correlated with motion sickness (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999a) whereas high-frequency motion at 1 Hz and above can cause discomfort or injury but do not provoke motion sickness (Cheung & Nakashima, 2006).

The maximum point of the lateral acceleration was almost 10 times higher than the maximum point of the longitudinal acceleration. The large difference between these two accelerations was expected as it was previously mentioned in this study setup that the longitudinal acceleration was controlled to be kept at a minimum, and the lateral acceleration was intended to be in the range of 0.15 g to 0.42 g. On the other hand, although the vertical acceleration showed a high-frequency motion, only a low peak was formed. This was due to the fact that the route used in the study was constructed of brick that may induce a high-frequency low-amplitude vertical acceleration.

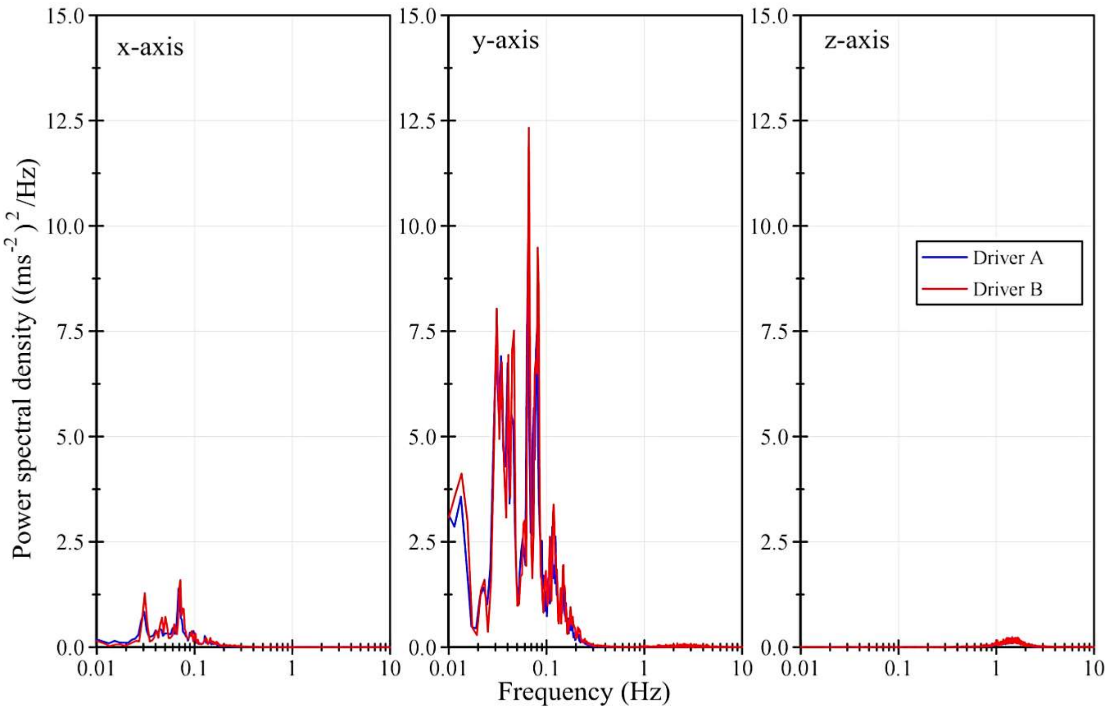


Figure 3-28: Mean acceleration power spectral densities in tri-axial directions for both drivers (Adapted from Karjanto et al., 2018)

Based on PSD results, only low-frequency motions of acceleration in longitudinal and lateral directions were reflected in the MSDV in Figure 3-29. It can be seen that the squared MSDVs increased almost in proportion to the duration and are almost similar for both drivers. All MSDVs of 23 driving sessions were averaged into a single line in each acceleration for each driver. At the end of each driving session, on average, Driver 1 produced MSDV of 2.27 ms$^{-1.5}$ (SD = 0.35) in longitudinal and 6.68 ms-1.5 (SD = 0.99) in lateral directions while Driver 2 produced MSDV of 2.47 ms-1.5 (SD = 0.23) in longitudinal and 7.29 ms$^{-1.5}$ (SD = 1.16) in lateral directions.

In a study by (Griffin & Newman, 2004b), one of the study setups was no outside view of the participants when being driven on roads around the suburban area with a maximum speed of 48 kmh-1. This setup is almost similar to our main focus to investigate motion sickness while engaging in non-driving related tasks (i.e. not looking outside). The means of their MSDV values for 30 minutes riding, about 16.4 ms$^{-1.5}$ in longitudinal and 14.7 ms$^{-1.5}$ in lateral directions, were comparable to our MSDV values at a 9 minutes duration and sufficient to get people to experience any motion sickness symptoms.

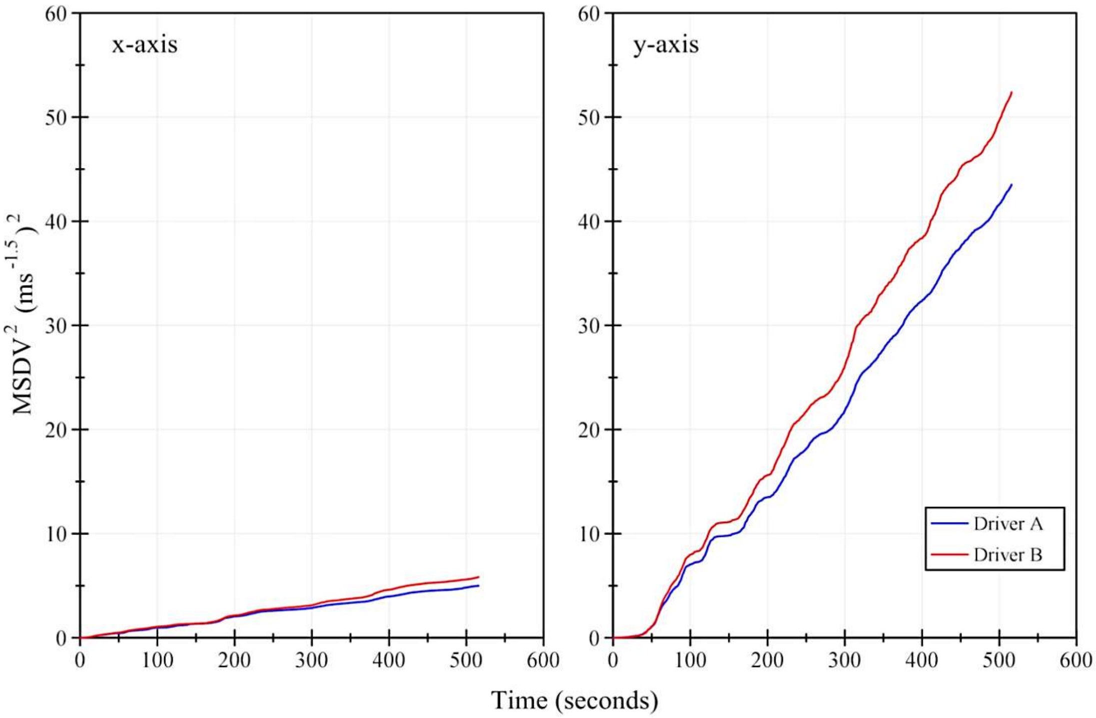


Figure 3-29: Mean accumulated squared motion sickness dose value (MSDV^2) in the longitudinal and lateral accelerations for two drivers (Adapted from Karjanto et al., 2018)

3.4. Chapter Summary

In summary, we explained the design and development of the Mobility Lab to be used as our test platform. In the first part of the chapter, we identified the autonomous driving style based on the driver's driving style. Since previous studies have shown that drivers' driving styles are multidimensional, and drivers are driving based on their own personality traits (Hooft van Huysduynen et al., 2015; Karjanto et al., 2017; Summala, 2007; Taubman-Ben-Ari et al., 2004; Vaa, 2013), and our study focus is related to motion sickness induced by acceleration, we defined the autonomous driving styles based on the sensation-seeking trait that is highly correlated with accelerations. Thus, we proposed the LRT, defensive, and assertive driving styles that were defined according to accelerations. Then, we tested whether these autonomous driving styles can be executed consistently or not with the guidance of AUTOAccD, a device that assists the driving wizard to drive according to the defined acceleration. We found that the AUTOAccD can assist the driving wizard in consistently maintaining the defined acceleration if given enough time to execute an autonomous driving style. Later, we evaluated the autonomous driving styles on both defensive and assertive drivers. We found that the defensive driving style was the preferred autonomous driving style and drivers indicated that this driving style was a reflection of their own driving style. Basu, Yang, Hungerman, Singhal, and Dragan (2017) also found similar findings that drivers tend to prefer more defensive driving style as a user than being a driver. In addition, depending on the contexts and situations, the assertive driver may not be an assertive driver for the whole time, and the assertive driver might not like the way he/she drives when being driven by other drivers (Summala, 2007). Thus, we opted for the defensive driving style to be our autonomous driving style in our study.

In the second part of the chapter, we explained the development of the Mobility Lab based on existing prototypes and concepts of autonomous vehicles. Several test setup variations are possible to be conducted in future studies specifically to study effects of engagement of non-driving related tasks in an autonomous vehicle and ways to mitigate the motion sickness that may likely occur in such situations. Furthermore, the Mobility Lab also was designed to mimic autonomous vehicle appearance with a visible sensor on the car exterior and invisible driver in the cabin area. Continuous measurements from various sensors (either analogue or digital output) can be recorded depending on the requirement of the studies. The validation study showed that the Mobility Lab is capable of simulating the defensive driving style consistently by designated drivers on the real road. Hence, depending on the context and requirements of the future studies, the same amount of motion sickness dose can be administered to the participants for every session in an experiment.

Chapter 4. Measurements

4.1. Introduction

In this chapter, we will explain the main types of measurement which were used in our study (Figure 4-1). The first type of measurement is called the consistency measurement which is used to inspect the consistency of each experiment. It consists of car acceleration in the tri-axial directions which were analysed in terms of Power Spectral Density (PSD) and Motion Sickness Dose Value (MSDV). The second type of measurement involves the use of measurements that assesses the effect of haptics' cues on participants. Motion Sickness Susceptibility Questionnaire (MSSQ), Motion Sickness Assessment Questionnaire (MSAQ) and physiological measurements were used to evaluate motion sickness of the participants, while Situational Awareness Rating Technique (SART) was used to assess the situation awareness. In addition, the Rating Scale Mental Effort (RSME) was used to measure the mental workload. The third type of measurement is the prototype measurement. The User Experience Questionnaire (UEQ) was used to evaluate the interaction between the participants and the haptic cues prototype.

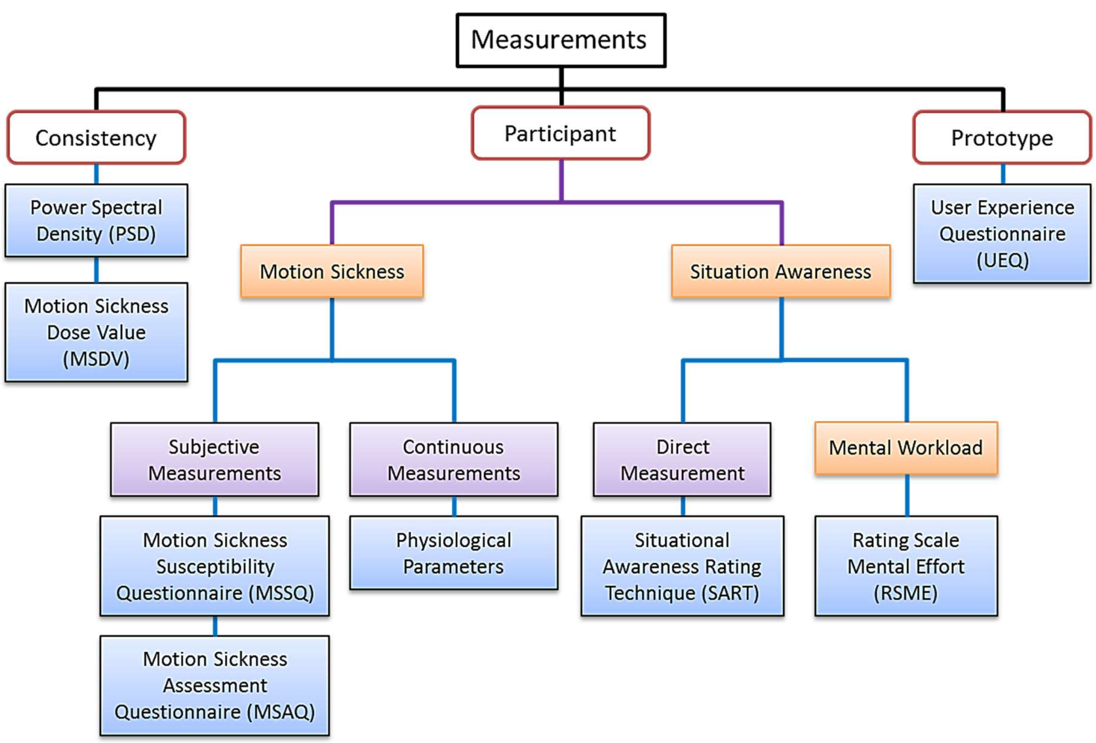


Figure 4-1: The main measurements

4.2. Consistency Measurements

Since our studies were conducted in a non-simulated environment, the consistency of the simulated sessions is important, in order to make sure that the collected data are reliable. The power spectral density (PSD) was used to analyse the consistency of the acceleration. In addition, PSD was used to assess the dominant acceleration frequencies which can lead to motion sickness. The motion sickness dose value (MSDV) was used to evaluate the consistency of the dose of motion sickness from the accelerations given to the participants. See Section 2.3.3 and Section 3.3.4 for more detailed explanations.

4.3. Participant Measurements

Motion sickness and situation awareness were the two main dependent variables in our study. Several measurements were used to measure and evaluate the effect of haptic cues on the abovementioned dependent variables.

4.3.1. Motion Sickness Measurements

There are many metrics used to measure motion sickness. Experienced motion sickness, as reported by passengers (or participants in a study), can be classified as a subjective measurement and usually can only be assessed using a questionnaire. Existing questionnaires include the Pensacola motion sickness questionnaire (MSQ; Kellogg, Kennedy, & Graybiel, 1965), the Pensacola diagnostic index (PDI; Graybiel, Wood, Miller, & Cramer, 1968), the simulator sickness questionnaire (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993), the motion sickness susceptibility questionnaire (MSSQ; Golding, 1998), and the motion sickness assessment questionnaire (MSAQ; Gianaros, Muth, Mordkoff, Levine, & Stern, 2001). On the other hand, in order to evaluate motion sickness objectively and continuously, some studies use methods which are based on motion components such as MSDV (Förstberg, 2000a; Griffin & Newman, 2004a; Lawther & Griffin, 1987; Turner & Griffin, 1999b, 1999c), and methods based on physiological parameters such as heart rate, blood pressure, breathing rate, galvanic skin response (GSR), and electrogastrography (EGG). This section gives details only on the measurements that were used in our experimental studies.

4.3.1.1. Motion Sickness Susceptibility Questionnaire

The original motion sickness susceptibility questionnaire (MSSQ) was developed by Reason and Brand (1975) and was later revised by Golding (1998). The MSSQ used in our study is based on the shorter version originated from Golding (2006b) (see Appendix 6). It consists of two sections that ask for previous sickness occurrences when travelling by cars, buses or coaches, trains, small boats, ships, swings and roundabouts in playgrounds, and theme park rides. The first section is about the history of motion sickness as a child (before the age of 12) and the second section is about the motion sickness occurrences over the last 10 years. The MSSQ using a rating scale from 0 (never felt sick) to 3 (frequently felt sick). The raw score as a child (MSA) or over the last 10 years (MSB) is defined as:

$$MSA \ or \ MSB = \frac{(TSS) * 9}{9 - t} \tag{4-1}$$

where TSS is the total sickness score for each mode of ride and t is the number of types of transportation that were never travelled in. Then, the MSSQ raw score is defined as:

$$MSSQ \ raw \ score = MSA + MSB \tag{4-2}$$

Based on the MSSQ raw score (ranging between 0 and 54), an estimation of MSSQ percentile rating y is used to classify how susceptible a person is to motion sickness either using a polynomial calculation with x, the MSSQ raw score, and a = 5.11609, b = -0.05517, c = -0.00068, d = -1.07147e^{-5}, or using a graph (Figure 4-2).

$$y = ax + bx^2 + cx^3 + dx^4 \tag{4-3}$$

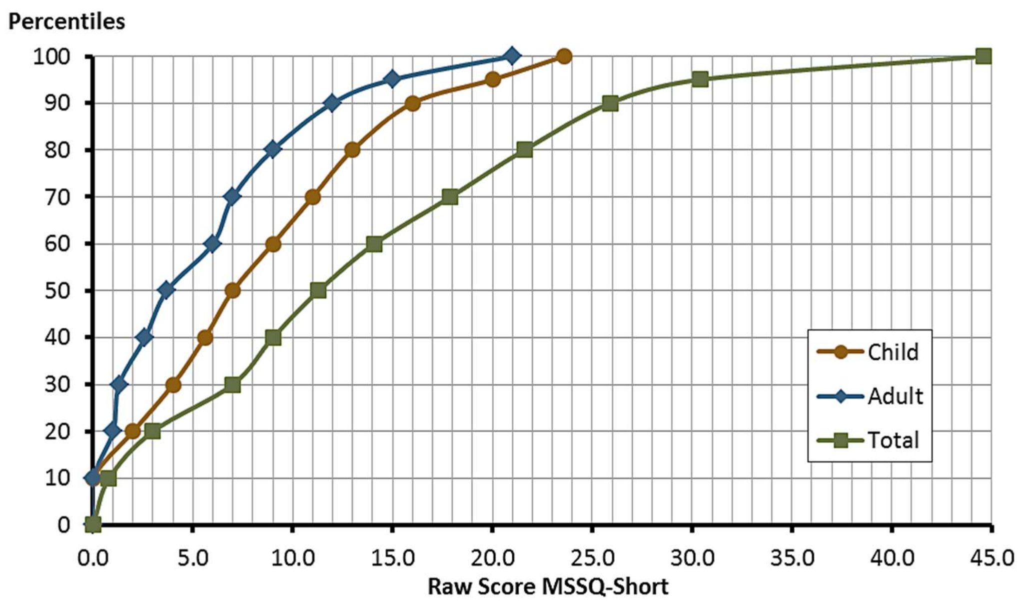


Figure 4-2: Cumulative distribution percentiles of the MSSQ raw score (Source: Golding, 2006b)

Before conducting an experiment, participants were asked to fill in the MSSQ. Since our main research focuses on car, the MSSQ scores used here are based on land vehicle elements only. This is done in order to classify or stratify the participants based on their susceptibility to motion sickness. Based on their percentile rating, the participants are defined as low-susceptibility (first quartile), mild-susceptibility (second quartile), moderate-susceptibility (third quartile), and high-susceptibility (fourth quartile) groups (Fowler, Sweet, & Steffel, 2014).

4.3.1.2. Motion Sickness Assessment Questionnaire

In measuring the level of experienced motion sickness in an experiment, the motion sickness assessment questionnaire (MSAQ) were used (Gianaros et al., 2001). It is a multidimensional questionnaire, consisting of gastrointestinal- (stomach sickness, queasy, nauseated, may vomit), central- (faint-like, lightheaded, disoriented, dizzy, feel like spinning around), peripheral- (sweaty, clammy/cold sweat, hot/warm), and sopite-related (annoyed/irritated, drowsy, tired/fatigued, uneasy) dimensions (see Appendix 7). The MSAQ uses a 9-point Likert scale (ranging from 1 = Not at all, to 9 = Severe). The subscale (gastrointestinal-, central-, peripheral-, or sopite-related dimensions) and overall motion sickness scores are obtained by calculating the percentage of total points scored over the maximum score:

$$Overall\ MSAQ\ score = \frac{total\ points\ from\ all\ items}{144} * 100 \tag{4-4}$$

$$Subscale\ MSAQ\ score = \frac{total\ points\ of\ all\ subscale\ items}{total\ numbers\ of\ allsubscle\ items * 9} * 100 \tag{4-5}$$

In general, MSAQ scores range from 11.1 % (no symptoms) to 100.0 %. This is due to the fact that the total points from all items are between 16 (all items are scored with 1) and 144 (all items are scored with 9). In our study, MSAQ was used to evaluate the differences in motion sickness levels and was applied in the experiment before and after a specific condition (either the control- or the test- condition). This is due to the fact that the motion sickness level may be different between participants at the beginning of the experiment. The participants answered the MSAQ as pre- and post-experimental questionnaires and the difference in the scores between those two was then considered as the changes in participant's level of motion sickness. For example, if a participant answered a 2 for "*drowsy*" in the pre-experimental questionnaire and answered a 5 at the end of the experiment, the exact item score would be 3 (= 5 - 2). Furthermore, there are possibilities that an item is scored 0 if the participant responded with the same scores in both pre- and post-experimental questionnaires. Hence, including other item scores, the MSAQ percentage range also changed, from 0.0 % (no symptoms, all items are scored with 0) to 88.9 % (all items are scored with 8).

4.3.1.3. Physiological parameters

Muth (2006) pointed out that motion sickness will affect the autonomic nervous system, and the heart rate is regulated by this autonomic nervous system. The two primary technologies for measuring heart rate are photoplethysmography (PPG) and electrocardiography (ECG) sensors (Kranjec, Beguš, Geršak, & Drnovšek, 2014). PPG sensors use a light-emitting diode (LED) to measure the rate of blood flow by illuminating the skin and detecting the amount of light which reflects back to a photodiode, whereas ECG sensors use conductive silver/silver chloride or Ag/AgCl electrodes to measure the electric potential generated by the electrical activity of the heart.

Previous studies have shown that motion sickness increases the heart rate in beats per minute (BPM) (Cowings, Suter, Toscano, Kamiya, & Naifeh, 1986; Kim, Kim, Kim, Ko, & Kim, 2005; Stout, Toscano, & Cowings, 1995) and that heart rate decreases immediately following the termination of the motion sickness stimulus (Cowings et al., 1986; Kim et al., 2005; LaCount et al., 2011). However, motion sickness was also found to have no significant effect on the heart rate (Mullen, Berger, Oman, & Cohen, 1998). As highlighted by Riener, Jeon, Alvarez, and Frison (2017), heart rate data alone is useless to identify human factor elements in the driving environment.

On the other hand, heart rate variability (HRV) is known to be correlated to many aspects in psychophysiological research such as on health phenomena and cognitive load which is linked to the self-regulation mechanisms (Laborde, Mosley, & Thayer, 2017). HRV is the variation in the time interval between heartbeats (called RR-interval or NN-interval; normal to normal R-peaks) with the QRS complex being the most striking waveform (see Figure 4-3). HRV represents the activity of two subsystems of the autonomic nervous system; the sympathetic and parasympathetic nervous systems. The sympathetic nervous system is responsible for activating the fight-or-flight response which occurs in response to a stressful or threatening condition, while the parasympathetic (or vagal tone) nervous system is responsible for activating the rest-and-digest response which occurs in response to help in preventing stressful conditions and calming the body down (McCorry, 2007). Moreover, studies have found that an increase in the sympathetic activity, together with a decrease in the activity of parasympathetic nervous system represents the development of motion sickness (Kim et al., 2005; LaCount et al., 2011).

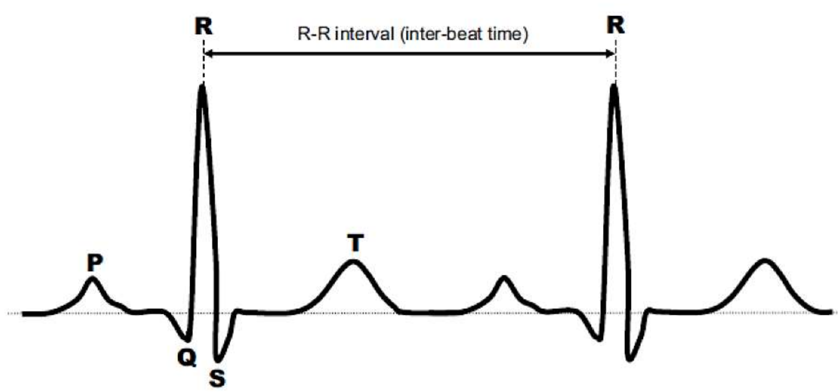


Figure 4-3: Heart rate variability on an electrocardiogram (ECG) trace consists of P-wave (the first short upward movement of the ECG tracing), the QRS complex (Q - a downward deflection after the P-wave, R - an upward deflection, S - a downward deflection), and T-wave (represents the ventricular repolarization, or recovery)

Generally, HRV can be evaluated in two main categories; time- and frequency-domain analyses (Laborde et al., 2017). In the time-domain analysis, the root-mean-square of successive differences (RMSSD) and the percentage of successive normal sinus RR-intervals which is more than 50 ms (pNN50) are two parameters that are usually used to evaluate the parasympathetic nervous system activity. However, RMSSD was found to be a better assessment of the parasympathetic nervous system compared to pNN50 (Otzenberger et al., 1998). In the frequency-domain analysis, the original RR-interval series are transformed and filtered into different frequency bands by using the fast Fourier transform (FFT) calculation. The very-low-frequency (VLF) band's range is between 0.0033 and 0.04 Hz, which represents long-term regulation mechanisms, thermoregulation, and hormonal regulation mechanisms. The low frequency (LF) band's range is between 0.04 and 0.15 Hz, which represents a combination of the sympathetic and parasympathetic nervous system activities. The high-frequency (HF) band's range is between 0.15 and 0.40 Hz, and this represents the activity of the parasympathetic nervous system. Finally, the LF/HF ratio represents the combination or balance between both nervous systems activities. However, it was found that there is a non-linear and non-reciprocal relationship between sympathetic and parasympathetic nervous systems activity (Billman, 2013). Nevertheless, 65 % of the published articles are based on this ratio (Heathers, 2014).

In our study, heart rate and HRV measurements are used as a continuous measurement which can be analysed together with other motion sickness measurements. These measurements also will not depend on the users' perception and will not interfere with the participants' tasks (Alexandros & Michalis, 2013). As suggested by Laborde et al. (2017), three phases were implemented in our study when recording heart rate or HRV data, usually known as a baseline, event, and post-event (Figure 4-4). From these three phases, tonic HRV (referred to as data taken at baseline, event, and post-event) and phasic HRV (referred to as changes between two phases; reactivity and recovery) can be investigated.

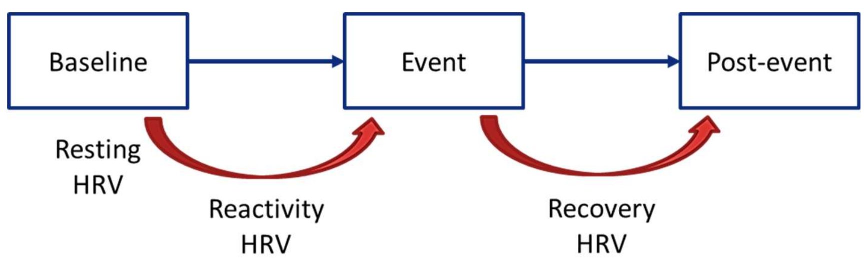


Figure 4-4: Typical experiment structure for HRV experiments. (Adapted from Laborde et al., 2017)

4.3.2. Situation Awareness Measurements

Newly developed technologies which try to enhance situation awareness of the operator (or the user) should be empirically tested in order to detect any undesirable effects on the user (Endsley & Jones, 2004). This evaluation is preferably done in the early process of technology development. As highlighted by Endsley and Jones (2004), the evaluation of situation awareness can be done either by inferring situation awareness from observable processes, behaviours, performance outcomes or by directly assessing the user's situation awareness (see Figure 4-5).

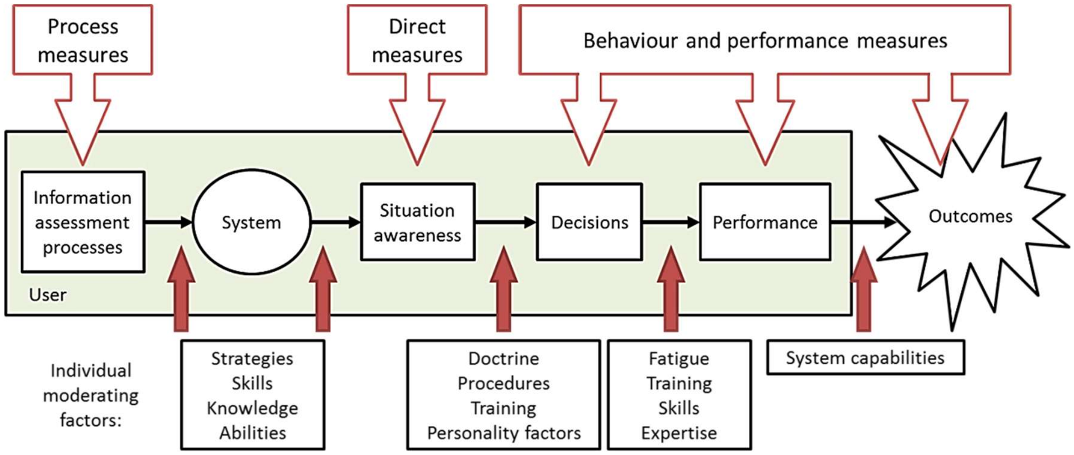


Figure 4-5: Approaches to situation awareness measurement from Endsley and Jones (2004), adapted from Endsley and Garland (2000)

The process measurements include the verbal protocol (e.g. the user is asked to "*think out loud*" while doing a task), communication analysis which focuses on verbal exchanges between users in a task, and psychophysiological measure (e.g. eye movement). The behaviour and performance measurements are measurements which infer situation awareness through user's action or behaviour, and their overall performance. However, inferring situation awareness by abovementioned measurements (the process, behaviour and performance measurements) may not really reflect on the real situation awareness as there is a number of factors that influence the result which is not situation awareness elements (Endsley & Jones, 2004).

Endsley and Jones (2004) pointed out that direct measurement of situation awareness is the best way to evaluate SA. Direct measurement of situation awareness can consist of subjective or objective measurements. Subjective measurements include self-ratings of situation awareness by the user him/herself (e.g. the situational awareness rating technique (SART; Taylor, 1990) and the situation awareness subjective workload dominance (SWORD; Vidulich, 1989) technique), and observer rating done by the experimenter who observes the user (e.g. the situation awareness rating scale (SARS; Waag & Houck, 1994). Objective measurements will play the role of evaluating situation awareness by comparing the user's stated situation awareness in reality. The objective measurement methods include freeze probe techniques (e.g. the situation awareness global assessment technique (SAGAT; Endsley, 1995a) and real-time probe techniques (e.g. the situation awareness for solutions for human-automation partnerships in the European air traffic management system (SASHA; Jeannot, Kelly, & Thompson, 2003). This section only provides details on the measurements which were used in our experimental studies.

4.3.2.1. Situational Awareness Rating Technique

In evaluating situation awareness of participants in an experiment, the situational awareness rating technique (SART) is used. SART was initially used to assess pilot situation awareness

(R. M. Taylor, 1990) and was known to be the best and widely used subjective technique to measure situation awareness in other similar domains (Endsley & Jones, 2004). It consists of 10 items on a seven-point rating scale which are divided into three constructs; understanding of the situation (U), attentional demand (D) and attentional supply (S). The 10 items were defined based on information which was gathered from experienced aircrew (Selcon & Taylor, 1990) (Table 4-1). The obtained ratings were then combined into a single score of situation awareness of passengers, SA = U-(D-S), ranging from -14 (lowest SA) to 46 (highest SA).

Table 4-1: SART construct definitions (R. M. Taylor, 1990)

Constructs	Description
Understanding of the situation (U)	
Information quantity	Amount of knowledge received and understood
Information quality	Goodness or value of knowledge communicated
Familiarity	Degree of prior experience/knowledge
Attentional demand (D)	
Instability of situation	Likeliness to change suddenly
Complexity of situation	Degree of complication
Variability of situation	Number of variables/factors changing
Attentional supply (S)	
Arousal	Degree of alertness; readiness for activity
Concentration of attention	Degree to which thoughts are brought to bear
Division of attention	Distribution/spread of focus of attention
Spare mental capacity	Mental ability available for new variables

Since SART was originally developed for aviation purposes, the original items (see Appendix 8) were modified specifically for our study and for a better understanding of the participants (see Appendix 9 for modified version). For example, in attentional demand item, "*How many variables are changing within the situation?*" is then changed into "*How many variables (e.g. the speed of the car, forces felt inside the car, etc.) are changing in the situation?*".

4.3.2.2. Rating Scale Mental Effort

In addition to situation awareness measurement, the mental workload was also known to affect situation awareness (Parasuraman, Sheridan, & Wickens, 2000; Stanton & Young, 2000). Parasuraman, Sheridan, and Wickens (2008) explained on mental workload as the relationship between mental resources demanded by a task and those resources available to be supplied. The Rating Scale Mental Effort (RSME) was used to measure the mental workload in our study (see Appendix 10). RSME was realized as a unidimensional scale in assessing the subjective mental workload of the participants (Zijlstra, 1993). It consists of a vertical line with a length of 150 mm long (1 mm is equal to 1 point) and has nine anchor points that represent descriptive labels indicating a degree of effort from "*absolutely no effort*" to "*extreme effort*".

4.4. Prototype Measurements

The participants also assessed the implemented prototypes by answering User Experience Questionnaire (UEQ). The UEQ was constructed and evaluated by Laugwitz, Held, and Schrepp (2008) to indicate users' feelings, impressions, and attitudes that arose when they interacted with a product. It consists of 26 items that fall into six scales; attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. The attractiveness scale is about the general impression towards the products (e.g. annoying or enjoyable). The perspicuity scale is about the understandability with the product (e.g. complicated or easy). The efficiency scale is about an effort to use the product (e.g. impractical or practical). The dependability scale is about interaction with the product (e.g. unpredictable or predictable). The stimulation scale is about motivation and excitement when using the product. The novelty scale is about the innovativeness of the product that grabs users' attention (e.g. creative or dull). Excepting the attractiveness scale, the other UEQ scales can be grouped into pragmatic quality (Perspicuity, Efficiency, Dependability) and hedonic quality (Stimulation, Originality). Pragmatic quality defines task related quality aspects whereas hedonic quality defines the non-task related quality aspects.

The UEQ is a 7-point Likert scale from 1 to 7. Depending on the UEQ item (see Appendix 11), the number 1 or 7 in the Likert scale can be the extreme of positive or negative evaluation. Then, the answered numbers were transformed into a range between -3 (horribly bad) and 3 (extremely good). The mean values of the corresponding scale between -0.8 and 0.8 represent a neutral evaluation, while values above 0.8 represent a positive evaluation and values below -0.8 represent a negative evaluation.

4.5. Chapter Summary

Since the conducted experiments in our study used the same measurements for each experiment, this chapter was aimed to explain those measurements in details. Three main types of measurement were used to assess the consistency of each experiment, to investigate the effect of haptic cues and to evaluate the users' (or participants') experience towards the prototype. In the following two chapters, we present our conducted experiments to study the effect of the haptic cue when engaging in a non-driving related task while riding in an autonomous vehicle, the Mobility Lab.

Chapter 5. Gaining Situation Awareness through a Peripheral Vibrotactile Display to Mitigate Motion Sickness in Autonomous Vehicles

5.1. Introduction

Information regarding the intention of imminent acceleration motion of a car needs to be conveyed in a very subtle way so that the autonomous vehicle passengers can keep their focus on the non-driving related tasks, but will still be aware of the information given and prepare themselves for any required actions. This alteration between main focus and periphery of attention is called peripheral interaction (Bakker, Hausen, & Selker, 2016), which is part of the calm technology which was introduced by Weiser and Brown (1996). Thus, peripheral displays can be used as an approach to provide the information to passengers.

Normally, taking a corner at a junction induces lateral acceleration in a short period and in a single direction only. This condition is not enough to produce motion sickness. However, taking a corner at another junction again after a short time, especially in the opposite direction, can build up the effect of motion sickness on passengers. This usually happens in urban or residential areas where junctions can be found easily near to each other. On the same note, when someone is riding in a vehicle on a winding road with a reverse curve[2], there is a higher chance that motion sickness will occur. The reverse curve also can be found when riding towards a roundabout, in which the vehicle needs to turn into the right direction for a while before following the direction to the left along the roundabout and turn to the right again when exiting the roundabout. On the other hand, repetitive braking and acceleration (fore-and-aft motions) do rarely happen, except in a traffic jam. Although it can be expected that every turn might be associated with deceleration (and maybe braking), it can be predicted that an autonomous vehicle may cross a junction without stopping due to car-to-car communication (Fajardo et al., 2011). Hence, only horizontal motion of lateral acceleration is considered as important information which needs to be conveyed to the passengers so that they can react accordingly in time to mitigate motion sickness.

In this chapter, we investigated the effects of a peripheral vibrotactile display which indicates that the autonomous vehicle is going to take a turn or a corner on the situation awareness and motion sickness of passengers while performing a non-driving related task (watching a

[2] A curve to the left or right is followed immediately by a curve in the opposite direction.

video). Two experimental conditions (with and without vibrotactile display) were conducted in order to examine whether the peripheral information can enhance situation awareness and mitigate motion sickness. Subjective and objective measurements were performed to measure the situation awareness and the motion sickness, including the mental workload which may influence the situation awareness. Lateral acceleration, which is caused by car taking corners, was utilized as a means to induce motion sickness. In general, we hypothesized that there is a significant difference in the level of situation awareness with peripheral information about driving compared to not having any information, and there is a significant difference in the level of motion sickness with peripheral information about driving compared to not having any information.

5.2. Methodology

5.2.1. Experimental Design

All participants (or passengers) were subjected to two experimental conditions, with (the test-condition) and without (the control-condition) the vibrotactile display in an instrumented car. A minimum gap of three days, between the two conditions, was chosen for each participant to diminish the motion sickness effects that might have occurred from the first condition of the experiment. A fully-counterbalanced order (2! = 2 orders) was applied to balance the potential order or learning effects. In order to ensure experimental consistency, all sessions were conducted outside office hours and located at the exact same route on the Eindhoven University of Technology's terrain (Eindhoven University of Technology (TU/e), 2017) where there was no or only limited traffic present, and a maximum speed restriction of 30 km/h was mentioned. For additional safety precaution, the TU/e security was informed about the study and permission to use the designated route was granted. Similar to the methodology mentioned in Section 3.3.4.1 (see Figure 3-27), the route used in this experiment would also consist of 18 corners, either to the left (8 times) or to the right (10 times). The independent variable used in this experiment was the presence or absence of the vibrotactile display, and the dependent variables were assessments on situation awareness, motion sickness and mental workload of the participants. This experiment is compliant with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) (Association of Universities in the Netherlands [VSNU], 2014).

5.2.2. Prototype: Vibrotactile Display

The prototype was designed based on a taxonomy of ambient information systems introduced by Pousman and Stasko (2006). Although the most sensitive areas for vibrations are the fingertips, a vibrotactile display was designed to be used on the forearm so that it gives more freedom to the passengers to perform non-driving related tasks, especially tasks that require hand movements.

The vibrotactile display consists of two sets of three coin-shaped shaftless vibration motors from Adafruit with a dimension of 10.0 mm in diameter and 2.7 mm in thickness. Each vibration motor was soldered on a small SparkFun LilyPad protoboard so that it can be easily sewed on a fabric (Figure 5-1). The vibration motors had a maximum speed of 11000 rpm which can be translated to a frequency of 183 Hz at 5.0 V of power supply and were connected to an Arduino Mega R3 board as the main controller processor. As mentioned by Jonghyun Ryu et al. (2010), frequencies which are higher than 60 Hz can avoid temporal masking when conveying in-vehicle information. Frequencies which are lower than 60 Hz can be masked as a result of external vibration such as engine vibration. Three motors were placed equidistant (25.0 mm) from each other and attached to a strip of hook-and-loop fasteners in each set. Each set presented information on the forearm of the participants which indicate the intention of the car either turning to the left (left-hand set) or to the right (right-hand set). The vibrotactile display was designed to provide information about the vehicle's manoeuvre 3 seconds before a turn. The vibration motors were activated for 0.6 seconds and deactivated for another 0.6 seconds, and this cycle was repeated for 3.0 seconds before the car turns into a corner.

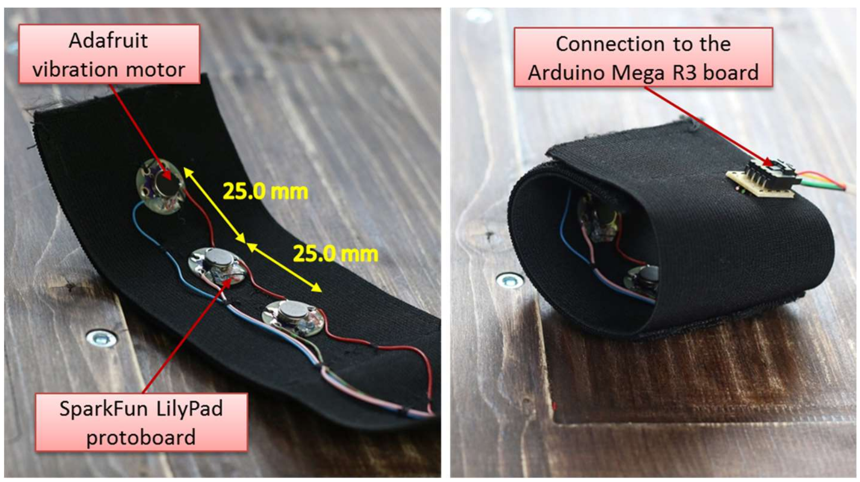


Figure 5-1: The vibration motors attached to the stretchable fabric

5.2.3. Equipment and Wizard

The experiment was conducted using the Mobility Lab (refer to Section 3.3). The Mobility Lab was specially developed to replicate an autonomous car of the future for research on the experience of comfort (Karjanto et al., 2018). In this experiment, the Mobility Lab windows were made opaque to prevent participants from looking outside so that they could only get the information about upcoming manoeuvres (the car turning to the left or right) from the vibrotactile display, and not by looking outside which might give hints about future manoeuvres. For the current experiment, in order to avoid saccadic eye movements which can lead to eye strain, only a smaller video size of about 24-inch (aspect ratio of 16:9) was displayed on TV, with a black coloured background was displayed (Boothroyd, 2008; Knoche, 2010). For safety reason, an emergency button was made available on the table for the passengers if the passengers felt severe nausea and not able to continue the study (Figure 5-2). An alarm buzzer will be triggered, and it will notify the driver to stop the car immediately if road conditions allow. The temperature inside the car was maintained at 20.0° Celsius.

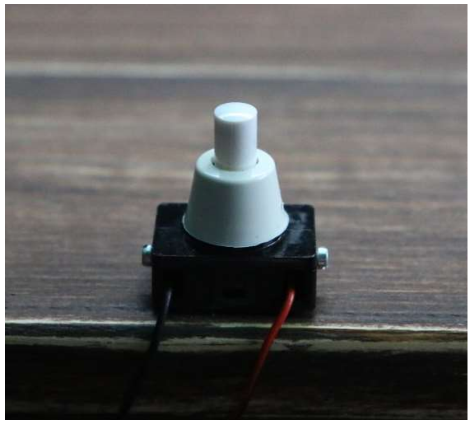


Figure 5-2: Emergency button

Based on the work of Baltodano et al. (2015), an accomplice of the experimenter acted as a driving wizard to simulate an autonomous vehicle riding experience. This is done by realizing the intended accelerations with the help of the AUTOAccD (refer to Section 3.2.3.1.1). The defensive driving style was used in this experiment because it was generally preferred by drivers in previous studies (Basu et al., 2017; Md. Yusof et al., 2016). The lateral acceleration was maintained at around 0.29 g, while the longitudinal (fore-and-aft) acceleration is controlled to be kept at a minimum, as it was predicted by Fajardo et al. (2011) in which an autonomous vehicle can always cross a junction without stopping due to car-to-car communication. The experimenter was the only one who was interacting with the participants for the whole experiment. Markers which helped the experimenter in triggering the vibrotactile display at 3 seconds before each street corner were deployed at an appropriate distance from the street corners based on the predefined speed of the car.

5.2.4. Participants

Using a within-subject experimental design, 20 participants (12 male, 8 female), aged between 18 and 47 years old (mean = 26.4 years, standard deviation (SD) = 6.4 years), took part in this experiment. All participants were selected based on their scores (mean = 70.2 %, SD = 25.3 %) in the Motion Sickness Susceptibility Questionnaire (MSSQ; Golding, 1998). They answered the questionnaire few days before the day of the experiment and scored between 25 to 100 percentile rating (representing mildly-, moderately- and highly-susceptibility for motion sickness, see Fowler et al., 2014). Participants reported no heart-related sickness. They were paid € 20 for their participation.

5.2.5. Data Collection

The measurements (Figure 5-3) in this experiment were based on the explanation of the measurements in Chapter 4.

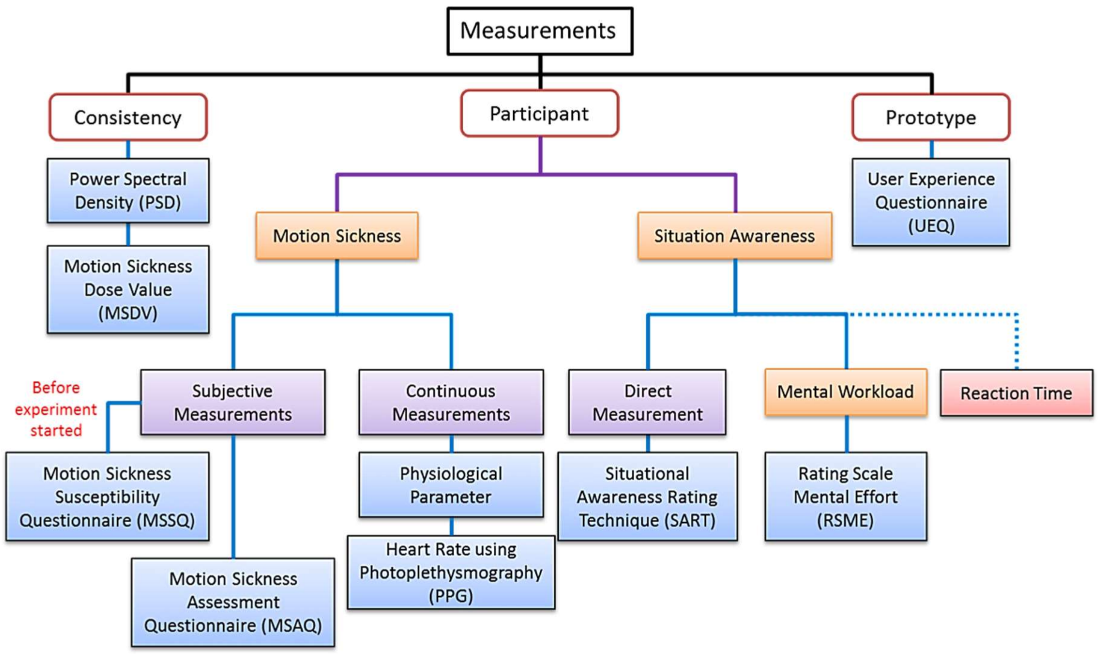


Figure 5-3: The main measurements in Chapter 5. The dashed line represents an additional measurement that was not discussed in Chapter 4.

For participants' data measurements, a pulse sensor or a photoplethysmography (PPG) sensor (Figure 5-4(a)) was attached to a specifically designed finger clip in measuring the heart rate in terms of beats per minute (BPM) of the participants as continuous motion sickness measurement. This is because the heart rate is correlated with motion sickness (Cowings et al., 1986; LaCount et al., 2011). In addition, a device called a Clicker (Figure 5-4(b)) was used to assess the participants' situation awareness in terms of reaction time. It has two buttons which designate the direction of the car (either turning left or right).

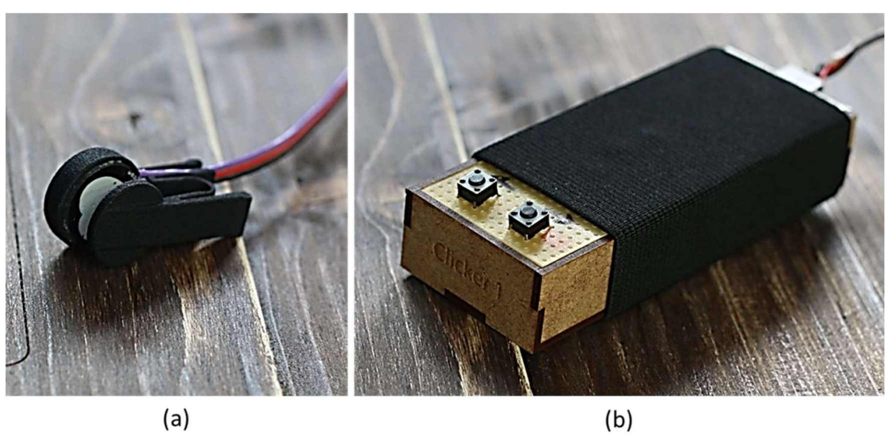


Figure 5-4: (a) Pulse sensor finger clip; (b) Clicker

5.2.6. Procedure

Firstly, the layout of the experiment was briefed to the participant by the experimenter, including his/her rights to withdraw from the study at any time. Then, the participant signed an informed consent form (see Appendix 13) and answered the pre-experimental questionnaire, the MSAQ. Next, the experimenter led the participant to the car from behind in such a way that the participant entered the car from the right side rear door to avoid him/her seeing the driving wizard who was already in the driver seat (Figure 5-5).

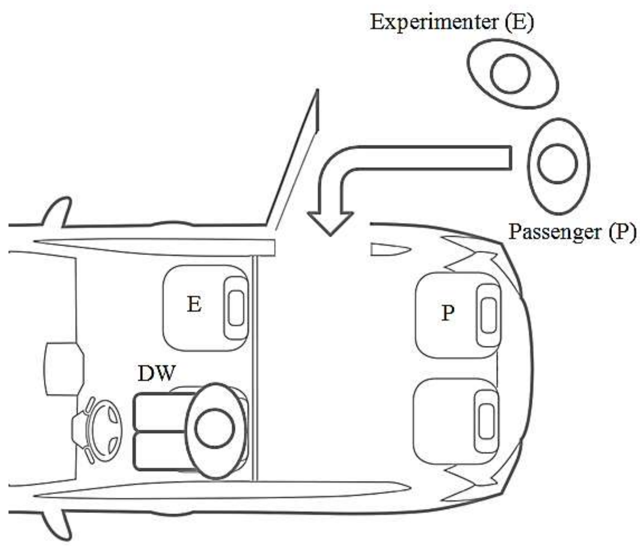


Figure 5-5: Illustration of procedure for participant entering the Mobility Lab

The participant 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 participant was instructed to keep an open palm facing upwards, and minimize the left-hand movement for the whole experiment in order to minimize the noise of the heart rate measurement. Two emotionally neutral videos (one for each condition) were used in the experiment in avoiding any feelings or emotions which may affect heart rate measurement. The videos were *Amsterdam* and *The Netherlands: Beyond Amsterdam* from Rick Steve's' YouTube Channel (Steves, 2015a, 2015b). In the test-condition, the vibrotactile display was placed on both left and right participant's forearms, and the clicker was held on his/her right hand as shown in Figure 5-6. Then, the experimenter was seated in the front seat of the car, next to the driving wizard.

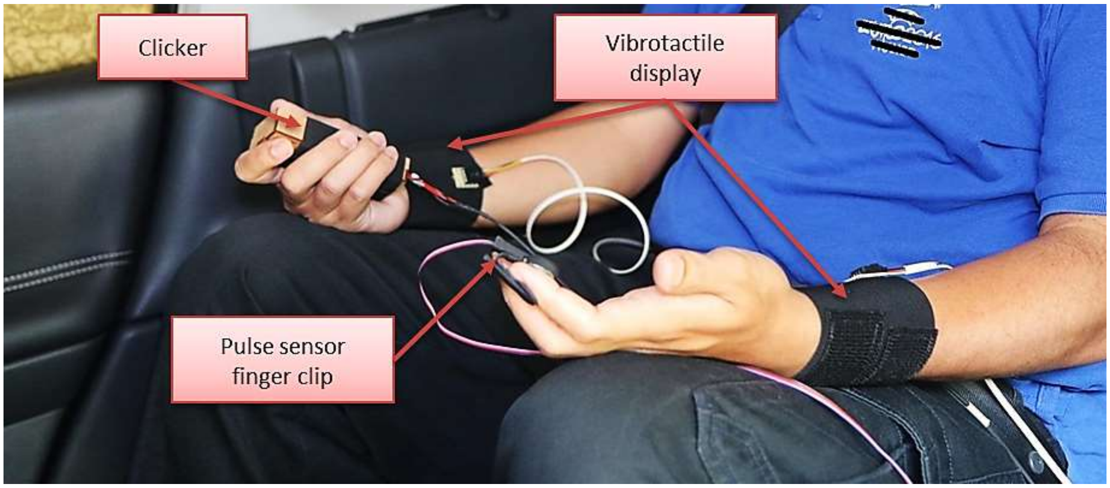


Figure 5-6: The position of the clicker, the pulse sensor finger clip, and the vibrotactile displays

The experiment itself was divided into three phases (Figure 5-7). In the pre-test (PT1) phase, the participant was asked to rest and watch a video. In this phase, the car was stationary with the engine turned on. During the driven around test (DAT) phase, the driving wizard drove the car on the predefined route while the participant continued watching the video. In the post-test (PT2) phase, the car was again in idle position. In this phase, the participant rested and still watching the video until the experimenter brought him/her back to the debriefing room.

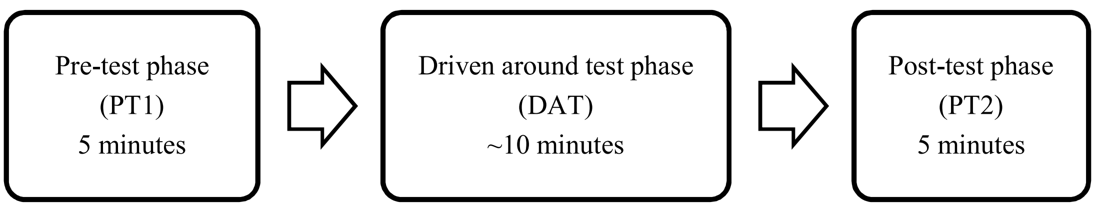


Figure 5-7: Schematic process of experiment phases

In debriefing room, the participant answered the post-experimental questionnaires (the MSAQ, the SART, the RSME, and the UEQ (only for the test-condition) and gave his/her opinions towards an open-ended question about the experiment before the study ended, and payment is made. The questionnaires were not presented between DAT and PT2 phases in order to avoid any interruption to the heart rate measurement.

During DAT phase of the control-condition, the only task for the participant was to watch the video. However, in the test-condition, every time the car approached a corner or junction, the experimenter triggered the vibrotactile display at the marker. The participant had to click the left or the right button on the clicker when he/she felt the vibration announcing either the car taking a left or right turn. The total duration of a session was one hour.

5.3. Results

5.3.1. Consistency of the Experiment

The power spectral densities (PSD) were calculated from the accelerometer data which represents the distribution of tri-axial acceleration across the frequency spectrum from the 40 sessions of the experiment. The means of PSD in both control- and test-condition were plotted in a semi-log graph as shown in Figure 5-8. Both conditions showed almost identical distributions, in which several peaks of acceleration were overlapping at different frequencies, especially in longitudinal (x-axis) and lateral (y-axis) accelerations. Both accelerations were dominant at below 0.25 Hz while vertical (z-axis) acceleration peaked between 1 to 2 Hz. In addition, the PSD graphs in Figure 5-8 were almost identical with the PSD graphs in Figure 3-28 due to the fact that the route used in this experiment was the same as in the validation study in Section 3.3.4.1 (see Figure 3-27).

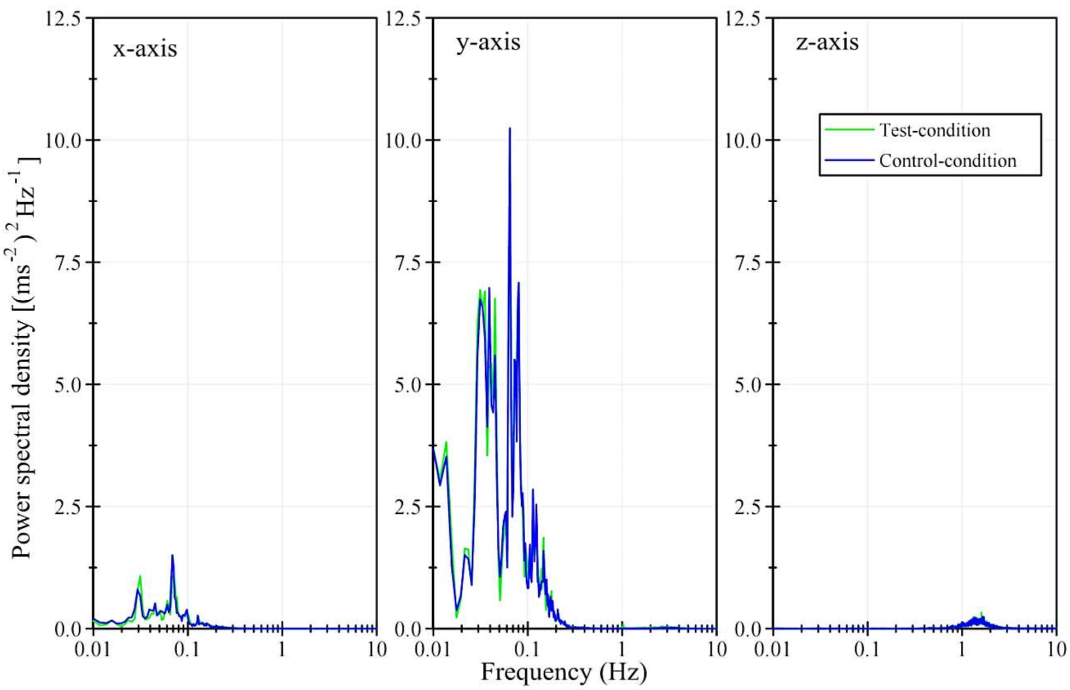


Figure 5-8: Mean acceleration power spectral densities in longitudinal, lateral and vertical in the test-condition (with the vibrotactile display) and in the control-condition (without the vibrotactile display)

As mentioned before, low-frequency motions below 0.5 Hz are highly correlated with motion sickness (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999a), only accelerations in longitudinal and lateral directions were presented in the Motion Sickness Dose Value (MSDV) graph in Figure 5-9. In overall, the mean MSDV given to all participants at the end of the riding phase were 2.26 $ms^{-1.5}$ (SD = 0.06) in longitudinal and 6.55 $ms^{-1.5}$ (SD = 0.07) in lateral directions. Compared to a study done by Griffin and

Newman (2004b), the MSDV value shown in the lateral direction should be enough to provide mild motion sickness.

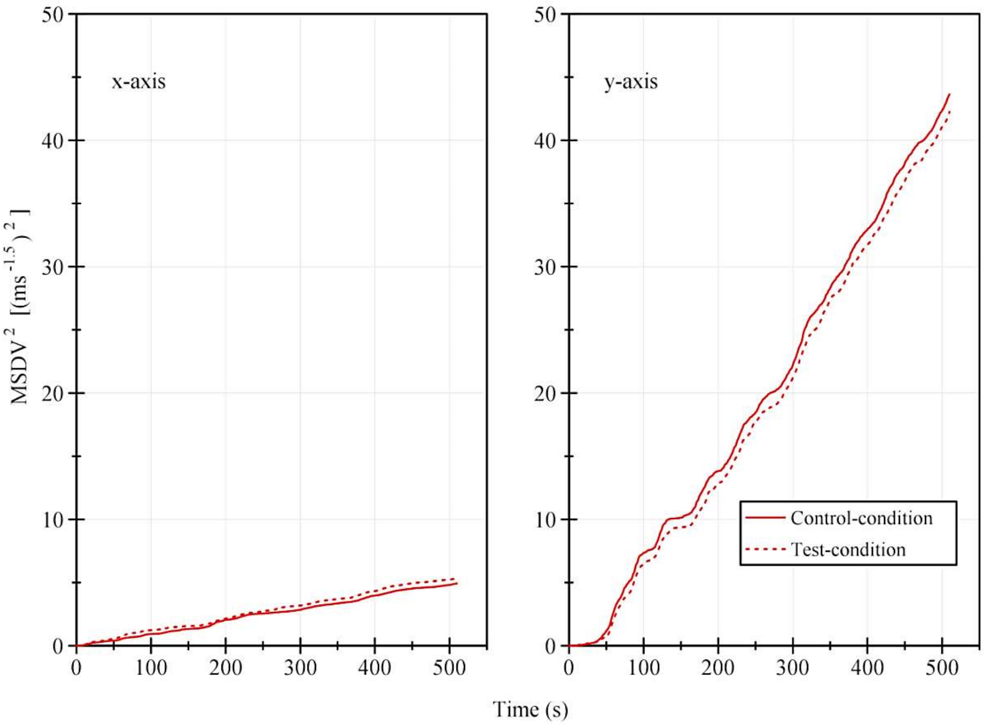


Figure 5-9: Mean accumulated squared motion sickness dose value (MSDV^2) in the longitudinal and lateral directions in both conditions

5.3.2. Effects of the Haptic Display

Statistical analysis was performed using IBM SPSS Statistics Version 23 (IBM Corp, 2015). A non-parametric test, the Wilcoxon signed-rank test (Wilcoxon, 1945), was used to investigate the effect of the vibrotactile display on situation awareness of the participants based on the SART scores (Table 5-1).

In general, situation awareness of 18 participants increased in the test-condition compared to the control-condition while the other two participants had their situation awareness reduced. There were significant effects in the total and all constructs' scores of SART except in the understanding-construct. The effect size r of the understanding-construct was converted into Cohen's d (0.402) (Lenhard & Lenhard, 2016). A power analysis was conducted using the software package, G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007) and the statistical power for the understanding-construct was found to be 0.518. Hence, the total sample sizes needed for this understanding-construct to achieve a power of 0.800 (β = 20%) was found to be 53.

Table 5-1: Results of SART scores with median and interquartile range (IQR) between both conditions

SART Constructs	Group	Median	*IQR*	Wilcoxon Signed-Rank Test
Understanding (U)	Control	10.00	(7.25 - 12.00)	z = 1.243, r = 0.197, p = 0.214
	Test	10.50	(7.25 - 14.75)	
Demand (D)	Control	12.50	(10.00 - 15.00)	z = -3.284, r = 0.519, p = 0.001*
	Test	7.00	(5.25 - 9.00)	
Supply (S)	Control	13.50	(10.25 - 16.75)	z = 2.446, r = 0.387, p = 0.014*
	Test	16.00	(13.25 - 18.75)	
Total SART	Control	9.50	(5.25 - 16.00)	z = 3.569, r = 0.564, p = 0.001*
	Test	17.50	(15.00 - 27.00)	

Note:
** Indicates significant effect (p < 0.05) (two-tailed)*
SART-D and SART-U = ranging from 3 (lowest) to 21 (highest).
SART-S = ranging from 4 (lowest) to 28(highest).
SART-Total = ranging from -14 (lowest SA) to 46 (highest SA).

Based on 20 sessions which were run in the test-condition with 18 corners for each session, the clicker measurement showed that two participants clicked the button on the clicker in the wrong direction once (two out of 360 corners from the whole study). All other participants had a perfect perception of the direction prompted by the vibrotactile display. The average result of the measured reaction time was 1.093 s (SD = 0.316 s)

The RSME scores were analysed using the Wilcoxon signed-rank test. There was no statistically significant difference between the control- and the test-condition on the RSME. The median of mental effort for the control-condition whereby participants were not presented with peripheral information from the vibrotactile display was 37.50, compared to the test-condition where the median was 27.50 ($z = -1.645$, $r = 0.260$, $p = 0.100$). The effect size r was converted into Cohen's d (0.539), and power analysis was conducted, and it has revealed that the statistical power for this analysis was found to be 0.73. Thus, the total sample sizes needed for this RSME score to achieve a power of 0.800 ($\beta = 20\%$) was found to be 31.

The MSAQ scores in the control- and the test-condition were compared by using the Wilcoxon signed-rank test (Table 5-2). There was no statistically significant difference found in the total score of MSAQ between the control- and the test-condition. The effect size r was converted into Cohen's d (0.597) and a power analysis revealed that the statistical power for this analysis was found to be 0.81. In addition, there were no statistically significant differences for the central-, the peripheral- and the sopite-related dimensions between both conditions. Power analyses were conducted and revealed that the statistical power for this analyses was found to be 0.58 for central-related dimension, 0.09 for peripheral-related dimension, and 0.24 for sopite-related dimension. Therefore, the total sample sizes needed for these analyses to achieve a power of 0.800 ($\beta = 20\%$) was found to be 33 for central-related dimension, 425 for peripheral-related dimension, and 94 for sopite-related dimension. Only the gastrointestinal-related dimension was significantly lower in test-condition compared to the control-condition.

Table 5-2: Results of MSAQ scores with median and interquartile range (IQR) between both conditions

MSAQ Dimensions	Group	Median	*IQR*	Wilcoxon Signed-Rank Test
Gastrointestinal (G)	Control	2.78	(0.00 - 28.48)	z = -2.554, r = 0.404, p = 0.011*
	Test	1.39	(0.00 - 8.33)	
Central (C)	Control	7.78	(2.22 - 18.89)	z = -1.603, r = 0.253, p = 0.109
	Test	6.67	(2.22 - 17.23)	
Peripheral (P)	Control	0.00	(-6.48 - 15.74)	z = -0.440, r = 0.070, p = 0.660
	Test	0.00	(0.00 - 3.70)	
Sopite (S)	Control	9.72	(0.00 - 21.53)	Z = -0.938, r = 0.148, P = 0.348
	Test	5.56	(0.00 - 18.75)	
Total MSAQ	Control	5.56	(0.52 - 21.70)	z = -1.811, r = 0.286, p = 0.107
	Test	5.21	(0.35 - 9.72)	

Note:
** Indicates significant effect ($p < 0.05$) (two-tailed)*
All MSAQ dimensions ranging from 0.0 % (no symptoms) to 88.9 % (most severe symptoms).

As the heart rate was measured in beats per minute (BPM) in the PT1, DAT, and PT2 phases, a two-way repeated measures analysis of variance (ANOVA) (Field, 2009) was conducted to determine the effect of vibrotactile display implementation on the heart rate. The two conditions and the three phases were two within-subject factors (our independent variables).

There were no outliers, as assessed by examination of studentized residuals for values which are greater than ±3, and the measurement data were normally distributed, as assessed by Shapiro-Wilk's test of normality (Shapiro & Wilk, 1965) on the studentized residuals ($p > 0.05$). Mauchly's test of sphericity (Mauchly, 1940) 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. The main effect of conditions (the control- and the test-condition) was also not significant. On the other hand, the main effect of phase showed a statistically significant difference in heart rate mean between phases (Table 5-3).

Table 5-3: Results of the two-way repeated measures ANOVA for heart rate measurement

Within-Subject Effect	Two-way Repeated Measures ANOVA	Main Effects	
2 Conditions X 3 Phases	F (2, 38) = 2.617, partial η^2 = 0.121, p = 0.086	Conditions	F (1, 19) = 1.019, partial η^2 = 0.051, p = 0.325
		Phases	F (2, 38) = 22.889, partial η^2 = 0.546, p < 0.001*

Note:
** indicates significant effect (p < 0.05) (two-tailed)*

Post-hoc analysis with a Bonferroni adjustment revealed that heart rate was statistically significantly increased from PT1 to DAT (mean difference = 3.18 BPM, 95% CI [1.26, 5.09], p = 0.001), and was statistically significantly decreased from PT1 to PT2 (mean difference = 2.34 BPM, 95% CI [0.42, 4.27], p = 0.014) and from DAT to PT2 (mean difference = 5.52 BPM, 95% CI [2.97, 8.07], p < 0.001) (Figure 5-10).

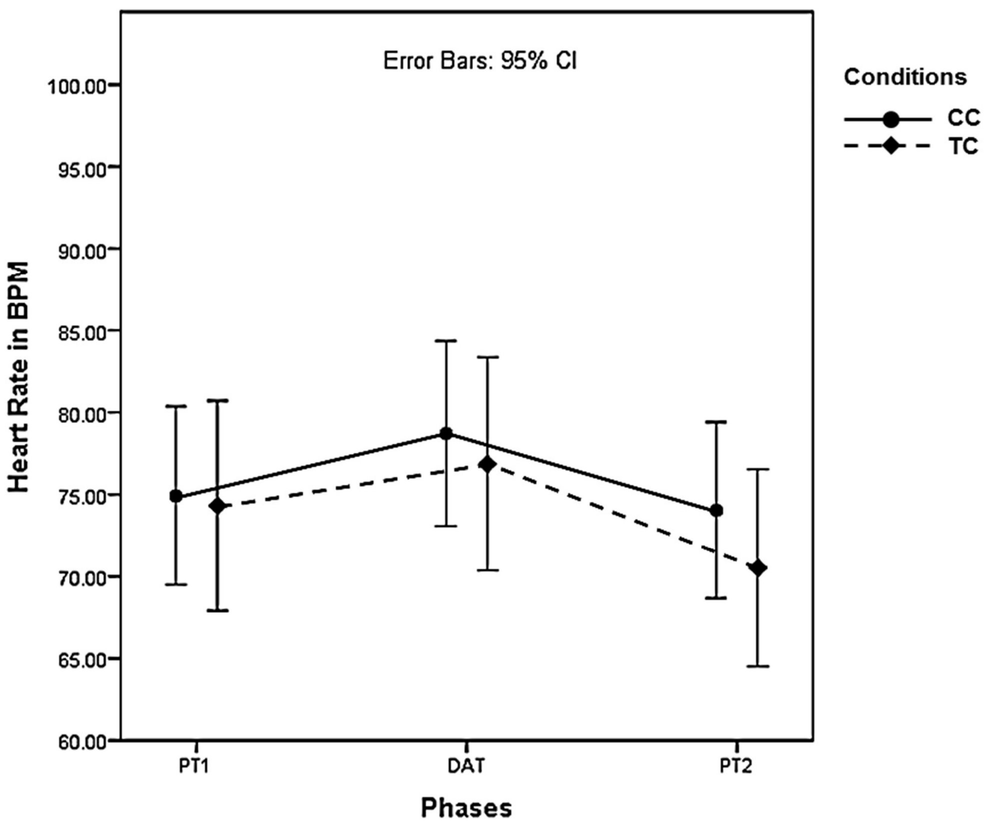


Figure 5-10: Estimated marginal means for heart rate at each phase of the two conditions (CC = control-condition, TC = test-condition)

The vibrotactile display was assessed subjectively by the participants in the test-condition by using the UEQ. The means, the standard deviations (SD), and the Cronbach's α consistency (Cronbach, 1951) were calculated and presented in Table 5-4. The result showed that the values of Cronbach's α for all categories were acceptable ($\alpha > 0.7$), except for perspicuity and dependability. All mean values of the UEQ scores were above 0.8, indicating that the overall rating for each category was positive.

Table 5-4: UEQ scores of the vibrotactile display

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

Note:
The rating is a 7-point scale, -3 (horribly bad), +3 (extremely good).

5.4. Discussion

5.4.1. Consistency of the Experiment

Based on the semi-log graphs of power spectral densities (PSD) of the longitudinal and lateral accelerations (see Figure 5-8), both conditions (the control- and the test-condition) showed almost identical distributions over the acceleration frequency spectrum, especially in longitudinal (x-axis) and lateral (y-axis) accelerations. The distributions overlapped on each other. As a result, the driving wizard managed to execute the defensive driving style consistently in all 40 sessions of this experiment by driving through the corners at almost the same time and by generating almost the same required accelerations in every corner.

The vertical (z-axis) acceleration which was peaked between 1 and 2 Hz had a low amplitude compared to longitudinal and lateral accelerations. In this experiment, the designated route (see Figure 3-27) was made of brick. Based on direct measures from the brick's geometry, vertical acceleration should be dominant at the frequency of 55 Hz, 30 km/h car speed. However, due to transmissibility (i.e. how much vibration is transmitted between two systems), the vibration was damped because of suspension's stiffness, damper or the car's weight (Suciu, Tobiishi, & Mouri, 2011). Griffin and Newman (2004a) also found similar findings of the PSD that the vertical acceleration is peaked between 1 and 2 Hz with the magnitude of about 0.25 $ms^{-4}Hz^{-1}$. In addition, the dominant frequency which was above 1 Hz in the vertical acceleration was found to be physically uncomfortable but not a factor in contributing to MS (Cheung & Nakashima, 2006).

On the other hand, the longitudinal and the lateral accelerations were dominant around 0.5 Hz, in which frequency is highly correlated with motion sickness (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999a). Hence, only these accelerations were analysed in terms of MSDV. The MSDV results revealed that the motion sickness's dose which was exposed to the participants at the end of each session, was similar in both conditions and it was three times higher in the lateral acceleration than in the longitudinal acceleration. Thus, we consistently able to induce similar motion sickness's dosage in every session of the experiment. The difference between MSDVs of longitudinal (2.26 $ms^{-1.5}$) and lateral (6.55 $ms^{-1.5}$) accelerations was expected, as previously mentioned in our experimental setup. In the experimental setup, the accelerating and braking of the Mobility Lab were controlled to be kept to a minimum, and the lateral acceleration was manipulated in the range of the defensive driving style. These findings are being supported by the PSD graphs which have shown low-frequency motions with lower magnitudes in the longitudinal acceleration compared to the lateral acceleration.

5.4.2. Effect of the Haptic Display

Based on statistical analysis results, 20 participants who participated in this experiment were considered sufficient in providing significant (total score of SART) or non-significant (total score of MSAQ) results with a large effect (Pearson's correlation coefficient, r, is equal to or larger than 0.5) and a statistical power of 0.8 and above. However, several statistical analyses were found to have a lower value than 0.8 for their statistical power, which means that a higher sample size is needed. On the other hand, an addition of more than 400 participants for the peripheral-related dimension of MSAQ analysis was considered not practical in conducting this experiment. A larger number of participants might succeed in getting significant results for small effect sizes, but that it may be questioned whether such small effects are interesting from a design perspective: the effects need to be large enough so that they have substantial impact for most or all of the participants.

In general, participants' level of situation awareness was higher with peripheral information compared to when they are not given information based on SART scores. However, the fact that there were no statistically significant differences between both conditions in the understanding-construct indicates that the difference between the SART scores for test-condition and control-condition was not due to better understanding induced by the peripheral display. One interpretation is that participants gave more effort to understand the situation in the control-condition than in the test-condition. This is in line with the finding that the attentional demand construct was higher for the control-condition compared to the test-condition. This dimension represents how much attention is needed when there are sudden changes during the car's manoeuvre. The result showed that less attention was needed in the test-condition. The fact that the attentional supply construct score, which expresses the quality and quantity of the information, was significantly higher for the test-condition than for the control-condition further corroborates this interpretation. Finally, this interpretation is also supported by the RSME findings, indicating that the average score for the mental effort was lower in the condition with peripheral information than in the control-condition. Although there was no statistically significant difference found, the effect size for the RSME was quite large. In addition, based on the clicker measurement, a very short response time indicates that the peripheral information was perceived almost immediately after the vibrotactile was activated.

Initially, it was hypothesized that providing peripheral information about the intention of the car (either turning to the left or to the right) could reduce or lessen motion sickness symptoms. The MSAQ result showed that the vibrotactile display did not help in reducing motion sickness in general, although the Wilcoxon signed-rank test indicated a medium to large effect size with a power of 0.81. A potential explanation might be in terms of another theory of motion sickness, the postural stability theory (Riccio & Stoffregen, 1991). Postural instability may occur when someone cannot predict the upcoming dynamics (or forces) and cannot carry out the appropriate actions for the upcoming dynamics. In addition, when taking a corner, drivers usually do not just lean but also tilt their head toward the curve centre or toward the origin of the centrifugal force whereas passengers' head usually tilts in the opposite direction. Bles et al. (1998) mentioned that the changes of head orientation relative to the gravity vector, also called gravito-inertial force (GIF), can also provoke motion sickness. Studies done by Golding et al. (2003) and Wada et al. (2012) found that an active head tilt might reduce motion sickness symptoms. In the current experiment, although passengers knew which direction the car will turn, the exact time needed to react (by tilting their head) can be either too late or too early. Furthermore, information regarding how big or small the corner was, and whether it was a short or a long corner was not presented in the vibrotactile display. These may lead to a misalignment between the head and the GIF vectors. This interpretation should be validated through head movements' analysis in future research.

Only the gastrointestinal-related dimension from MSAQ was found to score lower in the test-condition compared to the control-condition. As explained by Walton, Lamb, and Kwok (2011) based on Reason and Brand (1975), an exposure to a long period of mild nauseous motion will result in "*head*" symptoms first before proceeding to "*gastric*" symptoms, while a short exposure to a severely nauseous motion (as in our current experiment) will quickly develop "*gastric*" symptoms, and any "*head*" symptoms could be unnoticeable. However, keep in mind that even though the result for the gastrointestinal-related dimension was significant, medians in both conditions were low. One reason for this maybe that the severity of induced motion sickness in our study is sufficient to provide mild motion sickness only (see Matsangas, McCauley, & Becker, 2014), but was not enough to show any significant changes in both conditions. As mentioned by Holmes and Griffin (2001), moderate or severe motion sickness might result in significant effects. Hence, a higher dose of MSDV (possibly above 7.00 $ms^{-1.5}$) should be applied in future research.

Results from heart rate measurements were comparable to the current MSAQ results in which there were no significant differences in motion sickness level when comparing the control- and the test-condition. In both conditions, heart rate increased during the DAT phase and dropped again during the PT2 phase. The increase in heart rate was smaller for the test-condition compared to the control-condition (although the difference was not significant). Earlier studies (Cowings et al., 1986; Kim et al., 2005; LaCount et al., 2011) also found similar results with heart rate decreases immediately following nausea stimulus termination. In general, the fact that the heart rate was higher in PT1 compared to PT2 may be explained by the passengers' expectancies of possible discomfort at the beginning of the experiment.

In overall, the user experience of the vibrotactile display was evaluated with positive scores using UEQ. The low values of Cronbach's α for perspicuity and dependability suggest that several passengers may have interpreted the item in these categories in an unexpected way. For example, item 17 in the dependability category represents a "*secure - not secure*" scale, which can be understood differently from one passenger to another passenger (Rauschenberger, Schrepp, Perez-Cota, Olschner, & Thomaschewski, 2013). Although the general rating can be considered to be explicitly positive, some items were rated below 0.8, representing a neutral evaluation. Some of these items were item 1 ("*annoying - enjoyable*" scale) and item 6 ("*boring - exciting*" scale). In the open-ended question, several passengers mentioned that even though the vibrotactile display can provide the information peripherally, the display itself could be annoying as it was attached to the forearm and connected to a cable, and this may have affected the item 1 score. 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 related task.

5.5. Conclusion

In this experiment, a vibrotactile display was proposed in order to help passengers of an autonomous vehicle to increase their situational awareness and reduce motion sickness symptoms when they take their eyes off the road while doing a non-driving related task. The results of the experiment show a clear trend: the peripheral information from the vibrotactile display increased the situation awareness but did not help in reducing the motion sickness. Only the gastrointestinal-related dimension from MSAQ (sick to the stomach, may vomit) showed a significant decrease in the test-condition. Even though passengers knew the direction of the car, additional information was not presented such as the exact time of the induced forces and the magnitude of the forces when entering the corners. This may have resulted in uncontrolled movements of the head and may cause a misalignment between the head and the GIF, which may induce motion sickness symptoms. In the next experiment, the focus of the work will be devoted to the improvement of the prototype, especially to include a mechanism that is actively adjusting the GIF alignment, and to the study of its effect in reducing motion sickness in an autonomous vehicle.

Chapter 6. Mitigating Motion Sickness through an Active Movement Mechanism while Reading in an Autonomous Vehicle

6.1. Introduction

In the previous chapter, we found that the vibrotactile display was capable of increasing situation awareness but did not help in reducing motion sickness. One of the conclusions made was that the participants still have uncontrollable movements of their head. As described by Riccio and Stoffregen (1991) regarding the postural instability theory, the prolonged uncontrolled movements can induce motion sickness symptoms. The misalignment between the head and the gravito-inertial force (GIF) vectors can also elevate motion sickness (Bles et al., 1998). Actively leaning the body or head tilting towards the direction of the motion can reduce the development of motion sickness.

Furthermore, the assumption that we made due to no statistically significant differences of motion sickness (the Motion Sickness Assessment Questionnaire (MSAQ; Gianaros et al., 2001) and beats per minute (BPM) results) in the previous experiment was that the induced motion sickness dosage to the participants during the driven around test (DAT) phase was a mild dosage, and probably not enough to reveal any significant effects (Holmes & Griffin, 2001). Based on scores of the Motion Sickness Susceptibility Questionnaire (MSSQ; Golding, 1998), selected participants in the previous experiment also consisted of people with a large variety of susceptibility towards motion sickness. Other than focusing on three groups (mild-, moderate- and high-susceptibility for motion sickness), focusing on one group, the highly-susceptibility for motion sickness, was expected to show significant results.

In addition, a reading task was selected as the non-driving task in this experiment as many studies found that future users of an autonomous vehicle ranked reading as their top choice of non-driving related tasks to do in an autonomous vehicle compared to other tasks (Pfleging et al., 2016; Schoettle & Sivak, 2014; Vallet, 2013). However, the main reason was to make sure that the participants in the current experiment would experience motion sickness as the reading task was found to be one of the worst activities which can intensify the development of motion sickness (Isu et al., 2014; Kato & Kitazaki, 2006, 2008; Schoettle & Sivak, 2009).

This is why current passengers regularly look outside of the window at the horizon for a few minutes in order to anticipate the vehicle's trajectory before continuing the reading task. The visual information about artificial earth-reference was shown to increase anticipation and reduce carsickness (Bos et al., 2012; Tal et al., 2012), and it is one of the coping mechanisms that passenger normally apply in order to achieve situation awareness (Terken et al., 2017). In addition, even though users of an autonomous vehicle might have the comfort of not manually driving the vehicle, the non-driving related tasks might be interrupted in gaining situation awareness. In addition, the mental workload will not only influence situation awareness (Parasuraman et al., 2000; Stanton & Young, 2000) but also might affect the performance of the tasks (de Winter et al., 2014; Ma & Kaber, 2005). As mentioned by Recarte and Nunes (2003), an increase in mental workload on visual search (looking outside of the vehicle in our study) can reduce the performance of the driving (performance of the reading task in our study).

As a result, the focus of this experiment was to investigate the implementation of a mechanism which can actively adjust the posture of the body of the users, while they are engaging in a non-driving related task in an autonomous vehicle. In addition, another type of modality, a visual display, was also designed and tested on situation awareness and mental workload in providing peripheral information about the direction of the autonomous vehicle movement to the user. This is because although the visual modality was found to be a distraction for the users to enjoy a non-driving related task (van Veen, Karjanto, & Terken, 2017), another study found that the visual modality did not degrade the performance of the non-driving related task (Karjanto et al., 2018). It was hypothesized that there are significant differences in terms of the level of situation awareness and motion sickness between the implementation of two proposed peripheral information displays (haptic and visual) and without any information. We also hypothesized that both peripheral information systems have significant differences in terms of the mental workload when they are compared to the non-peripheral information system condition. In addition, it was hypothesized that both peripheral information systems have significant effects on the performance of reading, as a non-driving related task in this study.

6.2. Methodology

6.2.1. Experimental Design

All participants underwent three experimental test conditions (within-subject) termed as control-condition (without any information displays), haptic-condition (with a haptic display), and visual-condition (with a visual display). A fully-counterbalanced order (3! = 6 orders) of test conditions of the experiment was applied in mitigating any order or learning effects. In addition, a minimum gap of three days between each session was administered to avoid any carry-over effects (the prolonged motion sickness from the previous session). The dependent variables were evaluations of motion sickness, situation awareness, mental workload and the assessment of reading performance. The independent variable was the three test conditions. The experiment was conducted within the compound of Eindhoven University of Technology's route where regulations of Dutch traffic laws apply with a maximum speed restriction of 30 km/h was mentioned. As an additional safety precaution, the TU/e security was informed about the experiment and permission to use the designated route was granted.

There were 38 corners (16 to the left, 22 to the right) with an average radius of 9.2 m (SD = 3.3 m) (Figure 6-1). This experiment was compliant with the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) (Association of Universities in the Netherlands [VSNU], 2014).

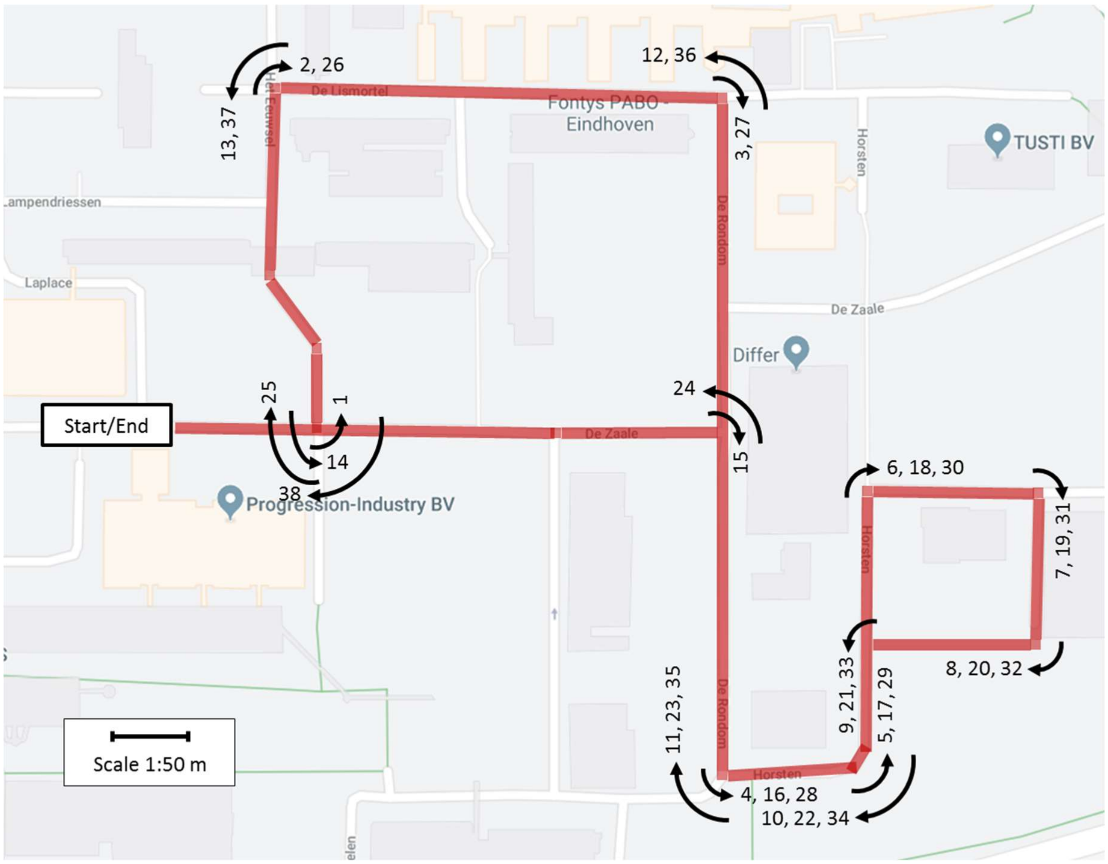


Figure 6-1: The designated route starting from corner 1 to 38

6.2.2. Prototypes

Two information displays were used in this experiment. One of the two information displays was the haptic display. The idea of the haptic display design was based on just not to convey the navigational information through a vibrotactile display but also to provide an active movement that pushes or holds the participants' body in the direction of the corner. The design of the vibrotactile display was based on the prototype in Section 5.2.2, and its function is to convey the information through vibrating sensation on the forearms (see Figure 6-2). The display consisted of two sets of vibration motors which were attached on two strips of hook-and-loop fasteners.

For the active movement, the mechanism consisted of two movable plates fixed on the backrest of the car seat and covered with foam cushion and fabric. Three seconds before the car turned to the left or to 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. Immediately afterwards, 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.

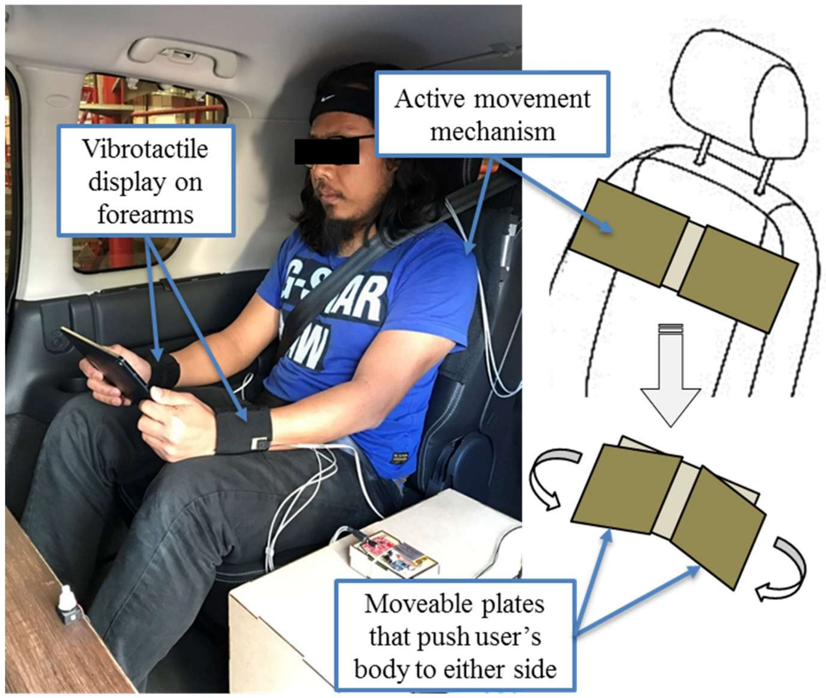


Figure 6-2: Haptic display with an active movement mechanism

Even though the process of constraining the head from uncontrollable movements might probably reduce motion sickness, passively aligning GIF by pushing the head can lead to whiplash injury, which is a neck injury caused by a sudden movement of the head forwards, backwards or sideways. In addition, constraining the occupants' head appeared to produce a bad user experience in autonomous vehicles. Thus, the shoulder was selected to be pushed at the corners rather than the head. Since the defensive driving style was the preferred autonomous driving style with 0.29 g of lateral acceleration (see Section 3.4), the expected tilt angle of the GIF to align with the gravity vector is about 16° (Figure 6-3). Hence, about 40° turning forward of the moveable plate is enough to push the participants' shoulder at about 16° sideways.

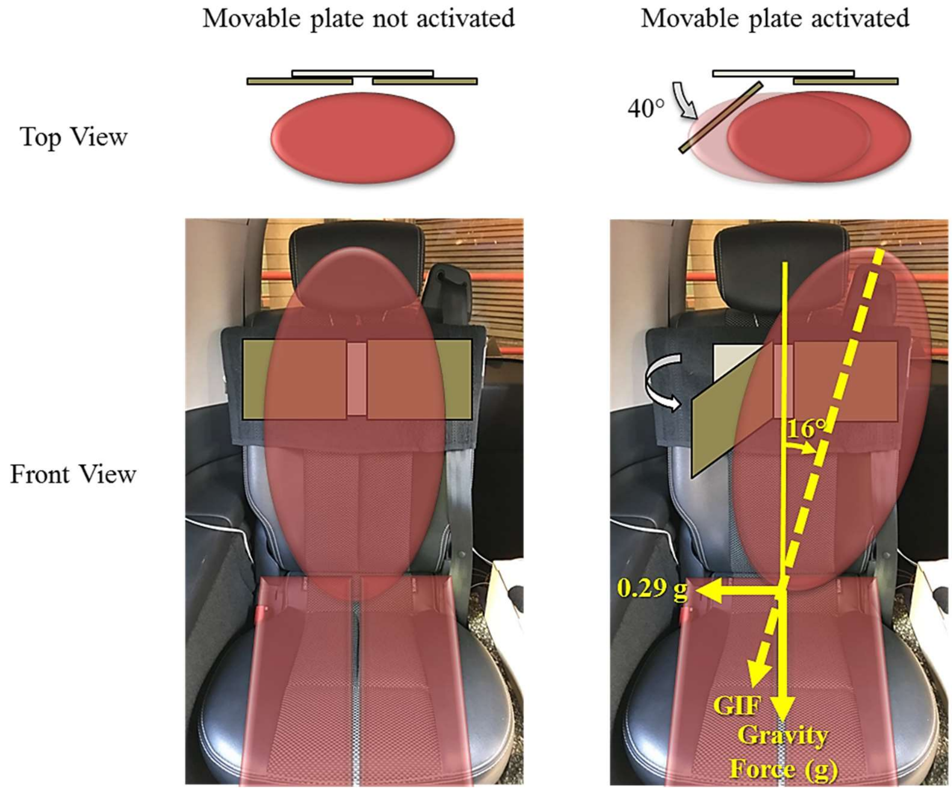


Figure 6-3: The tilted angle of the GIF from the moveable plate

The other information display was the visual display. The idea of the visual display design was based on the outcome of a workshop which is about ambient peripheral displays (Löcken et al., 2017). The visual display utilizes the human peripheral field of vision in conveying navigational information of the autonomous vehicle to the participants, and it was an iteration from another prototype which was used in the previous study (Karjanto et al., 2018). The visual display consisted of a 4.0” display and two pairs of light-emitting diode (LED) strip on both sides of the 4.0” display (Figure 6-4). This layout was mounted on top of 8.9” tablet. The reading material was displayed on the 8.9” tablet display. Live streaming of the front windshield camera was displayed on the 4.0” display during the entire session of the experiment. Three seconds before the car turned to the left or to the right, the LEDs were illuminated in such a way that either the left or the right pair of the LEDs were lit in a movement from bottom to the top for three cycles. In order to ensure that the visual display can grab the attention of the participants but still not interrupting their reading performance, the LEDs were diffused with a Perspex® acrylic sheet.

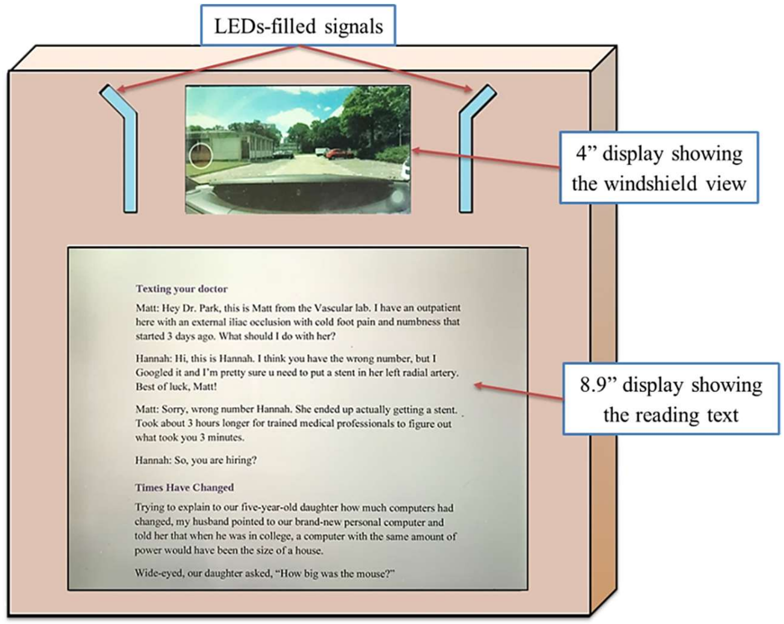


Figure 6-4: Visual display

6.2.3. Equipment and Wizard

The experiment was conducted using the Mobility Lab which has been modified for human factor studies in an autonomous vehicle. The detailed description regarding the design, setups, and functions of the Mobility Lab is explained in Section 3.3. The Mobility Lab is able to provide a transparent or opaque window setup. In this experiment, the car windows were transparent in order to let participants have a normal outside view (Figure 6-5).

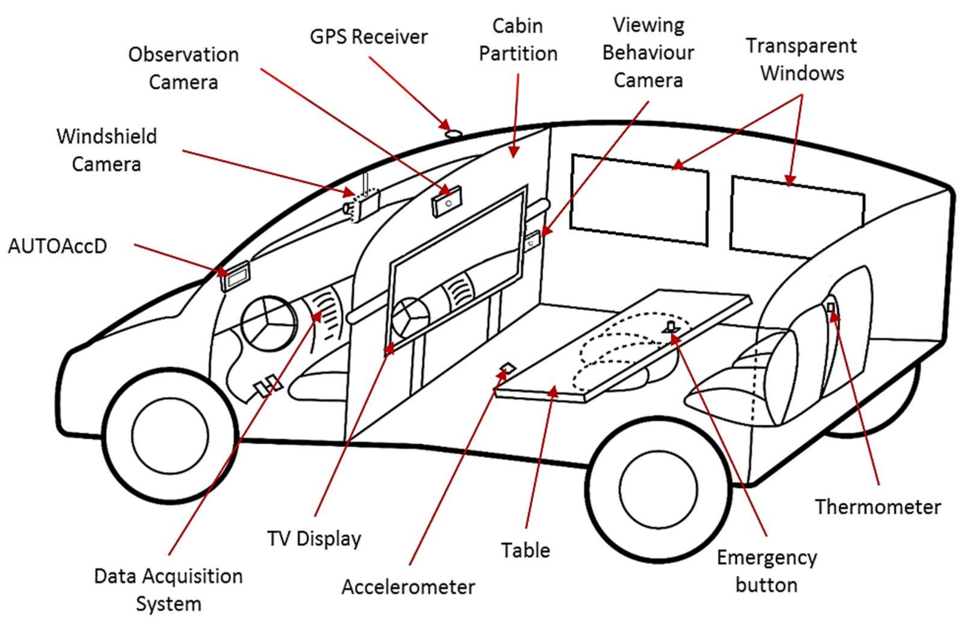


Figure 6-5: Mobility Lab interior layout. The window blinds were not used in the current experimental setup. (Adapted Karjanto et al., 2018)

The mounted TV display in the Mobility Lab 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. For safety reason, an emergency button was available on the table in case 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. The temperature inside the car was maintained at 20.0° Celsius by the air conditioning.

Similar to Chapter 5, the experiment was conducted by using a Wizard of Oz autonomous car simulation environment which was inspired by Baltodano et al., (2015) and based on Karjanto et al., (2018) method. An accomplice of the experimenter acted as a driving wizard. The primary task of the driving wizard was to simulate the autonomous vehicle riding experience with the help of the AUTOAccD (refer to Section 3.2.3.1.1). The AUTOAccD was developed to guide the driver in simulating the intended acceleration in autonomous vehicle driving style in a typical car. In this experiment, the defensive driving style was used because it was generally preferred by drivers in previous studies (Basu et al., 2017; Md. Yusof et al., 2016). The lateral (cornering or turning) acceleration was maintained at around 0.29 g or 2.84 ms^{-2} (refer to Section 3.2.2). On the other hand, the longitudinal (fore-and-aft) acceleration was controlled to be kept at a minimum level, and it can be expected that an autonomous vehicle can always cross an intersection without stopping due to car-to-car communication (Fajardo et al., 2011).

During the experiment, the experimenter was the only person who interacted with the participants. In addition, markers were deployed at an appropriate distance from the street corners. These markers were used to guide the experimenter in triggering the vibrotactile display 3 seconds before each street corner based on the predefined speed of the car. Then, the experimenter activated the moveable plate on the condition that the cornering took place.

6.2.4. Participants

A total of 18 participants (9 males and 9 females) aged between 22 and 33 years old (mean = 28.4 years, standard deviation (SD) = 3.0 years) took part in the experiment. They were recruited through social media as well as through flyers being put up around the campus. Stratified sampling was used, and it is based on the participants' scores (mean = 79.1 %, SD = 17.3 %) in the Motion Sickness Susceptibility Questionnaire (MSSQ; Golding, 1998). They answered the questionnaire a few days before the experiment and scored between 75 to 100 percentile rating (representing highly-susceptibility for motion sickness, see Fowler et al., 2014). They were paid € 30 for their participation.

In addition, heart rate variability (HRV) was used to evaluate motion sickness. Since different individuals have different variations which actually can influence the HRV (Quintana & Heathers, 2014), stable and transient participant's variables need to be controlled (Laborde et al., 2017). For the stable participant's variables, all selected participants were non-smoker

(Umetani, Singer, McCraty, & Atkinson, 1998), non-habitual drinker who scored below 8 for males and below 6 for females using the Alcohol Use Disorders Identification Test (AUDIT; Aalto, Alho, Halme, & Seppä, 2009; Bush, 1998), had a Body Mass Index (BMI) between 20 and 30 (mean = 21.6 BMI, SD = 2.0 BMI) (Molfino et al., 2009), and none of the participants had any heart-related sickness. For the transient participant's variables, the participants were asked to follow a normal sleep routine the day before the experiment (Stein & Pu, 2012), not to participate in any intense physical exercise 24 hours before the experiment (J. Stanley, Peake, & Buchheit, 2013), not to consume any meals (Lu, Zou, Orr, & Chen, 1999) and caffeinated drinks (Zimmermann-Viehoff et al., 2016) at least two hours before the experiment.

6.2.5. Data Collection

The measurements (Figure 6-6) in this experiment was based on the explanation of the measurements in Chapter 4.

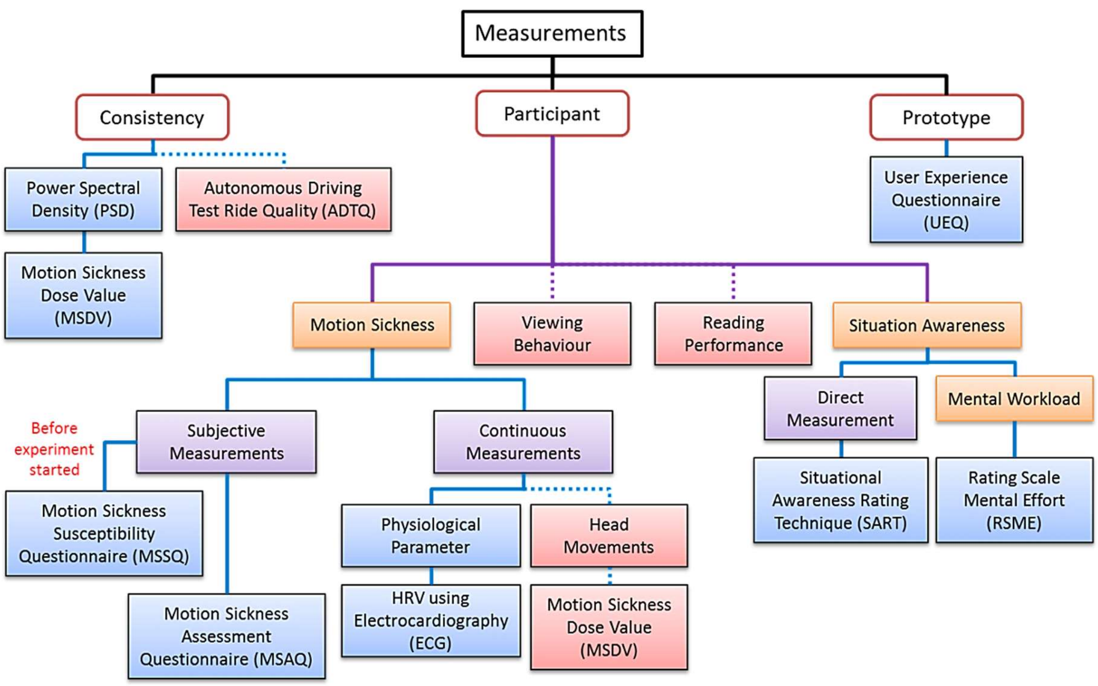


Figure 6-6: The main measurements in Chapter 6. The dashed line represents an additional measurement that was not discussed in Chapter 4.

For consistent data measurements, the Autonomous Driving Test Ride Quality (ADTQ) (see Appendix 14) was included as a subjective measurement in addition to the power spectral density (PSD) and the motion sickness dose value (MSDV) analysis. The ADTQ is a question which asks about how real was the autonomous driving experience when being driven around inside the Mobility Lab. The question uses a ten-point Likert scale (1 = very unrealistic, 10 = very realistic).

For participants' data measurements, electrocardiogram (ECG) sensors were used to measure the heart rate activity of the participants as a continuous motion sickness measurement. This is in line with the previous experiment in Chapter 5, in which the heart rate was measured in terms of beats per minute (BPM). Furthermore, recorded ECG data were used for heart rate variability (HRV) assessment in which the HRV was evaluated in the time- and frequency-domain analysis. In terms of time-domain analysis, the root-mean-square of successive differences (RMSSD) was used to assess the parasympathetic nervous system. A decrease in the parasympathetic nervous system represents the development of motion sickness (Kim et al., 2005; LaCount et al., 2011). In terms of frequency-domain analysis, the high-frequency (HF) component that ranged between 0.15 and 0.40 Hz was analysed to assess the parasympathetic nervous system. Further details about HRV data measurement are explained in the experiment procedure (Section 6.2.6).

In addition, as many studies also found that motion sickness is developed due to the involuntary movement of the head (e.g., Wada et al., 2012), participant head's movement (in terms of acceleration) was measured continuously using accelerometer-equipped headband (Figure 6-7). The recorded acceleration data were analysed using the PSD and the MSDV, similar to the technique that was used to evaluate the consistency of the experiment.

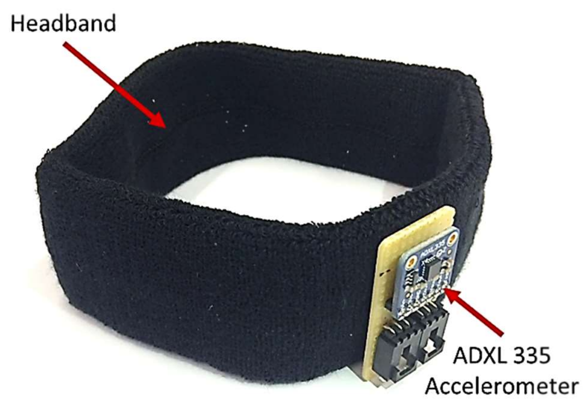


Figure 6-7: Accelerometer-equipped headband

The viewing behaviour was assessed by a combination of the observation camera (Logitech HD c920 webcam) and the viewing behaviour camera (OMRON B5T-007001-010) (refer to Figure 6-5). Both cameras were used to continuously record the participant's behaviour and viewing behaviour during the entire experiment. The recorded videos from the webcam were analysed by advancing them at 1 s intervals, resulting in an average of 900 frames which were observed. From this data, what can be observed were participant's action and behaviour during the experiment. On the same hand, the data measured from the viewing behaviour camera were analysed for gazing behaviour. The percentage of the viewing behaviour (how long the participants' eyes look directly at the tablet) was calculated over the total period of the autonomous driving period.

The reading performance was assessed by three different sets of questions from three different texts. Refer to Appendix 15, Appendix 16 and Appendix 17 for the questions. The reading materials are the compilations of jokes taken from Reader's Digest magazine (Reader's Digest, 2018). This type of reading material was chosen to encourage participants to read the texts. Each set was designated for a different condition, and each questionnaire consists of 10 questions with four choices of answers. Each correct answer scored the participants 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*).

6.2.6. Procedure

In general, all sessions of the experiment consisted of seven stages (Figure 6-8). Stage 1 took place in a meeting room while Stage 2 through 6 were done inside the Mobility Lab. Stage 7 was started inside the Mobility Lab and continued in the meeting room.

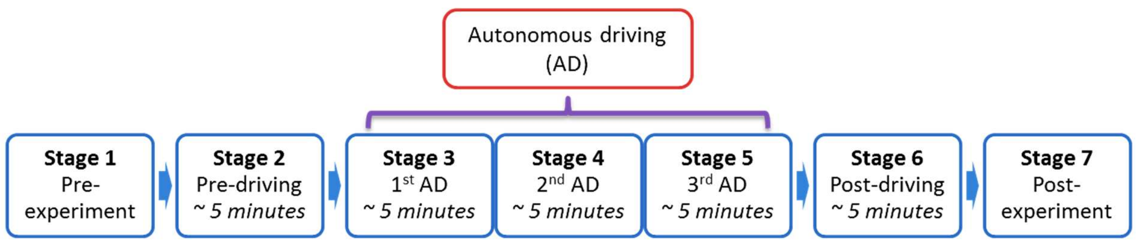


Figure 6-8: The seven stages of the experiment for the three conditions (control-, visual-, and haptic-condition)

At the pre-experiment stage (Stage 1), the participant was briefed on the layout of the experiment, including the right to withdraw at any time. After the briefing, the participant signed the informed consent form (Appendix 18) and answered the pre-experimental questionnaire, the MSAQ. Next, the participant was explained on how to attach disposable ECG electrodes, the Kendall H135SG ECG Electrodes, on his/her torso. Since all participants were a mixed-gender group, he/she was allowed to attach the disposable ECG electrodes him/herself based on an illustration of the ECG electrodes placement on the body (Figure 6-9). It was based on Shaffer and Combatalade (2013) suggestion that a lower torso placement is less sensitive to movement artefacts, and this placement is ideal for people who don't like to expose their chest.

Next, the experimenter ushered the participant to the right side rear door of the Mobility Lab from behind (similar to Figure 5-5). This is done to make sure that the participant did not see the driving wizard who was already in the driver seat when entering the vehicle. The participant was asked to wear the seat belt and the accelerometer-equipped headband. The ECG connector was then connected to the AD8232 Single Lead Heart Rate Monitor from SparkFun which was coupled to the data acquisition (DAQ) system of the Mobility Lab. The ECG measurement was measured and recorded continuously from Stage 2 until Stage 6 with a sampling rate of 250 Hz. Since our study involves an environment which constantly moves with lots of vibrations, connecting a person to an electronic device that runs off a significant power source could be dangerous (Yeo, Khan, & Derek, 2007). Thus, an optocoupler (optically isolated) was used as our electrical isolation (Figure 6-10).

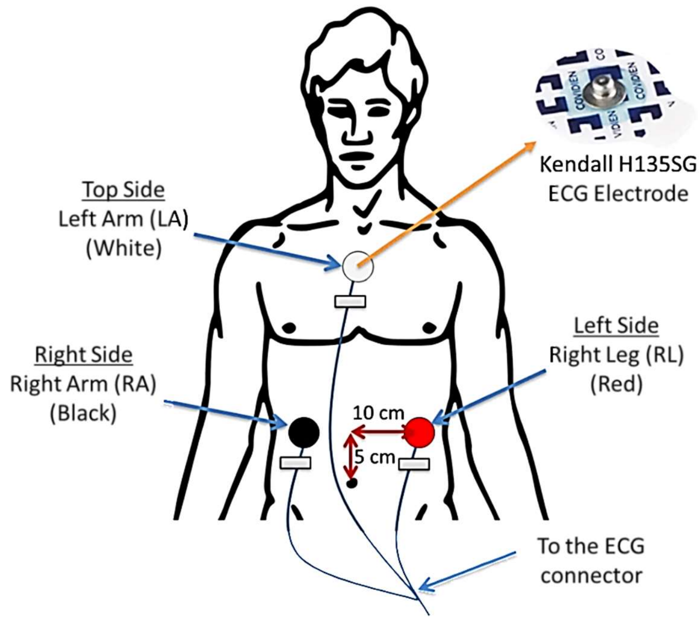


Figure 6-9: The ECG electrodes placement. The marked symbols (LA, RA and RL) represent the original placement of the electrodes.

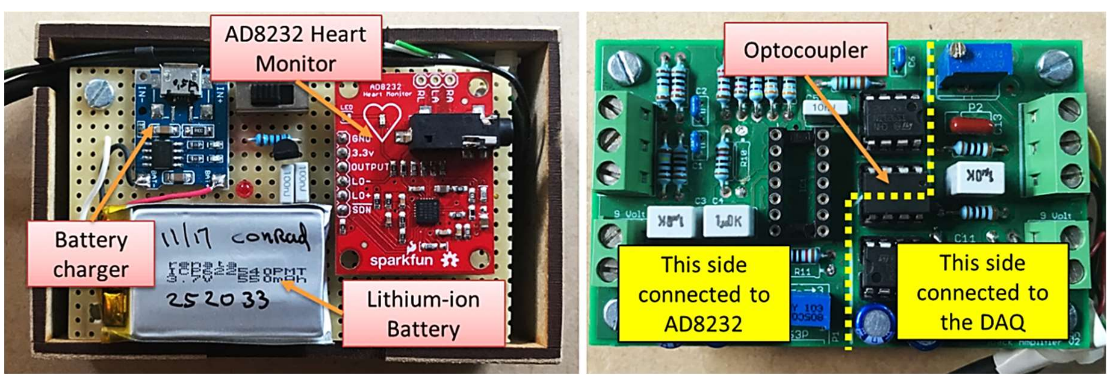
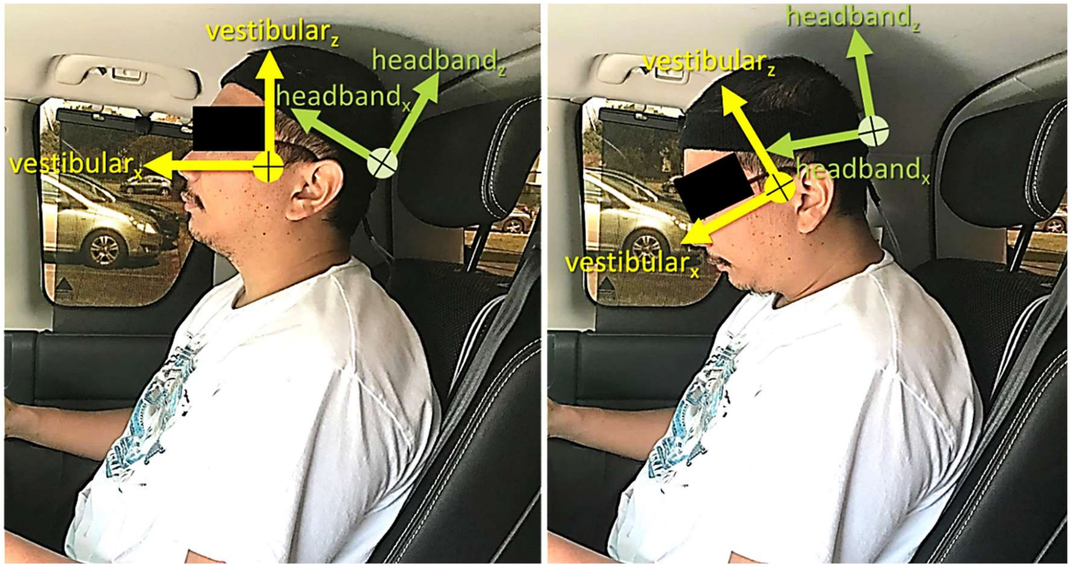


Figure 6-10: The top view (left) and the bottom view (right) of the electronic circuit for the HRV data measurement with an optocoupler connected between the AD8232 Heart Monitor and the DAQ system

Furthermore, as different participants have different positions in wearing a headband, calibration was done every time the participant wore the accelerometer-equipped headband. The participant was asked to sit comfortably, and then to look straight ahead for about 10 seconds for the experimenter to measure and calibrate the initial vestibular acceleration from the accelerometer-equipped headband in the x-, y-, and z-axis directions (Figure 6-11). In addition, an explanation regarding the use of the emergency button was given before Stage 2 started.



(a) (b)

Figure 6-11: (a) Calibration position and (b) reading position

With regards to the task and the peripheral information system, the explanations were given depending on the condition of the session. In all three conditions, the only task for the participant inside the Mobility Lab was to read the texts which were taken from Reader's Digest (2018). A different set of reading material, with a font size of 15, was used for each condition. In the control-condition, the participant was reading from a tablet. In the visual-condition, the participant was reading from the visual display. In the haptic-condition, the participant was reading from a tablet with the implementation of the haptic display (the vibrotactile display on both forearms combined with the active movement mechanism on the backrest of the car seat) (see Figure 6-2). The participant was told that they would be rewarded an extra € 5 if they managed to answer most of the questions about the reading material correctly at the post-experiment stage (Stage 7). This was done to motivate the participant to keep reading from Stage 2 to Stage 6.

During the pre-driving stage (Stage 2), the Mobility Lab was stationary with the engine turned on for about 5 minutes. At the autonomous driving stages (Stage 3, 4 and 5), the driving wizard drove the Mobility Lab on the predefined route (see Figure 6-1) with the defensive driving style (Md. Yusof et al., 2016) for about 15 minutes.

The total data points for each HRV measurement was about 225,000 (250 Hz for 15 minutes). As suggested by Laborde et al., (2017), the recorded HRV data were analysed according to the three-R structure (i.e., resting HRV, reactivity HRV, and recovery HRV) as shown in Figure 6-12. The baseline HRV or also known as resting HRV was taken in Stage 2. The reactivity HRV was the change in HRV data between Stage 2 and any of the autonomous driving stages (Reactivity 1 = Changes between Stage 2 and 3, Reactivity 2 = Changes between Stage 2 and 4, Reactivity 3 = Changes between Stage 2 and 5). The recovery HRV was the change in HRV data between Stage 2 and 6.

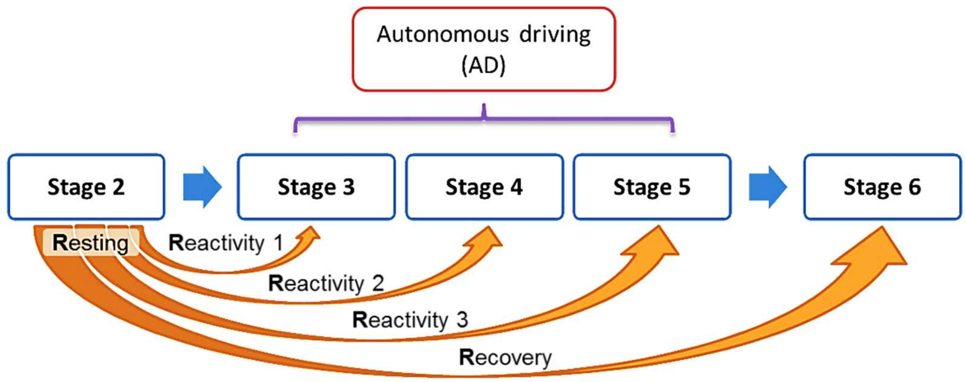


Figure 6-12: Three-R structure of HRV measurement and analysis used in this study

During the post-driving stage (Stage 6), the Mobility Lab was stopped and idled for another 5 minutes with the engine turned on. During the post-experiment stage (Stage 7), the participant was given a set of questionnaires consisting of the ADTQ, the MSAQ, the SART, the RSME, the reading performance questionnaire, and the UEQ (only for the visual- and the haptic-condition). These questionnaires have to be immediately answered inside the Mobility Lab right after Stage 6 finished. Next, the experimenter guided the participant back to the meeting room where a debriefing was performed.

In addition, a separate test was done in order to check the upper and lower (chance level) boundaries for the comprehension of the reading task used in this particular study. We recruited another 14 different participants (8 males and 6 females) aged between 22 and 36 years old (Mean = 27.5 years, SD = 9.0 years). They were students of the Eindhoven University of Technology, and there are also other students from other universities. They were asked only to answer two sets of questionnaires (see Appendix 15 and Appendix 16) from the same reading materials (Reader's Digest, 2018), in which one comes with a reading text, and another one comes without the reading text. For the set of the questionnaire with the reading material, the participants have to read the text before answering the questionnaire. For the set of questionnaire without the reading material, the participants have to directly answer the questionnaire. The test was done inside a typical office room, and the result was compared with the reading performance in the experiment.

6.2.7. Statistical Analysis

Statistical analyses were performed using the IBM SPSS software (Version 23; IBM Corp, 2015) to compare the effects of the three conditions. The outliers should first be checked and removed from the result. However, if the outliers did not reveal them to be extreme (less than three times the interquartile range (IQR), either from above the third quartile or below the first quartile of a boxplot), all data were included in the analysis (Lund & Lund, 2015). Then, 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 (Lund & Lund, 2015). If data were normally distributed, a parametric test was used whereas if data were not normally distributed, a non-parametric test was used.

In order to compare the means for the three conditions, a one way repeated measures analysis of variance (ANOVA) was used for the parametric analysis (Lund & Lund, 2015). 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 (Lund & Lund, 2015). If the Mauchly's test of sphericity was met ($p > 0.05$), the sphericity assumed value was used to determine the result of the one way repeated measures ANOVA. 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.

On the other hand, 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 (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 ($r = 0.5$) (J. Cohen, 1992) was conducted using the software package, G*Power software (Faul et al., 2007). 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) (Lund & Lund, 2015).

6.3. Results

6.3.1. Consistency of the Experiment

The distributions of tri-axial accelerations across the frequency spectrum for all 54 sessions were plotted in three semi-log graphs as a function of power spectral densities (PSD) (see Figure 6-13). All three conditions showed similar distributions where they were overlapped on each other. The longitudinal (x-axis) and lateral (y-axis) accelerations were dominated at below 0.2 Hz while the vertical acceleration (z-axis) was peaked between 1 and 2 Hz. The maximum amplitude of the lateral acceleration was almost 10 times higher than the maximum amplitude of the longitudinal acceleration, whereas the maximum amplitude of the vertical acceleration barely exceeded 0.25 $ms^{-4}Hz^{-1}$.

Since motion sickness has been shown to be highly correlated with low-frequency motions (below 0.5 Hz) while the high-frequency motions (1 Hz and above) are found to be not provocative to motion sickness (Cheung & Nakashima, 2006), only the low-frequency motions of longitudinal and lateral accelerations were used to calculate the Motion Sickness Dose Value (MSDV) (Figure 6-14). The vertical acceleration was also included in the figure only for a comparison between the Mobility Lab and the passengers' head movements for later results. For the whole 15 minutes of the autonomous driving stages, the MSDVs were similar in the longitudinal acceleration for the control-condition (mean = 3.049 $ms^{-1.5}$, SD = 0.530), the haptic-condition (mean = 3.092 $ms^{-1.5}$, SD = 0.410), and the visual-condition (mean = 2.987 $ms^{-1.5}$, SD = 0.437). The MSDVs were also similar in the lateral acceleration for the control-condition (mean = 8.756 $ms^{-1.5}$, SD = 1.194), the haptic-condition (mean = 9.286 $ms^{-1.5}$, SD = 0.852), and the visual-condition (mean = 9.028 $ms^{-1.5}$, SD = 1.187).

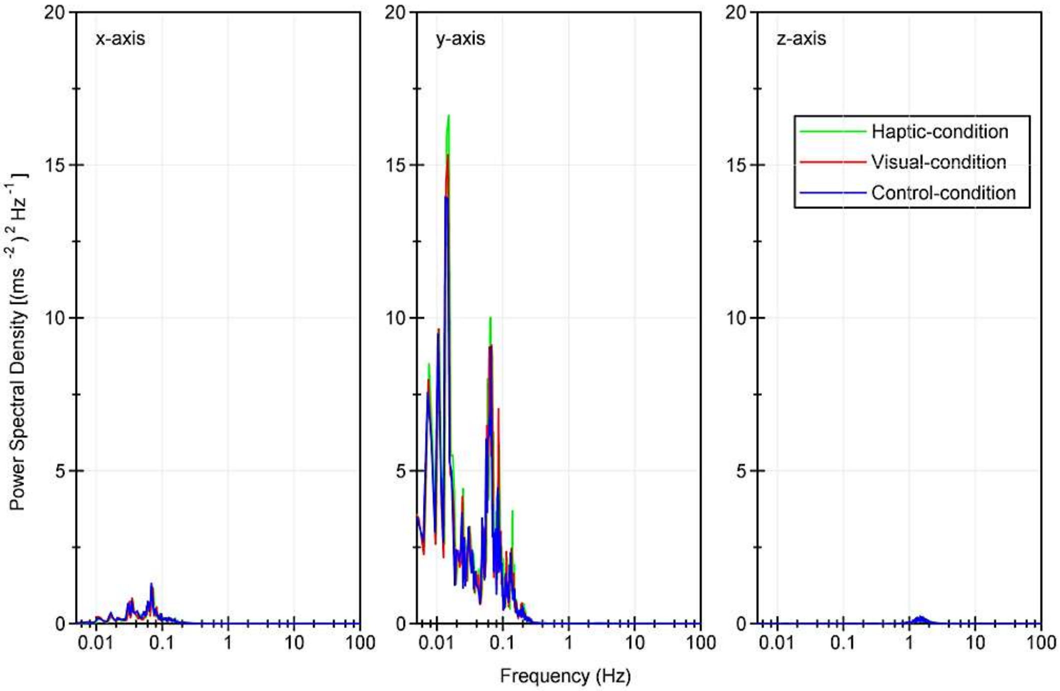


Figure 6-13: Power Spectral Densities (PSDs) of mean acceleration for the control-, visual-, and haptic-condition

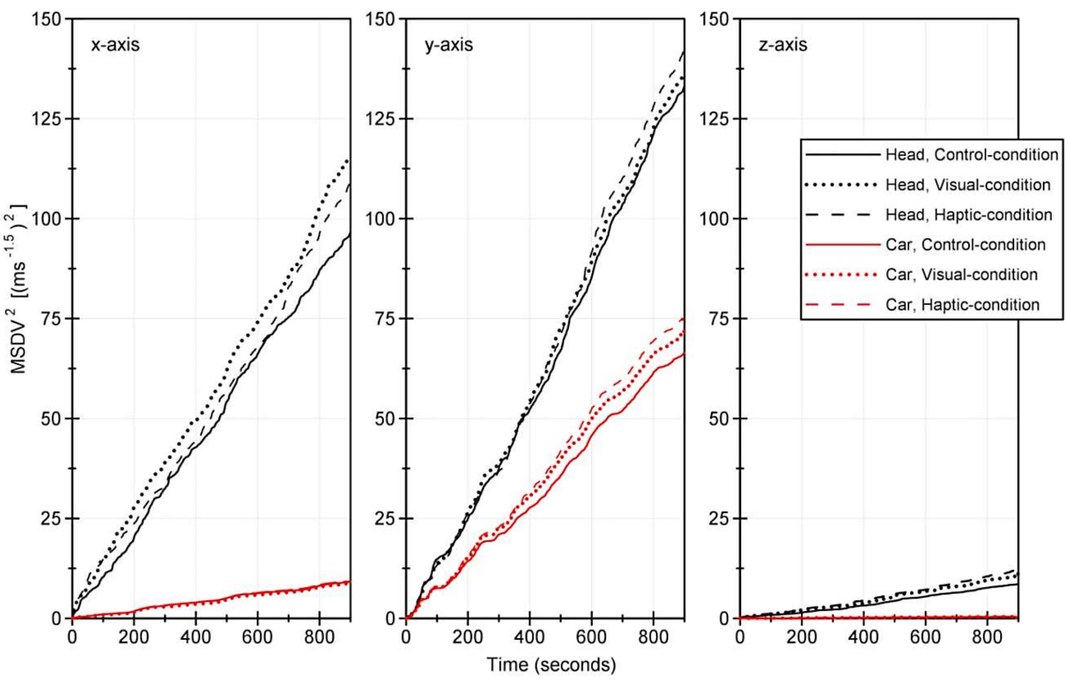


Figure 6-14: Comparison of mean accumulated squared motion sickness dose value (MSDV^2) between the Mobility Lab and the passengers' head movements in tri-axial directions for the three exposed conditions

For the Autonomous Driving Test Ride Quality (ADTQ), a one way repeated measures ANOVA (Field, 2009) was conducted to determine if there were statistically significant differences between the test ride quality, experienced by the participants across the three conditions (Table 6-1). It was found that there was a statistically significant difference in the test ride quality across the conditions. However, further post-hoc analysis using a paired samples t-test with a Bonferroni adjustment ($p < 0.017$) revealed that there was no statistically significant difference between any of the two paired conditions.

Table 6-1: Results of statistical analysis on Automated Driving Test Ride Quality (ADTQ)

Conditions	Mean	*SD*	One-Way Repeated Measures ANOVA	Group	Paired Samples *T*-Test
Control	6.8	1.4	$F(2, 34) = 3.704$, partial $\eta^2 = 0.179$, $p = 0.035$*	Control Haptic	95% CI [-1.788, -0.101] $t(17) = -2.411$, $d = 0.556$, $p = 0.030$
Haptic	7.8	1.7		Control Visual	95% CI [-1.053, 0.275] $t(17) = -2.361$, $d = 0.291$, $p = 0.233$
Visual	7.2	1.6		Haptic Visual	95% CI [-1.243, 0.131] $t(17) = -1.706$, $d = 0.403$, $p = 0.106$

Note:
** Indicates significance, p < 0.05 (two-tailed)*
The rating is a 10-point scale, 1 = very unrealistic, 10 = very realistic

6.3.2. Effect of the Peripheral Information Displays

For situation awareness (SART) and mental workload (RSME) assessments, there was one outlier in the understanding-construct of SART for the haptic-condition. However, this outlier was kept in the analysis because it was considered genuine data (an outlier that was not due to measurement error but was due to being an extreme value). 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 situational awareness by the participants between the control-condition and the conditions with the peripheral information systems (Table 6-2).

There was no statistical significance found in the score of RSME, either with the haptic or with the visual display. Power analyses were conducted, and the statistical power was found to be 0.497 between the control- and the haptic-condition and 0.103 between the control- and visual-condition. Hence, the total sample size needed to achieve a power of 0.800 ($\beta = 20\%$) to compare means between the control- and the haptic-condition was found to be 34 and between the control- and visual-condition was found to be 266.

In terms of the total score of SART, it was found that both conditions with the peripheral information systems (the visual- and the haptic-condition) were rated significantly higher 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 gave a statistically significant increase compared to the control-condition in providing information to the participants. As regards to the visual-condition, a power analysis was conducted, and the statistical power was found to be 0.167. Hence, the total sample size needed to achieve a power of 0.800 (β = 20%) for this paired samples t-test was found to be 125.

Table 6-2: Results of statistical analyses on situation awareness (SART) and mental workload (RSME) data between control-condition and visual-/haptic-condition

Parameters	**Conditions**	**Mean**	***SD***	**Group**	**Paired Samples *T*-Test**
RSME	Control	77.9	34.3		
	Haptic	62.1	27.8	Control Haptic	95% CI [-1.896, 33.674] t (17) = 1.885, d = 0.444, p = 0.077
	Visual	72.7	22.3	Control Visual	95% CI [-9.096, 19.540] t (17) = 0.770, d = 0.181, p = 0.452
SART (Demand)	Control	11.0	4.5		
	Haptic	6.7	2.2	Control Haptic	95% CI [1.769, 6.898] t (17) = 3.565, d = 0.840, p = 0.002*
	Visual	8.0	3.5	Control Visual	95% CI [0.618, 5.381] t (17) = 2.657, d = 0.626, p = 0.017*
SART (Supply)	Control	13.5	2.9		
	Haptic	16.6	2.3	Control Haptic	95% CI [-4.687, -1.424] t (17) = -3.952, d = 0.931, p = 0.001*
	Visual	14.2	2.6	Control Visual	95% CI [-2.533, 1.089] t (17) = -0.841, d = 0.198, p = 0.412
SART (Understanding)	Control	10.2	3.7		
	Haptic	11.7	2.8	Control Haptic	95% CI [-3.785, 0.896] t (17) = -1.302, d = 0.307, p = 0.210
	Visual	11.2	2.1	Control Visual	95% CI [-2.563, 0.563] t (17) = -1.350, d = 0.318, p = 0.195
SART (Total)	Control	12.7	5.9		
	Haptic	21.6	4.5	Control Haptic	95% CI [-12.351, -5.316] t (17) = -5.298, d = 1.249, p = 0.001*
	Visual	17.4	5.2	Control Visual	95% CI [-8.149, -1.294] t (17) = -2.907, d = 0.685, p = 0.010*

Note:
** Indicates significance, p < 0.05 (two-tailed)*
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)

For the understanding-construct of SART, there was no statistically significant difference found between with and without the peripheral information systems conditions. Power analyses were conducted, and the statistical power was found to be 0.417 between the control-and the haptic-condition and 0.229 between the control- and visual-condition. Hence, the total sample sizes needed to achieve a power of 0.800 (β = 20%) to compare means between the control- and the haptic-condition was found to be 41 and between the control- and visual-condition was found to be 84.

For motion sickness (MSAQ) assessment, a different method was used to assess the data. Rather than evaluating the differences in motion sickness levels between pre- and post-experiment (see Section 4.3.1.2), the MSAQ data were independently assessed at both stages across conditions (Stage 1 and Stage 7). This because we want to make sure that the MSAQ levels in the pre-experiment were similar across participants. In addition, the evaluations were also done across sessions. These were done to assess whether the motion sickness habituation effect occurred because of the exposure to the same dosage of motion sickness with the same motion profiles. Thus, Wilcoxon signed-rank tests were performed to determine if there were statistically significant differences for the MSAQ in the pre-experiment across conditions and sessions. However, there was no statistically significant difference found in the MSAQ either across conditions or sessions.

Table 6-3 shows the median and interquartile range (IQR) of the MSAQ in the pre-experiment across conditions and sessions.

Table 6-3: Median and IQR for the MSAQ in the pre-experiment across conditions and sessions

MSAQ Dimensions	**By Conditions**			**By Sessions**		
	Conditions	**Median**	***IQR***	**Sessions**	**Median**	***IQR***
Gastrointestinal (G)	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 (C)	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 (P)	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 (S)	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	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)

Note:
All MSAQ dimensions ranging from 11.1 % (no symptoms) to 100.0 % (most severe symptoms)

For the post-experiment, the Wilcoxon signed-rank tests were performed to determine if there were statistically significant decreases in motion sickness experienced by the participants between the control-condition and the conditions with the peripheral information systems (Table 6-4).

Table 6-4: Results of statistical analyses on the MSAQ in the post-experiment data between conditions

MSAQ Dimensions	Conditions	Median	*IQR*	Group	Wilcoxon Signed-Rank Test
Gastrointestinal (G)	Control	19.5	(11.1 - 19.5)		
	Haptic	13.9	(11.1 - 13.9)	Control Haptic	z = -1.767, r = 0.29, p = 0.08
	Visual	18.1	(13.2 - 66.0)	Control Visual	z = -0.421, r = 0.07, p = 0.67
Central (C)	Control	22.2	(18.9 - 61.1)		
	Haptic	18.9	(15.6 - 34.4)	Control Haptic	z = -1.962, r = 0.33, p = 0.05
	Visual	26.7	(15.6 - 69.4)	Control Visual	z = -0.044, r = 0.01, p = 0.97
Peripheral (P)	Control	11.1	(11.1 - 26.9)		
	Haptic	11.1	(11.1 - 23.4)	Control Haptic	z = -0.984, r = 0.16, p = 0.33
	Visual	14.8	(11.1 - 20.4)	Control Visual	z = -0.851, r = 0.14, p = 0.40
Sopite (S)	Control	30.6	(18.7 - 30.6)		
	Haptic	23.6	(18.7 - 40.3)	Control Haptic	z = -1.734, r = 0.29, p = 0.08
	Visual	33.3	(19.4 - 67.3)	Control Visual	z = -0.233, r = 0.04, p = 0.82
Total	Control	23.3	(17.4 - 54.2)		
	Haptic	18.4	(15.3 - 58.7)	Control Haptic	z = -2.298, r = 0.38, p = 0.02*
	Visual	23.6	(14.9 - 32.1)	Control Visual	z = -0.305, r = 0.05, p = 0.76

Note:
** Indicates significance, p < 0.05 (two-tailed)*
All MSAQ dimensions ranging from 11.1 % (no symptoms) to 100.0 % (most severe symptoms)

There was a statistically significant decrease found in the total score of MSAQ with the haptic display only, but not with the visual display. Actually, based on the median values, the visual display was found to induce more motion sickness compared to without the presence of the peripheral information system. Furthermore, a power analysis was conducted for the MSAQ total score, and the statistical power was found to be 0.057. Hence, the total sample size needed to achieve a power of 0.800 (β = 20%) for this Wilcoxon signed-rank test to compare means between the control- (mean = 33.9, SD = 22.9) and the visual-condition (mean = 35.4, SD = 23.3) was found to be 1952. Furthermore, the Wilcoxon signed-rank tests were also performed to determine if there were statistically significant decreases in motion sickness experienced by the participants between the first session (Session 1) with the other sessions (Session 2 and Session3) (Table 6-5).

Table 6-5: Results of statistical analyses on the MSAQ in the post-experiment data between sessions

MSAQ Dimensions	**Sessions**	**Median**	***IQR***	**Group**	**Wilcoxon Signed-Rank Test**
Gastrointestinal (G)	Session 1	26.4	(13.9 – 62.5)		
	Session 2	13.9	(11.1 – 65.3)	Session 1 Session 2	z = -1.011, r = 0.17, p = 0.31
	Session 3	13.0	(11.1 – 25.9)	Session 1 Session 3	z = -1.399, r = 0.23, p = 0.16
Central (C)	Session 1	31.1	(20.0 – 67.2)		
	Session 2	15.3	(11.1 – 42.4)	Session 1 Session 2	z = -2.134, r = 0.36, p = 0.03*
	Session 3	23.6	(16.7 – 56.3)	Session 1 Session 3	z = -1.483, r = 0.25, p = 0.14
Peripheral (P)	Session 1	16.7	(11.1 – 24.0)		
	Session 2	20.0	(15.0 – 48.9)	Session 1 Session 2	z = -1.183, r = 0.20, p = 0.24
	Session 3	22.2	(18.7 – 46.5)	Session 1 Session 3	z = -0.051, r = 0.01, p = 0.96
Sopite (S)	Session 1	38.9	(21.5 – 66.7)		
	Session 2	21.1	(15.6 – 32.8)	Session 1 Session 2	z = -1.847, r = 0.31, p = 0.07
	Session 3	17.7	(13.7 – 52.4)	Session 1 Session 3	z = -2.205, r = 0.37, p = 0.03*
Total	Session 1	27.4	(18.8 – 57.8)		
	Session 2	11.1	(11.1 – 14.8)	Session 1 Session 2	z = -2.070, r = 0.35, p = 0.04*
	Session 3	18.1	(15.3 – 31.1)	Session 1 Session 3	z = -1.587, r = 0.26, p = 0.11

Note:
** Indicates significance, p < 0.05 (two-tailed)*
All MSAQ dimensions ranging from 11.1 % (no symptoms) to 100.0 % (most severe symptoms)

There were statistically significant decreases found in Session 2 compared to Session 1 in the total score of MSAQ and one of its dimensions (central-related). On the other hand, only for the sopite-related dimension, a statistically significant decrease was found from Session 1 to Session 3. A power analysis was conducted for the total score of MSAQ between Session 1 (mean = 37.6, SD = 21.3) and Session 3 (mean = 28.4, SD = 20.8) and the statistical power was found to be 0.437. Hence, the total sample size needed to achieve a power of 0.800 (β = 20%) for this paired samples t-tests was found to be 46.

In terms of heart rate variability (HRV) data for motion sickness assessments, the Wilcoxon signed-rank tests were performed on the BPM, the RMSSD, and the HF component data to determine if there were statistically significant decreases in motion sickness experienced by the participants between the control-condition and the conditions with the peripheral information systems. However, there was no statistically significant difference found in any comparisons between the two conditions. Table 6-6 shows the median and interquartile range (IQR) of the HRV measurements across conditions.

Table 6-6: Median and IQR for the difference between stages of the HRV measurements across conditions

Variation	**Conditions**	**BPM**		**RMSSD**		**HF**	
		Median	***IQR***	**Median**	***IQR***	**Median**	***IQR***
Reactivity 1	Control	3.50	(-2.5 - 7.0)	10.00	(-0.3 - 59.3)	35.50	(-16.3 – 249)
	Haptic	3.00	(0.8 - 5.0)	7.00	(-1.5 - 67.3)	-3.00	(-183.0 – 29.5)
	Visual	3.50	(1.0 - 7.0)	4.50	(-2.0 - 57.0)	-3.00	(-183.0 – 29.5)
Reactivity 2	Control	2.00	(0.50 - 6.5)	-0.50	(-3.8 - 10.5)	8.00	(-22.8 – 121.5)
	Haptic	2.00	(-0.3 - 5.0)	14.50	(-1.0 - 39.8)	-4.50	(-42.5 – 182.0)
	Visual	3.50	(0.8 - 6.0)	8.00	(-4.0 - 32.3)	-9.00	(-249.0 – 93.3)
Reactivity 3	Control	2.00	(-1.0 - 5.0)	4.50	(-5.3 - 51.0)	-86.50	(-174.3 – 29.0)
	Haptic	1.00	(-2.0 - 4.3)	7.20	(-2.3 - 45.3)	-8.00	(-143.8 – 80.1)
	Visual	2.50	(0.0 - 4.3)	10.00	(-0.5 - 35.0)	-1.50	(-92.5 – 84.3)
Recovery	Control	-1.00	(-5.8 - 0.3)	7.50	(-1.5 - 63.3)	-30.50	(-79.0 – 108.8)
	Haptic	-2.00	(-5.5 - 0.5)	0.00	(-6.3 - 7.5)	14.00	(-56.8 – 83.8)
	Visual	0.00	(-5.0 - 1.3)	0.00	(-3.0 - 7.8)	7.00	(-66.5 – 84.0)

Note:
Reactivity 1 = difference between Stage 3 and 2
Reactivity 2 = difference between Stage 4 and 2
Reactivity 3 = difference between Stage 5 and 2
Recovery = difference between Stage 6 and 2

Furthermore, the Wilcoxon signed-rank tests were also performed on the BPM, the RMSSD, and the HF component data across sessions (Table 6-7 and Table 6-8). The results were mixed, and mostly there were no statistically significant decreases found in motion sickness from the HRV data.

Table 6-7: Median and IQR for the difference between stages of the HRV measurements across sessions

Variation	Sessions	BPM		RMSSD		HF	
		Median	*IQR*	Median	*IQR*	Median	*IQR*
Reactivity 1	Session 1	4.0	(-1.0 – 6.3)	16.5	(0.0. – 39.8)	53.5	(-42.5 - 182.0)
	Session 2	3.0	(2.8 – 5.5)	8.5	(-7.0 – 37.5)	31.5	(-177.0 - 304.5)
	Session 3	3.0	(0.8 – 5.3)	5.0	(-2.0 – 43.3)	-4.5	(-27.8 - 144.5)
Reactivity 2	Session 1	2.5	(-1.0 – 5.5)	20.5	(-0.5 – 47.8)	-32.5	(-126.8 - 63.3)
	Session 2	3.0	(0.8 -5.3)	1.5	(-2.8 – 25.8)	-40.5	(-182.5 - 9.5)
	Session 3	2.0	(0.5 – 3.5)	4.5	(0.0 – 41.8)	3.0	(-155.5 - 44.8)
Reactivity 3	Session 1	2.0	(-1.0 – 5.0)	16.0	(-0.5 – 65.8)	-32.5	(-126.8 - 63.3)
	Session 2	2.0	(-0.3 – 4.3)	1.5	(-6.8 – 13.8)	-47.0	(-116.8 - 1)
	Session 3	2.0	(-1.0 – 3.5)	8.2	(0.8 – 39.3)	18.5	(-81.5 - 93.0)
Recovery	Session 1	-0.5	(-5.0 – 0.3)	0.0	(-6.8 -12.3)	6.0	(-32.0 - 235.5)
	Session 2	-1.5	(-5.0 – 2.0)	-1.0	(-7.3 – 1.8)	0.0	(-88.0 - 35.8)
	Session 3	-1.5	(-5.3 – 0.3)	-0.3	(-0.3 – 10.0)	32.5	(-68.8 - 93.5)

Note:
Reactivity 1 = difference between Stage 3 and 2
Reactivity 2 = difference between Stage 4 and 2
Reactivity 3 = difference between Stage 5 and 2
Recovery = difference between Stage 6 and 2

Table 6-8: Results of statistical analyses on motion sickness (BPM, RMSSD, and HF component) data between sessions

Variation	Group	Wilcoxon Signed-Rank Test		
		BPM	RMSSD	HF component
Reactivity 1	Session 1 Session 2	z = -1.847 r = 0.30, p = 0.07	z = -0.698, r = 0.12, p = 0.49	z = -0.568, r = 0.10, p = 0.57
	Session 1 Session 3	z = -0.310, r = 0.05, p = 0.76	z = -0.631, r = 0.11, p = 0.53	z = -0.544, r = 0.09, p = 0.60
Reactivity 2	Session 1 Session 2	z = -0.052, r = 0.00, p = 0.96	z = -1.895, r = 0.32, p = 0.06	z = -1.965, r = 0.33, p = 0.05*
	Session 1 Session 3	z = -0.701, r = 0.12, p = 0.48	z = -0.785, r = 0.13, p = 0.43	z = -0.631, r = 0.11, p = 0.53
Reactivity 3	Session 1 Session 2	z = -0.114, r = 0.02, p = 0.91	z = -2.386, r = 0.40, p = 0.02*	z = -1.372, r = 0.23, p = 0.17
	Session 1 Session 3	z = -0.130, r = 0.02, p = 0.90	z = -1.373, r = 0.23, p = 0.17	z = -0.544, r = 0.01, p = 0.59
Recovery	Session 1 Session 2	z = -0.063, r = 0.01, p = 0.95	z = -1.394, r = 0.23, p = 0.16	z = -1.720, r = 0.29, p = 0.09
	Session 1 Session 3	z = -0.342, r = 0.06, p = 0.73	z = -0.261, r = 0.04, p = 0.80	z = -1.067, r = 0.18, p = 0.29

Note:
** Indicates significance, p < 0.05 (two-tailed)*

Further observations of the BPM, MRSSD and HF component data were done based on three plotted graphs of the means with 95 % confidence intervals (CI) bars (Figure 6-15). For the BPM data, the patterns of means were about the same for all three conditions. The BPM value increased from Stage 2, peaked and maintained at Stage 3 through Stage 5 before it was decreased at Stage 6. For the RMSSD data, the mean patterns were also similar for all three conditions. The RMSSD value only increased once the autonomous driving started at Stage 3 and approximately maintained before it decreased back to around the baseline's value when the autonomous driving stopped at the end of Stage 5. For the HF component data, different patterns were found for each condition. In the control-condition, the mean HF component value was increased at Stage 3 and dropped at Stage 4 before increased and maintained at Stage 5 and 6, higher than the baseline's value. In the visual-condition, the mean HF component value was decreased in Stage 3 and increased and maintained at Stage 5 and 6. In the haptic-condition, the mean HF component value was found to be almost unchanged through all stages.

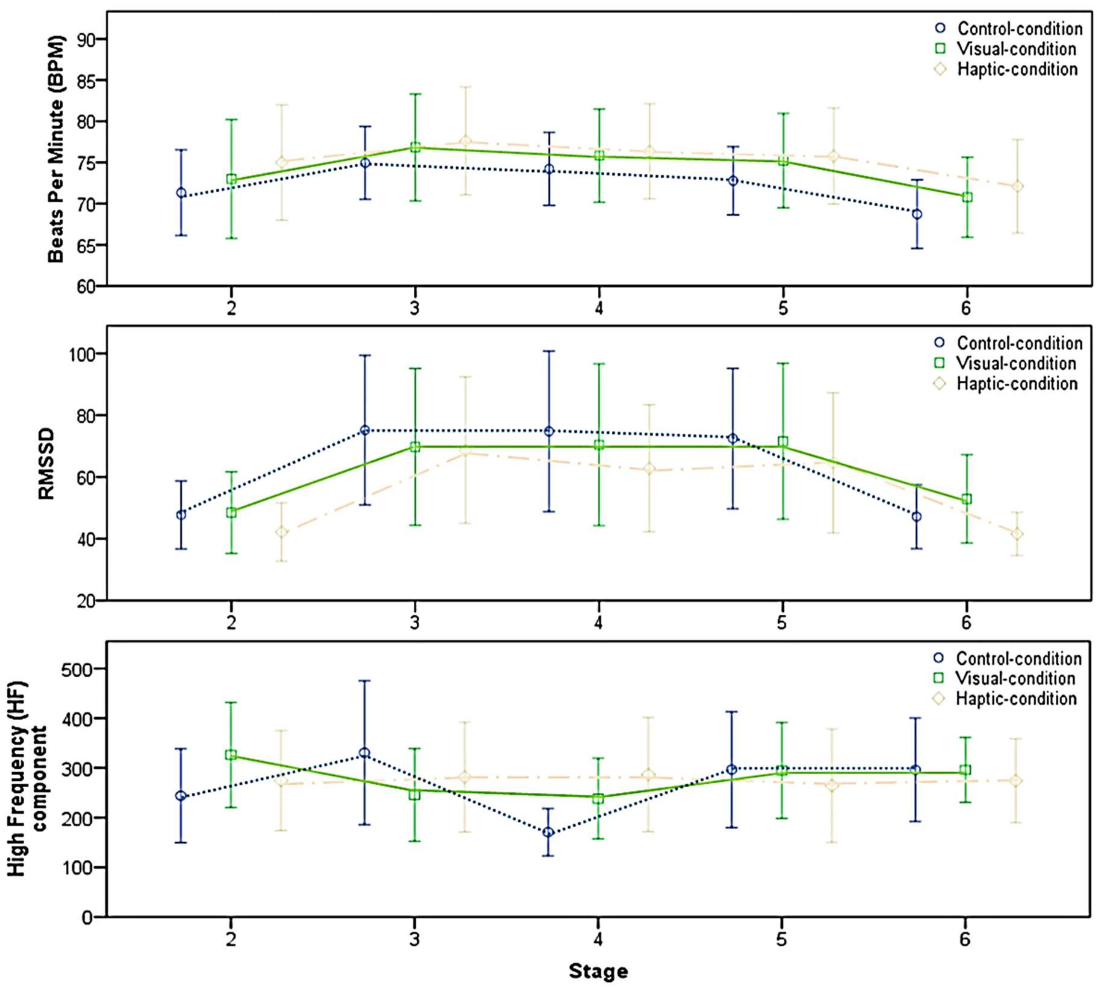


Figure 6-15: Graph of mean values of the BPM, the RMSSD, and the HF component for the three conditions (control, visual, and haptic). Error bars represent the 95 % confidence intervals (CI)

For participants' head movements' assessments, the Wilcoxon signed-rank tests were performed on the MSDV analysis that was based on the recorded acceleration of head measurements. There was no statistically significant difference found between the head movements in the three conditions or in the three sessions. On the other hand, the mean squared MSDVs of the head movements were generally found to be higher than the mean squared MSDVs of the Mobility Lab (refer to Figure 6-14). Additionally, the MSDVs of the head movements were relatively similar across the conditions and the sessions for all three acceleration directions (longitudinal, lateral, and vertical) (Table 6-9).

Table 6-9: Median MSDV of the passengers' head movements in tri-axial directions across conditions and sessions

Parameter	By Conditions			By Sessions		
	Conditions	**Median**	***IQR***	**Sessions**	**Median**	***IQR***
$MSDV_x$ (Longitudinal)	Control	9.4	(7.0 - 12.1)	Session 1	10.2	(8.6 - 12.3)
	Haptic	9.3	(7.8 - 11.8)	Session 2	8.9	(6.5 - 14.0)
	Visual	10.2	(8.1 - 12.8)	Session 3	10.0	(7.4 - 12.1)
$MSDV_y$ (Lateral)	Control	10.3	(8.9 - 12.6)	Session 1	10.3	(9.3 - 13.8)
	Haptic	9.9	(9.2 - 13.9)	Session 2	10.2	(9.2 - 13.3)
	Visual	10.6	(9.6 - 13.2)	Session 3	10.5	(8.5 - 12.0)
$MSDV_z$ (Vertical)	Control	2.8	(2.1 - 3.9)	Session 1	3.3	(2.2 - 4.5)
	Haptic	3.1	(2.8 - 3.4)	Session 2	2.8	(2.1 - 3.5)
	Visual	2.9	(2.8 - 3.2)	Session 3	2.0	(2.7 - 3.4)

6.3.3. Viewing Behaviour and Reading Performance

There was no outlier found in both viewing behaviour and reading performance data. In terms of the viewing behaviour, all data were not normally distributed, while in terms of the reading performance, all data were normally distributed. Hence, Wilcoxon signed-rank tests and paired samples t-tests were performed to determine if there were statistically significant differences in the viewing behaviour and the reading performance of the participants between the control-condition and the conditions with the peripheral information systems (Table 6-10 and Table 6-11).

There were no statistically significant differences found in the viewing behaviour between any paired conditions (either control-visual paired conditions or control-haptic paired conditions). Power analyses were conducted and the statistical power was found to be 0.206 for the control-haptic paired conditions and 0.065 for the control-visual paired conditions (control: mean = 71.8, SD = 25.4; haptic: mean = 79.0, SD = 24.0; visual: mean = 74.1, SD = 24.3). Hence, the total sample size needed to achieve a power of 0.800 (β = 20%) for these

Wilcoxon sign-rank tests were found to be 98 for the control-haptic paired conditions and 914 for the control-visual paired conditions.

Table 6-10: Results of statistical analyses on viewing behaviour

Parameter	Conditions	Median	*IQR*	Group	Wilcoxon Signed-Rank Test
Viewing behaviour (%)	Control	79.1	(47.6 - 98.8)		
	Haptic	86.4	(67.8 - 95.2)	Control Haptic	z = -0.719, r = 0.12, p = 0.47
	Visual	81.7	(54.4 - 98.8)	Control Visual	z = -1.590, r = 0.27, p = 0.11

Note:
Viewing behaviour is ranging from 0.0 % (not looking at the tablet) to 100.0 % (looking at the tablet)

In terms of determining statistically significant differences in the reading performance, there were also no statistically significant differences found between any paired conditions. Power analyses were conducted and the statistical power was found to be 0.258 for the control-haptic paired conditions and 0.058 for the control-visual paired conditions (control: mean = 5.9, SD = 2.7; haptic: mean = 6.9, SD = 3.2; visual: mean = 6.1, SD = 3.1). Hence, the total sample size needed to achieve a power of 0.800 (β = 20%) for these paired samples t-tests were found to be 76 for the control-haptic paired conditions and 1755 for the control-visual paired conditions. Furthermore, a higher mean of reading performance (with text) was found when an additional test was conducted in a room compared to the reading performance tested in the main experiment.

Table 6-11: Results of statistical analyses on reading performance

Parameters	Conditions	Mean	*SD*	Group	Paired Samples *T*-Test
Reading performance	Control	5.9	2.7		
	Haptic	6.9	3.2	Control Haptic	95% CI [-2.335, 0.446] t (17) = -1.433, d = 0.338, p = 0.170
	Visual	6.1	3.1	Control Visual	95% CI [-1.496, 1.273] t (17) = -0.169, d = 0.040, p = 0.868
	With Text [a]	8.7	1.6		n/a
	Without Text [a]	5.5	1.4		

Note:
Reading performance is a 10-point scale, 1 = cannot read, 10 = fully understand the text
[a] Tested in a room with another 14 participants

6.3.4. Assessments of the Prototypes

The peripheral information systems were assessed subjectively by participants in the visual- and haptic-conditions using the User Experience Questionnaire (UEQ). The means, standard deviations (SD), and consistency Cronbach's α for both conditions were calculated and presented in Table 6-12.

Table 6-12: Means and standard deviations (SD) on the UEQ results of both haptic and visual display including the benchmark scores based on Schrepp et al. (2017)

UEQ Constructs	*n*	Haptic Display			Visual display			Benchmark Average Scores
		Mean	*SD*	Cronbach's α	Mean	*SD*	Cronbach's α	
Attractiveness	18	1.42	1.10	0.94	0.96	0.87	0.85	1.17
Perspicuity	18	1.81	0.86	0.53	1.32	0.94	0.64	1.08
Efficiency	18	1.33	1.10	0.86	1.08	0.92	0.82	0.98
Dependability	18	1.38	1.04	0.73	1.06	0.83	0.57	1.14
Stimulation	18	1.60	0.92	0.62	0.94	0.80	0.72	0.99
Novelty	18	1.61	0.77	0.78	1.21	1.10	0.88	0.71

Note:
The rating is a 7-point scale, -3 (horribly bad), +3 (extremely good).

The reliability of the scale was acceptable with Cronbach's α being larger than 0.7 for all mean values for all constructs, except for the perspicuity-construct for each of the prototypes, the dependability-construct for the visual display, and the stimulation-construct for the haptic display. All mean values from each construct of the UEQ were above 0.8, indicating that the overall rating for each construct was positive. Compared to the benchmark of the UEQ data in Schrepp, Hinderks, and Thomaschewski (2017) (from 246 product evaluations with a total of 9,905 responses) some constructs were evaluated as below average for visual display while all categories were evaluated as above average for haptic display (Figure 6-16).

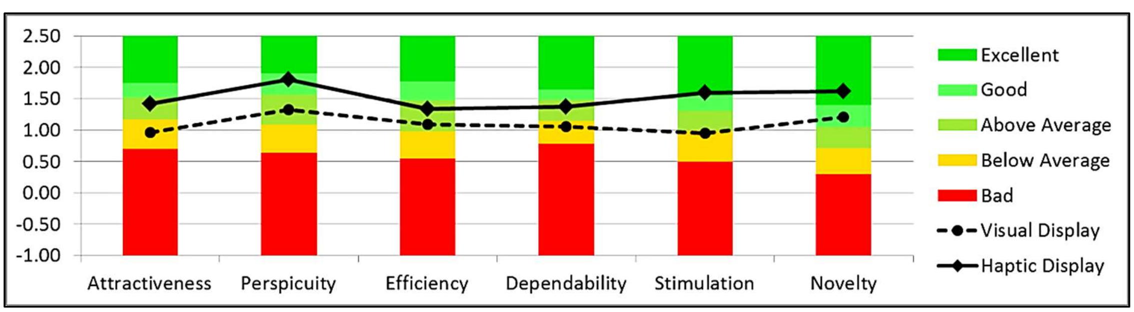


Figure 6-16: Visualization of the benchmark. The lines represent the results for the visual and haptic displays. The coloured bars represent the ranges for the scales' mean values.

6.4. Discussion

6.4.1. Consistency of the Experiment

In general, all experiment sessions showed almost identical distributions over the acceleration frequency spectrum in the Power Spectral Density (PSD) semi-log graphs where the distributions of the three conditions (the control-, the visual-, and the haptic-condition) were overlapped on each other. These results validated that the driving wizard managed to consistently simulate the defensive driving style with similar paces for each session.

Similar to the previous experiment in Chapter 5, the dominant frequencies were found to be below 0.2 Hz in the x-direction (longitudinal acceleration) and the y-direction (lateral acceleration), and these low-frequency motions were highly correlated with motion sickness (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999a). The big differences in acceleration magnitude between the x-direction (below 2 $ms^{-4}Hz^{-1}$) and the y-direction (peaked at over 16 $ms^{-4}Hz^{-1}$) were expected in this experiment. As was previously mentioned in the experiment setup (also in the previous experiment setup in Chapter 5), the longitudinal acceleration was controlled to be kept at a minimum, and the lateral acceleration was manipulated in the range of defensive driving style. The dominant frequency above 1 Hz in the z-direction (vertical acceleration) was found to be physically uncomfortable but not a factor in contributing to motion sickness (Cheung & Nakashima, 2006).

In all three conditions, the motion sickness dose values (MSDVs) were similar. These results indicated that the sessions were not just consistently executed, but the driving wizard managed to induce a similar motion sickness dose to the participants. Although, based on PSD, results showed that both low-frequency motions at longitudinal (peaked about 0.08 Hz) and lateral (peaked about 0.02 Hz) accelerations were highly correlated with motion sickness (below 0.5 Hz), the MSDV results revealed that the dosage of motion sickness exposed to the participants at the end of each session was three times higher in the lateral direction (considered as mildly to severely dosage) than in the longitudinal direction (considered as slightly or no motion sickness dosage) (Griffin & Newman, 2004b). Thus, this experiment managed to minimize the longitudinal acceleration and consistently succeeded in manipulating the lateral acceleration.

Participants were also consistent in rating the autonomous driving using the 10 points rating scale. Although the Autonomous Driving Test Ride Quality (ADTQ) results showed a statistically significant difference between the three conditions, the differences between the means of the scores in each condition were small. This is also one of the reasons why there were no statistically significant differences between any of the two paired conditions in the post-hoc analysis with the Bonferroni correction. This finding revealed that the test rides were subjectively felt similar in every condition. However, these findings should be interpreted with caution due to the fact that none of the participants has actual experience riding in a real autonomous vehicle prior to the experiment. Furthermore, the average scores of 6.8 (out of 10) and above indicated that the participants in this experiment were also positively inclined to the defensive driving style as the fully automated driving style. This result was similar to previous studies (Basu et al., 2017; Md. Yusof et al., 2016).

6.4.2. Effect of the Peripheral Information Displays

The detailed discussion regarding the visual-condition (with the implementation of the visual display) is included in another dissertation that focused on providing the peripheral information by visual modality in an autonomous vehicle when the users are engaging with non-driving related tasks (Karjanto, 2018). However, the order of the three sessions is discussed here to see if the results of the conditions were affected by the sessions.

In general, participants' level of situation awareness is higher with peripheral information compared to without any given information based on the Situational Awareness Rating Technique (SART) scores. However, there were no statistically significant differences between conditions in the understanding-construct. This reveals that the level of situation awareness increased was not due to better understanding prompted by the haptic display. Similar results were found in Chapter 5 with a different non-driving related task (watching a video on a TV display). As mentioned before in that chapter, one of the reasons could be that participants had to concentrate more on the situation in the control-condition compared to the haptic-condition. This interpretation is supported by the demand-construct results that showed statistically significant decreases from the control-condition to the haptic-condition. This suggests that less attention is needed with the peripheral information display when there are sudden changes in car motions.

Our finding on the demand-construct is also in line with the supply-construct results. This construct represents the quality and quantity of the information. The haptic display was found to have a significantly higher quality and quantity of the information compared to without any display. This suggests that the early transmitted information (about turning to the left or to the right) on the wrist, followed by the flap motions (that adjusting the participants' body to the direction of the turning) was sufficient to provide a clear picture of that particular situation.

Finally, this interpretation is also supported by the Rating Scale Mental Effort (RSME) finding, although there was no statistically significant difference between the haptic-condition and the control-condition. This result is similar to Chapter 5, in which the average score for the mental effort was lower in the haptic-condition compared to the control-condition. In addition, the SART result was also consistent with the finding in the previous chapter. Based on these, we might assume that the haptic display could be a suitable modality in providing the peripheral information regardless of the non-driving related tasks.

For motion sickness assessments, the MSAQ results (see Table 6-4) showed that there was a statistically significant decrease in the MSAQ total score. For the haptic-condition, compared to the control-condition, the reduction of the motion sickness levels might be due to the fact that the current haptic display was built with the idea of active movement on which the flapper automatically pushes participants' shoulder into the direction of the corner rather than being passively moved towards the opposite direction of the corner by the centrifugal acceleration. This finding was consistent with the findings by Golding, Bles, Bos, Haynes, and Gresty (2003) and Wada et al. (2012). They found that an active head tilt or under external control (e.g., active suspension) is able to lessen motion sickness symptoms. This interpretation is also supported by the finding of the study in the previous chapter (see Section 5.4.2). In that study, the vibrotactile display alone did not help in reducing motion sickness when engaging in a non-driving related task (watching a video) while being driven around. Furthermore, reading task (in the current study) was considered one of the worse activities to do in a moving vehicle that can escalate the development of motion sickness (Isu et al., 2014; Kato & Kitazaki, 2006, 2008; Schoettle & Sivak, 2009).

However, based on the recorded video for viewing behaviour analysis, the participants' head was seen to move towards the opposite direction of the corner passively. This means that although the implementation of the haptic display restrains the passengers' body from moving, their head (and vestibular system) still can freely move. The sum of gravitational and inertial forces, called gravito-inertial force (GIF), acting on the head that was misaligned to the gravity vector can provoke motion sickness (Bles et al., 1998). It was suspected that although the participants' body was actively tilted to the direction of the corner, the tablet for the reading task was considered fixed in one position (see Figure 6-2) and they might try to maintain their head position to continue the reading.

Concerning the order of the sessions, the MSAQ results showed a presence of motion sickness habituation effect in the total score and two of its dimensions, the central- and the sopite-related dimensions, with a significant result (see Table 6-5). Habituation to motion sickness is the reduction in the severity of motion sickness symptoms when a person is exposed to a repeated or continuous exposure to motion (Golding & Gresty, 2015; Murdin, Golding, & Bronstein, 2011; Schmal, 2013). A trend was found in which the MSAQ score for Session 1 was always the highest while Session 2 and Session 3 were about the same or not much of a difference. In other words, the percentage (the means) of motion sickness in the MSAQ total score and all its dimensions (with the exception of the peripheral-related dimension) were reduced from Session 1 to Session 2 (between 8.1 % and 11.1 %). As described by Schmäl (2013), a reduction in the motion sickness level is due to a repetition of the motion sickness stimulation exposure. However, there were no further reductions of the motion sickness level from Session 2 to Session 3 (less than 0.6 % reduction, with the exception of the sopite-related dimension with a reduction of 1.7 %), indicating that an optimum result could be achieved only starting at Session 2 onwards. Although the precaution measures (the counterbalanced order of each session and the gapped sessions) were taken to avoid any order or carry-over effects, the participants were exposed to the same motion profiles due to the identical route in each session. In addition, the car windows were open or transparent. Thus, there was a possibility that the participants already recognized the route in Session 2 and 3 compared to Session 1 in which they experienced the motion for the first time.

For the heart rate variability (HRV) analysis, in terms of the heart rate measurements in beats per minutes (BPM), a similar pattern was found when comparing this experiment results with the previous experiment (see Figure 5-10 and Figure 6-15). Although there was no statistically significant difference between the control- and the haptic-condition, the increased heart rate was less from Stage 2 to Stage 3 for the haptic-condition compared to the control-condition, indicating less motion sickness to the participants. Stage 3 was the first autonomous driving stage, in which the motion sickness stimulation from the motions of the Mobility Lab was started. In both conditions, the BPM value remained the same for the rest of the autonomous driving stages before decreasing back to the almost initial value at Stage 6. This finding was similar to other studies that found a decrement in heart rate just after termination of the motion sickness stimulus (Cowings et al., 1986; Kim et al., 2005; LaCount et al., 2011). Furthermore, the average BPM value at Stage 3 for the control-condition (74.9 BPM) and the haptic-condition (77.6 BPM) were interpreted as mildly-experienced motion sickness by the participants. As mentioned by Cowings, Naifeh, and Toscano (1990), a value of 77 BPM is indicating a mildly-experienced motion sickness while a value of 87 BPM represents a severely-experienced motion sickness. This result is also in line with the finding of the consistency of the experiment that showed that a mild to severe dosage was induced to the participants.

In terms of the root-mean-square of successive differences (RMSSD) and the high-frequency (HF) component, no significant changes were found in the activity of the parasympathetic nervous system between both conditions. Although a reduction in the parasympathetic nervous system activities was found as a development of motion sickness (Chin-Teng Lin, Chun-Ling Lin, Tzai-Wen Chiu, Jeng-Ren Duann, & Tzyy-Ping Jung, 2011; Cowings et al., 1986; Hu, Grant, Stern, & Koch, 1991; LaCount et al., 2009), our results (see Figure 6-15) showed that the RMSSD values were actually increased and maintained during the autonomous driving stages (Stage 3,4 and 5). In general, the sympathetic nervous system is activated (increased activity) for the fight-or-flight response during stressful or threatening conditions (in our case is the motion sickness development), while the parasympathetic nervous system is activated (increased activity) for the rest-and-digest response which prevents stressful conditions (McCorry, 2007). Hence, the participants might have relaxed in the experiment with the possibility of a sleepy condition, which finding can be supported by the sopite-related dimension (sleepiness, drowsiness) of the MSAQ.

One of the explanations could be that our experimental study setup was different compared to studies that found withdrawal of the parasympathetic nervous system activities during motion sickness stimulus activation. In most of the past motion sickness inducing experiments, the participants were instructed to keep their head still and look straight forward inside a rotating drum (or optokinetic drum), as the stimulus to induce motion sickness (e.g., Sjors & Dahlman, 2014). They found a decrement in RMSSD during the exposure. On the other hand, in this experiment, the participants were reading while sitting comfortably on a seat during the exposure that is resulting in an increment of the RMSSD. Foster (2017) investigated motion sickness symptoms related to sopite syndrome. The participants were instructed to sit upright in a comfortable chair with pillow, vacuum cushion and foam blocks, while the chair was fixed on a movable platform that is moving back and forth in low-frequency sinusoidal linear accelerations. Although not significant, she also found that the RMSSD was higher than the baseline condition. On the other hand, she found a significant increase of sopite symptom from one of the MSAQ dimensions.

In terms of frequency-domain analysis, only the high-frequency (HF) component was used to evaluate the motion sickness in this study. Usually, many researchers included their HRV analyses and discussed the sympathetic nervous system that is known to be highly correlated with the low-frequency (LF) component (Heathers, 2014). In addition, they also discussed the LF/HF ratio that is known as the autonomic balance between sympathetic and parasympathetic nervous systems activity. However, there is a loose relationship between the sympathetic nervous system and the LF component, and it was found that there is no linear relationship between the activity of the sympathetic and parasympathetic nervous system (Billman, 2013; Laborde et al., 2017). This because the LF component reflects a mix between sympathetic and parasympathetic nervous systems activity (Malik, 1996) and both nervous systems can be activated in opposite directions from each other (increased or decreased in activity), or both can increase or decrease in activity at the same time (Berntson, Cacioppo, & Quigley, 1991; Muth, 2006).

Based on the HF component results, no statistically significant interactions were found between conditions or stages. The HF component values can be seen to fluctuate in the control-condition but remain unchanged in the haptic-condition (see Figure 6-15). This finding is in line with the MSAQ results that showed less motion sickness in the haptic-condition (see Table 6-4). The fluctuation of the HF component in the control-condition might occur due to the respiration of the participants. As highlighted by Laborde et al. (2017), the parasympathetic nervous system can be affected by the respiration, and it was found better to record the HRV data in the resting condition. That is why the RMSSD is preferred as an indicator for the parasympathetic nervous systems activity as the time-domain analysis is not influenced by the respiratory activity (Hill & Siebenbrock, 2009). In our study, recording the HRV data in a moving environment may influence the participants' way of breathing. In the control-condition, the participants were affected by the uncontrolled motions. On the other hand, the fact that the HF component in the haptic-condition is almost constant could be due to the fact that the participants' body is stable with the help of the active movement mechanism that was fixed on the seat.

Concerning the order of the sessions, there were statistically significant differences in the BPM, the RMSSD, and the HF component data, indicating that habituation occurred. However, these significant differences only happened in a certain variation of stages (Table 6-8). These mixed results were similar to the MSAQ results across sessions. In general, Session 3 indicated the lowest experienced motion sickness compared to the other two sessions.

For the participants' head movements' assessments, the MSDV results showed that the head movements were generally higher than the Mobility Lab motions in all acceleration directions as seen in Figure 6-14. However, it should be noted here that in Figure 6-14, the accumulated MSDVs is lower than in the MSDV results in Table 6-9 because of the time scale is only up to 900 seconds, whereas the exact exposure periods (during the autonomous driving stages) were between 902.2 s and 1068.9 s. The differences in time exposures were due to the traffic conditions during the experiment sessions.

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 head down once the reading task began. Hence, the x-axis (longitudinal or fore-and-aft direction, see Figure 2-8) of the accelerometer already registered certain values of acceleration rather than zero value and the z-axis (vertical direction) was not equal to the gravity vector any more. 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 semicircular canals of the vestibular system (Figure 6-11). Thus, the recorded accelerations were exactly in the tri-axial directions of the semicircular 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 by Riccio and Stoffregen (1991), these uncontrolled movements can induce motion sickness. This might be due to the fact that all selected participants were highly-susceptible to motion sickness who might have difficulties to control their body in an unexpected motion environment.

Concerning the order of the sessions, there were no statistically significant differences between sessions in the head movements, indicating that the participants still cannot control their head although they were already suspected to recognise the route in Session 2 and Session 3.

6.4.3. Viewing Behaviour and Reading Performance

The viewing behaviour assessment was done to investigate how long the participants were able to look at the reading display during the autonomous driving stages (Stage 3, 4 and 5). There were no statistically significant differences between with and without application of the peripheral information system. But, when thoroughly inspecting the results (refer to Table 6-10), it can be seen that the participants were focusing more on the tablet with the haptic display compared to the control-condition. We may assume that the participants were able to process the information given by the peripheral information system. This interpretation is also supported by the results for the demand-construct of the SART (see Table 6-2) that indicated that the participants had lowered demand to look outside to regain their visual perspective of motion. As mentioned by many studies (e.g., Diels, 2014; Turner & Griffin, 1999c), occupants inside a vehicle who are reading something will try to look outside to avoid in getting carsickness.

Regarding the reading performance, the results were used to assess the reading comprehension of the participants. Based on the statistical analysis results (Table 6-11), the participants had almost similar average scores across the conditions from (5.9 to 6.9) and the sessions (6.1 to 6.6). The scores were based on the ten completed answers from each participant in each condition. We assumed that all participants managed to understand and remember around 60 to 70 % of the texts, either with or without application of the peripheral information systems. Again, when thoroughly inspecting the results (refer to Table 6-11), this finding is similar to the viewing behaviour results which indicated that the understanding of the texts is higher if the participants are focusing more on the reading material.

In a separate test that was done in a room to check the comprehension of the reading task, another 14 different participants were recruited only to answer two sets of similar questions (refer to Appendix 15 and Appendix 16) from the same reading materials. These participants were able to score an average of 8.7 (SD = 1.6) with the reading material which is higher than the participants' scores in the main study. Surprisingly, without the reading material, they were able to score an average of 5.5 (SD = 1.4) in which the probability of answering without text was expected at 25 % only (one correct answer out of four options). We assumed that the higher mental workload when reading inside a vehicle compared to reading in a room might affect the reading comprehension. In addition, we assumed that the participants might not know or remember the content of the texts but had a higher chance to pick a correct answer. This could be that the correct answer for some questions is expected to be selected compared to the other options. For example, in a question that asked: "What do you call an alligator in a vest?" (see Appendix 15), the participants might answer "Investigator" compared to other available answers ("Navigator," "Interrogator," and "Litigator"), even without reading the text.

6.4.4. Assessments of the Prototypes

Based on the User Experience Questionnaire (UEQ) results, the mean scores above 0.8 indicated that all participants had an explicitly positive impression regarding the user experience of the haptic display. This might reflect that the conveyed information from the haptic display made it easier to build situational awareness. This interpretation is supported by the SART findings for which the mean total score was higher in haptic-condition (21.6) than in the control-condition (12.7), and is also supported by the RSME findings for which the mean RMSE score was lower in the haptic-display (62.1) than in the control-display (77.9) (see Table 6-2).

Furthermore, the benchmark evaluation was done to assess the haptic display with other products that used the UEQ as their assessment for user experience. It was also the first indicator to evaluate whether the haptic display will be successful in the market (Schrepp et al., 2017). According to the results shown in Table 6-12 and Figure 6-16, haptic-display has a good chance to be successful in the market. However, some elements such as aesthetics value can be improved. Nevertheless, the main objective of this study was to convey the information in an unobtrusive manner to let the autonomous users engage with the non-driving related tasks without disturbance.

6.5. Conclusion

Although the sample size of 18 participants that participated in this experiment was less than in the previous experiment (20 participants in Chapter 5), this sample size is adequate to conduct the analyses to indicate a large effect (Pearson's correlation coefficient, r, is equal to or larger than 0.5) with a statistical power of 0.8 and above. Although several statistical analyses gave lower statistical power, adding an extra of 70 participants (i.e. 98 (extra sample size needed) - 18 (current sample size)) for viewing behaviour analysis does not seem practical in conducting this experiment. One of the reasons is each participant that took part in this experiment was selected with stratified sampling that was based on their susceptible to motion sickness and also based on the participant's variables for the HRV analysis.

In this experiment, a combination of a vibrotactile display from the previous experiment (Chapter 5) with an active movement mechanism was tested to evaluate the level of situation awareness, mental workload, motion sickness, viewing behaviour, and reading performance when engaging in the non-driving related task in an autonomous vehicle. The experiment was consistently executed by the assessment of the Motion Sickness Dose Values (MSDVs) of the Mobility Lab that was based on the longitudinal, lateral and vertical accelerations. Higher dose value of motion sickness was achieved compared to the previous experiment.

In general, we concluded that the haptic display was able to enhance situation awareness and also mitigate motion sickness symptoms. Situation awareness was found increased due to less effort, or cognitive load was needed when processing the peripheral information. These findings were similar to the findings in the previous experiment. Based on this fact, we could say that the vibrotactile display that was designed to be worn on the forearm could be one of the universal solutions to convey peripheral information regardless of any non-driving related task.

The level of motion sickness was reduced in the haptic-condition compared to the control-condition. This significant result indicated that the combination of peripheral display and active movement mechanism was effective in reducing motion sickness. In terms of the heart rate variability (HRV) assessment, the results were mixed, but most findings showed that motion sickness was experienced higher during the autonomous driving stages. In addition, the habituation effects of motion sickness were detected across the experiment sessions. This is probably due to the fact that the same route was used in all sessions so that the route could be recognised or remembered by the participants.

Chapter 7. Conclusions, Limitations, and Future Works

In this chapter, we summarise the contributions of the present research, answer the research questions that were formulated in Chapter 1, discuss the limitations of our study that might influence the interpretation of our findings, and discuss opportunities for future work.

7.1. Contributions

The practical relevance of this dissertation is to develop a better understanding of how to maximize comfort while being driven in the autonomous vehicle. In a more specific focus, we contribute to a better understanding of how to mitigate motion sickness when engaging in non-driving related tasks while riding in an autonomous vehicle. Based on the reviewed previous researches related to motion sickness, this dissertation has explored the applications of peripheral displays in the form of the haptic cue to enhance situation awareness of the autonomous vehicle users. In order to investigate the effects of peripheral displays on situation awareness and motion sickness, a reliable test platform was needed. Since the fidelity of a driving simulator might have had an effect on the driving experience, we also contribute to a new way to conduct a test on the real road.

The findings of this study were used to answer the main research questions:

a) *Do information displays help to enhance situation awareness while engaging in non-driving related tasks?*

   i. How to convey the information to the users?
   ii. Does the information display affect the non-driving related task performance?

   The main idea was to provide the information on the immediate manoeuvre intention of the autonomous vehicle's in a very subtle way, to avoid interruption of the engagement with non-driving related tasks. Although many researchers studied the application of the visual and auditory modalities as peripheral displays (Pielot & Oliveira, 2013), these two modalities were tested mostly related to driving tasks for drivers and not for passengers. Various non-driving related tasks require a different line of passengers' sight such as watching a video on a TV display or reading on a tablet. Socializing with other passengers or listening to the music also might be interrupted with extra auditory messages or sounds. On the other hand, *a haptic modality can provide information related to driving to the passengers in silent and private ways*. Hence, we chose to exploit the haptic modality as our peripheral display.

In Chapter 5, we designed a vibrotactile display that was based on the taxonomy of ambient information systems (Pousman & Stasko, 2006). The forearm has been chosen on the basis of giving more freedom to the passengers to do non-driving related tasks, especially the tasks that require hand movements. The vibrotactile display was designed to provide information about the vehicle's manoeuvre (either turning to the left or to the right) a few seconds before a turn or a corner. The concept was to build up situation awareness by knowing what is happening in that particular situation (Endsley, 2000) so that the mismatch between information supplied by the visual and the vestibular systems can be avoided, and the motion sickness symptom can be alleviated (Reason & Brand, 1975).

In answering the research question, based on the two conducted experiments in Chapter 5 and Chapter 6, *the results showed that the level of situation awareness was higher with peripheral information compared to without any given information*. However, when we further assessed the results that were based on the situational awareness rating techniques (SART; Taylor, 1990), we found that the higher level of situation awareness was not due to a better understanding of the information from the vibrotactile display but due to less effort being needed to process the information. That is because another construct in SART that represents how much attentional demand is required to process the quality and quantity of the information was relatively low with the vibrotactile display. The results of the mental effort using the Rating Scale Mental Effort (RSME; Zijlstra, 1993) support this finding in which the average scores for the mental effort were lower with the vibrotactile display.

In terms of the non-driving related task performance, in Chapter 5, *the vibrotactile display achieved to convey the information in enhancing situation awareness in a very short time when the participants were occupied with the non-driving related task*, watching a video. This performance indicated that the peripheral information was perceived almost immediately (~1 second) after the vibrotactile was activated (see Section 5.3.2). In Chapter 6, *the vibrotactile display achieved to reduce the needs of looking outside of the vehicle (~7 % of the travelling period) when the participants were reading on a tablet* (see Section 6.3.3). However, the reading comprehension results were questionable. This is due to the fact that although there was an increment of the scores in the haptic-condition, other people (not the participants) can still get an above average score when answering the questionnaires (see Appendix 15, Appendix 16, and Appendix 17) even without prior reading the related texts.

b) *Does increasing the situation awareness help to mitigate motion sickness in an autonomous vehicle?*

Based on the two conducted experiments of studying the effect of the peripheral information display, the motions of the Mobility Lab were able to induce enough dose of motion sickness (mild and severe) to the participants. However, in answering the research question, generally, *the vibrotactile display by itself (in Chapter 5) did not help to mitigate motion sickness, although it was proved to increase situation awareness of the participants while watching a video. On the other hand, the vibrotactile display in combination with an active movement mechanism (in Chapter 6) was able to mitigate motion sickness while reading on a tablet)*.

In Chapter 5, only the gastrointestinal-related dimension from the Motion Sickness Assessment Questionnaire (MSAQ) was found statistically lower with the presence of the vibrotactile display. It could be due to too short exposure to severely nauseous motion (e.g., sudden cornering) will develop "*gastric*" symptoms (e.g., feeling sick to the stomach or feeling to vomit) rather than any "*head*" symptoms (e.g., feeling dizzy) (Walton et al., 2011). However, this result came with a low difference in the median between the two test conditions. On the other hand, we summarized that the non-reduction of motion sickness level occurred because of the long exposure to uncontrolled head movements as a result of the Mobility Lab manoeuvres (Riccio & Stoffregen, 1991), and also because of the misalignment between the head and the gravito-inertial force GIF vectors (Golding et al., 2003; Wada et al., 2012).

In Chapter 6, we extended the vibrotactile display design by adding a mechanism that pushes or holds the passenger's body into the direction of the corner. The idea was to reduce the uncontrolled movements of the participants. There were statistically significant decreases found in between with and without the implementation of the design that was based on either the subjective measurement (MSAQ), but not in the continuous measurements (heart rate variability (HRV) data). We suspected that the selected participants, who are highly-susceptible to motion sickness, had difficulties in controlling their head movements although their body was already being controlled by the mechanism. This can be seen by the MSDV of the head movements that were much higher compared to the MSDV of the vehicle (see Figure 6-14). In addition, the reading task was known to exacerbate the motion sickness level in comparison with other non-driving related tasks.

Another research question, the methodological research question, was raised to address the study approach presented in this dissertation:

c) How to conduct our study in a real-world environment?
   iii. What is the predicted and preferred driving style of an autonomous vehicle?
   iv. How to maintain consistency of the conducted experiment in this study?

In Chapter 3, in order to conduct our study, *we designed and developed our own test platform called Mobility Lab*. The Mobility Lab is an instrumented car using a multi-purpose vehicle (MPV) that was developed to replicate an autonomous vehicle for research on comfort experience, especially in investigating the motion sickness and situation awareness. It can support various scenarios of users engaging in non-driving related tasks, depending on the study and experiment setups. In addition, the appearance of the Mobility Lab was designed based on current predicted and envisioned autonomous vehicles from car manufacturers such as a visible sensor on the car exterior (e.g. a fake rotatable LiDAR sensor) and invisible driver. We improvised the Wizard of Oz autonomous driving method, taking inspiration from Baltodano et al. (2015). Each autonomous test run involved two experimenters, with one of them a driving wizard who will never to be seen by participants. Only the other experimenter interacted with participants, but he/she also will not be seen during the autonomous test run. The idea was to increase the believability of the participants that they are riding in an autonomous vehicle without being observed by other people.

Before we started any experiment, we needed to define how exactly an autonomous vehicle should behave on the road. However, human drivers drive their cars based on emotions and motivations (Summala, 2007; Vaa, 2007) and different drivers have different driving styles (Hooft van Huysduynen et al., 2015; Karjanto et al., 2017; Taubman-Ben-Ari et al., 2004). As mentioned by Kuderer et al. (2015), more than one driving style for autonomous vehicle riding experience would be required. Since motion sickness was found to be correlated with motions caused by accelerations (Donohew & Griffin, 2004; Griffin, 1990; Lawther & Griffin, 1987; Turner & Griffin, 1999b, 1999a, 1999c), we defined our autonomous driving styles in regard to this fact. *We proposed three autonomous driving styles in reference to acceleration ranges (Karjanto et al., 2017), namely the assertive and defensive driving styles that are based on sensation-seeking trait, and the light rail transit (LRT) driving style that is based on a prediction that autonomous vehicles accelerate and decelerate slower than a typical car or equal to a train* (Le Vine et al., 2015). We tested these driving styles on two group types of drivers, the assertive and defensive drivers, who were selected based on their sensation-seeking trait. We found that regardless of the types of drivers, they *preferred a defensive driving style to be their autonomous driving style*, similar to a study done by Basu et al. (2017). This driving style is selected as one of our experiment settings.

A specific device was developed to help the driving wizard to consistently execute the autonomous driving style in every autonomous test run. This device, the Automatic Acceleration and Data controller (AUTOAccD), shows the generated longitudinal and lateral accelerations of the Mobility Lab by the driving wizard in real time and guiding the driving wizard to maintain a certain range of accelerations. In addition, the Mobility Lab is equipped with a tri-axial accelerometer to measure the accelerations and a data acquisition (DAQ) system to synchronize and record data from measurement sensors. With this equipment, the consistency of the test runs can be validated using the visualization of the power spectral density (PSD) by inspecting the amplitudes of its semi-log graph. Furthermore, the dominant frequency of accelerations below 0.5 Hz is highly correlated with motion sickness (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999a) and these data can be used to determine the consistency dosage of motion sickness given to the participants. This dosage of motion sickness is calculated according to the ISO 2631-1 (ISO, 1997) using motion sickness dose value (MSDV).

Based on the experiments conducted in our study, the results prove that our Mobility Lab is a valid test platform that is able to provide autonomous riding experience on real road environment for motion sickness and situation awareness studies.

7.2. Limitations

a) *Test Platform*

Due to the fact that most driving simulators are developed for different purposes and ignore other aspects of reality, we developed our own test platform, the Mobility Lab, that can be used it in a real-road environment. We acknowledge that with this type of test platform, it is difficult to produce the same simulation in each session consistently. 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 our control. For example, unexpected pedestrians crossing a road on our designated route could force the driving wizard to slow down or stop the Mobility Lab during the test. In addition, even though the temperature inside the Mobility Lab was controlled at 20.0° Celsius, the outside temperature could vary depending on the weather and the time of the day. The differences between inside and outside temperatures might affect the participants answering the questionnaires. In the future, we hope to conduct the work in a strictly controlled environment where the roads are only available to us. In addition, we wish to have a building or structure that allows the participants to move between a room and the Mobility Lab without having to be exposed to outdoor temperatures.

b) *Selected Participants*

Since our work related to motion sickness, we selected our participants based on their susceptibility to motion sickness based on the Motion Sickness Susceptibility Questionnaire (MSSQ). This questionnaire focused on experience motion sickness in different types of provocative environments such as transportation by land, air, sea, or funfair rides. Although a precaution is already taken in which the score should be focused on the land vehicle elements only (see Section 4.3.1.1), the answer options, "*rarely felt sick*" and "*sometimes felt sick*" (see Appendix 6), could be interchangeable as nobody knows how many exactly felt sick for these answer options. This might have an effect on the results of the MSSQ, and some of the selected participants probably are not highly-susceptible to motion sickness. In the future, we hope a new method or tool to define people's susceptibility to motion sickness with higher result accuracy is available. In addition, based on HRV analysis in Chapter 6, although the stable and transient variables of the participants were controlled, there were variations in the recorded data (refer to Figure 6-15). In the future, we suggest that the HRV analysis should be individually analysed or a more strict sampling method should be made that focuses on the similarity of the heart rate baseline reading.

c) *Research Environment*

The work in this dissertation was done with a high ecological validity that is based on real driving situations. Thus, we could generalise our findings to a real-world setting. However, there is a trade-off between ecological validity and experimental control. Drawbacks such as difficult to maintain experimental parameters were expected compared to a study done in a driving simulator. For example, the test route that was made of brick (see Section 3.3.4.2) generated extra vertical vibrations. In a low ecological validity such as when using driving simulator, these vibrations could be excluded from an experiment, and we minimised unwanted vibrations that could affect experiment measurements. Hence, the participants might perceive differently sitting in a simulator compare to sitting in a car. In the future, the trade-off between ecological validity and experimental control should be minimized.

7.3. Directions for Future Research

The research presented in this dissertation seems to have multiple suggestions for our understanding of how comfort riding experience can be enhanced in an autonomous vehicle, especially when users are engaging with non-driving tasks. Here, several possibilities of future research directions are discussed:

a) *Test Platform*

The test platform used in this dissertation was based on the envisioned autonomous vehicle by car manufacturers and designers (see Section 2.2.2). In general, their main focus is to redesign the interior of a conventional vehicle for an autonomous vehicle to enable the occupants to do non-driving related tasks. Yet, how exactly the AV behaves on the real road is still in question. This because there is no autonomous vehicle that exists yet for consumers and the technology itself is still in the development stage (Vincent, 2018). The only existing semi-autonomous vehicle technology for consumers is from Tesla company that is called Autopilot system. However, this system is currently aimed at highway driving where there is no junction or sharp corner with a small radius such as in an urban area that could induce a high lateral acceleration force. Furthermore, the driver in a Tesla car needs to be observant and be ready to take control of the car if needed (Lambert, 2018). Hence, in this dissertation, we developed our own test platform that can cater to the requirements of our study such as driving in an urban area with reverse corner (a curve to the left or right is followed immediately by a curve in the opposite direction) and doing non-driving related tasks without have to worry about driving tasks. Future work in this direction requires in-depth study about the behaviour of the autonomous vehicle in the urban area.

b) *Various non-driving Tasks*

In this dissertation, only two types of activities were tested as non-driving related tasks; watching a video (Chapter 5) and reading texts (Chapter 6). However, many other non-driving tasks were chosen by the future users of autonomous vehicles, such as playing games, working on a laptop, or socializing with other users (see Section 2.2.3). Each of these activities can be challenging or difficult when designing a universal solution to enhance situation awareness of the users. Thus, other research directions that are focussing more on certain activities inside autonomous vehicles could attract automakers in improving comfort experience in their vehicle.

c) *Modalities of Peripheral Information Display*

In continuity with the above research direction, other modalities to convey peripheral information in enhancing situation awareness could be tested. Although the haptic cue in this dissertation was able to enhance situation awareness, this type of modality alone could not mitigate motion sickness (Chapter 5). In addition, different modalities might be only suitable for certain types of non-driving related tasks. Future work in this direction may be an exploration of the different modalities, either a single modality or a combination of several modalities.

d) *Minimizing Involuntary Movement*

In Chapter 6, an active movement mechanism was considered to reduce the involuntary movement of the autonomous vehicle users. This, indirectly, helped in reducing or avoiding the prolonged postural instability that can develop motion sickness over time (Riccio & Stoffregen, 1991). Eliminating or minimizing involuntary movement by countering the effects of centrifugal force when turning into corners might be another research direction in providing comfort to the autonomous vehicle users. Collaboration between automotive engineers, designers, and human factors experts could realize this future research.

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Appendices

Appendix 1: Impulsive Sensation Seeking (ImpSS)

Instruction: Below you will find a series of statements that persons might use to describe themselves. Read each statement and decide whether or not it describes you. Please, try to answer every statement either *True* or *False*, and do not think too much before answering. There are no good or bad answers, so any option is correct.

1. I tend to start a new task or project, without much advance planning on how I will do it.
   - ☐ True
   - ☐ False

2. I usually think about what I am going to do before I do it.
   - ☐ True
   - ☐ False

3. I tend to do things on impulse.
   - ☐ True
   - ☐ False

4. I very seldom spend much time on the details of planning ahead.
   - ☐ True
   - ☐ False

5. I like to have new and exciting experiences and sensations even if they might be a little scary to me.
   - ☐ True
   - ☐ False

6. Before I begin a complicated job or project, I tend to make careful plans.
   - ☐ True
   - ☐ False

7. I would like to take off on a trip with no pre-planned or definite routes or timetable.
   - ☐ True
   - ☐ False

8. I enjoy getting into new situations where I can’t predict how things will turn out.
   - ☐ True
   - ☐ False

9. I like to do certain things just for the thrill of it.
   - ☐ True
   - ☐ False

10. I tend to change my interests frequently.
    - ☐ True
    - ☐ False

11. I sometimes like to do things that are a little frightening.
    - ☐ True
    - ☐ False

12. I will try anything once.
    - ☐ True
    - ☐ False

13. I would like the kind of life where I am on the move and travelling a lot, with lots of change and excitement.
    - ☐ True
    - ☐ False

14. I sometimes do crazy things just for fun.
    - ☐ True
    - ☐ False

15. I like to explore a strange city or section of town by myself, even if it means getting lost.
    - ☐ True
    - ☐ False

16. I prefer friends who are excitingly unpredictable.
    - ☐ True
    - ☐ False

17. I often get so carried away by new and exciting things and ideas that I never stop to consider possible complications.
    - ☐ True
    - ☐ False

18. I am generally an impulsive person.
    - ☐ True
    - ☐ False

19. I tend to enjoy ‘‘wild’’ uninhibited parties.
    - ☐ True
    - ☐ False

Scoring method (for experimenters):

For each item that was answered as indicated with "True" (T) or "False" (F), a point is awarded (otherwise no point) if the item is:

1 = T	5 = T	9 = T	13 = T	17 = T
2 = F	6 = F	10 = T	14 = T	18 = T
3 = T	7 = T	11 = T	15 = T	19 = T
4 = T	8 = T	12 = T	16 = T	

Appendix 2: Comfort Rating Survey

POI A/B/C/D:

R1. Consider the motion (driving through speed hump/accelerating from standstill/braking to a complete stop/cornering to the right) you have experienced, indicate your reaction to this motion:

1	2	3	4	5
Very Comfortable	*Comfortable*	*Neutral*	*Uncomfortable*	*Very Uncomfortable*

R2. How do you perceive this driving style?

1	2	3	4	5
Very Pleasant	*Pleasant*	*Neutral*	*Unpleasant*	*Very Unpleasant*

R3. In your opinion, this driving style is…

1	2	3	4	5
Very Safe	*Safe*	*Neutral*	*Dangerous*	*Very Dangerous*

R4. Is the driving style the same as yours if you were driving the vehicle?

1	2	3	4	5
Very True of Me	*Somewhat True of Me*	*Neutral*	*Somewhat Untrue of Me*	*Very Untrue of Me*

R5. After experiencing the acceleration, what should the force be in your opinion?

1	2	3	4	5
Extremely less force is required	*Slightly less force is required*	*I am satisfied with the currently induced force*	*Slightly more force is required*	*Extremely more force is required*

Appendix 3: Informed consent form used in the preferred autonomous vehicle driving styles study

Participant ID: Date:

TU/e Technische Universiteit Eindhoven University of Technology

EINDHOVEN UNIVERSITY OF TECHNOLOGY (TU/e)

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of the Project: Comfort in autonomous driving styles

Researcher: Juffrizal Karjanto and Nidzamuddin Md. Yusof

Faculty Supervisor: Jacques Terken, Frank Delbressine and Matthias Rauterberg

I. Purpose of this Research/Project

This research is done as part of a project (comfort in autonomous driving style). This experiment aims to determine the comfort within autonomous vehicle with different autonomous driving styles especially on the selection of accelerations.

II. Procedures

a) Participants will take a pre-task questionnaire to provide personal information relevant to the experiment.

b) Then, participants will sit in the car, an autonomous vehicle simulator on the real road, and experience the driving styles as passengers with the different simulated accelerations.

c) Participants need to feel the forces induced by the simulated accelerations at different road profiles. Participants will also be required to rate the comfort experience regarding the simulated accelerations.

III. Risks

Please notify the researchers immediately if you start feeling the signs of motion sickness and cannot continue with the experiment.

IV. Benefits

Your participation in the study would provide the information that will help evaluate the comfort level in different autonomous driving styles. This will contribute in understanding the comfort riding inside autonomous vehicle.

Your personal benefits are independent of the benefits of this study. You are entitled to contact the investigators of this study at a later time for a summary of the research results.

Participant ID: Date:

Technische Universiteit Eindhoven University of Technology

V. Extent of Anonymity and Confidentiality

As a participant of this study, you will be ensured confidentiality. Your name or any other personal identification will not be collected or recorded at any time during the study. Any data associated with you will be assigned a numbered code. This study is being conducted solely for research and development purposes, and the resulting data and interpretations will also be a part of the researchers' academic work.

VI. Freedom to Withdraw

Participation in this study is entirely voluntary and you have the right to withdraw from the study at any time you wish.

VII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities: perform experimental tasks, and answer the questionnaire to the best of my ability.

VIII. Subject's Permission

I have read this consent form and conditions of this experiment. I am aware of the potential risks in the experiment. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

Date_______________________________

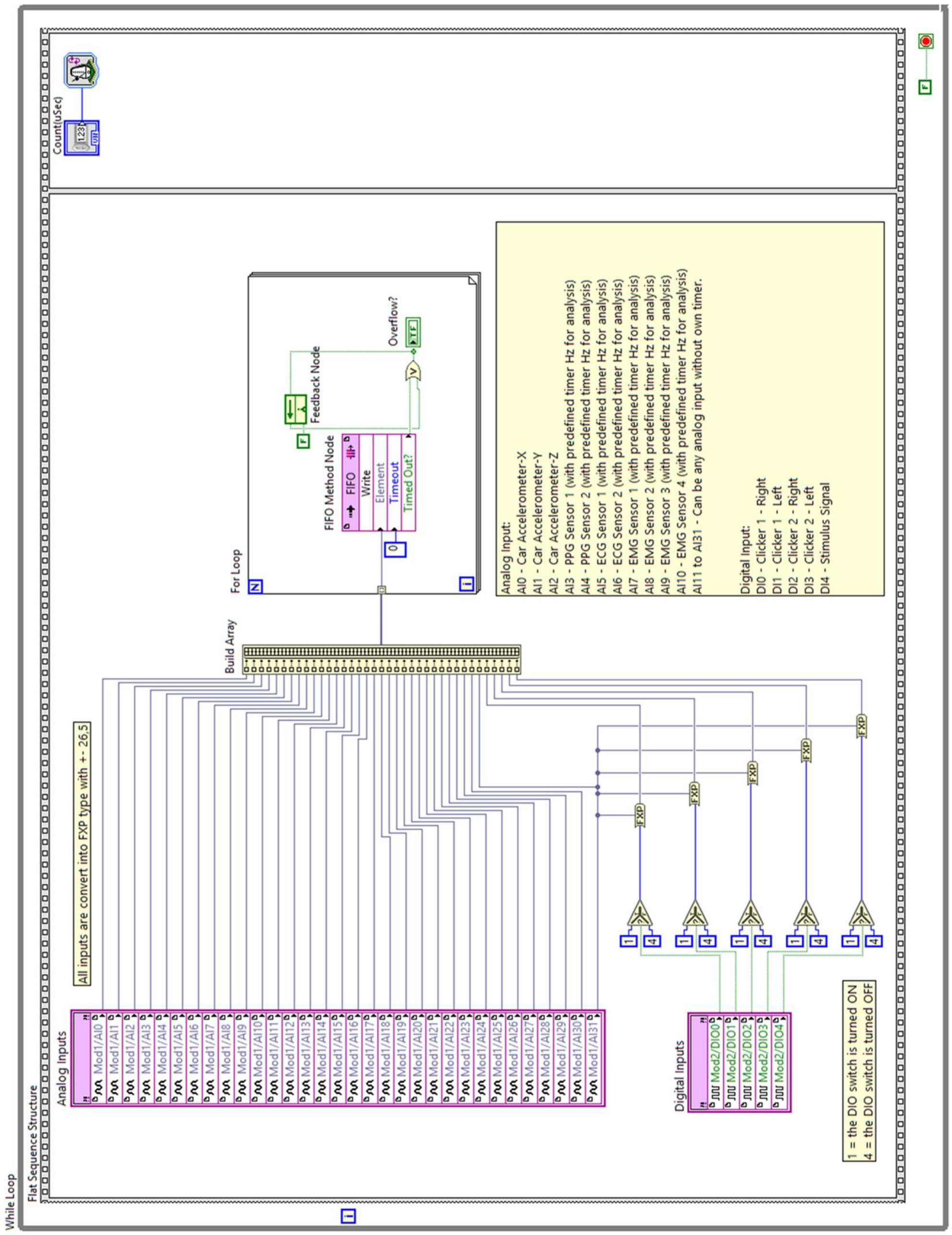
Participant signature_______________________________

Should I have any pertinent questions about this research or its conduct, I may contact:

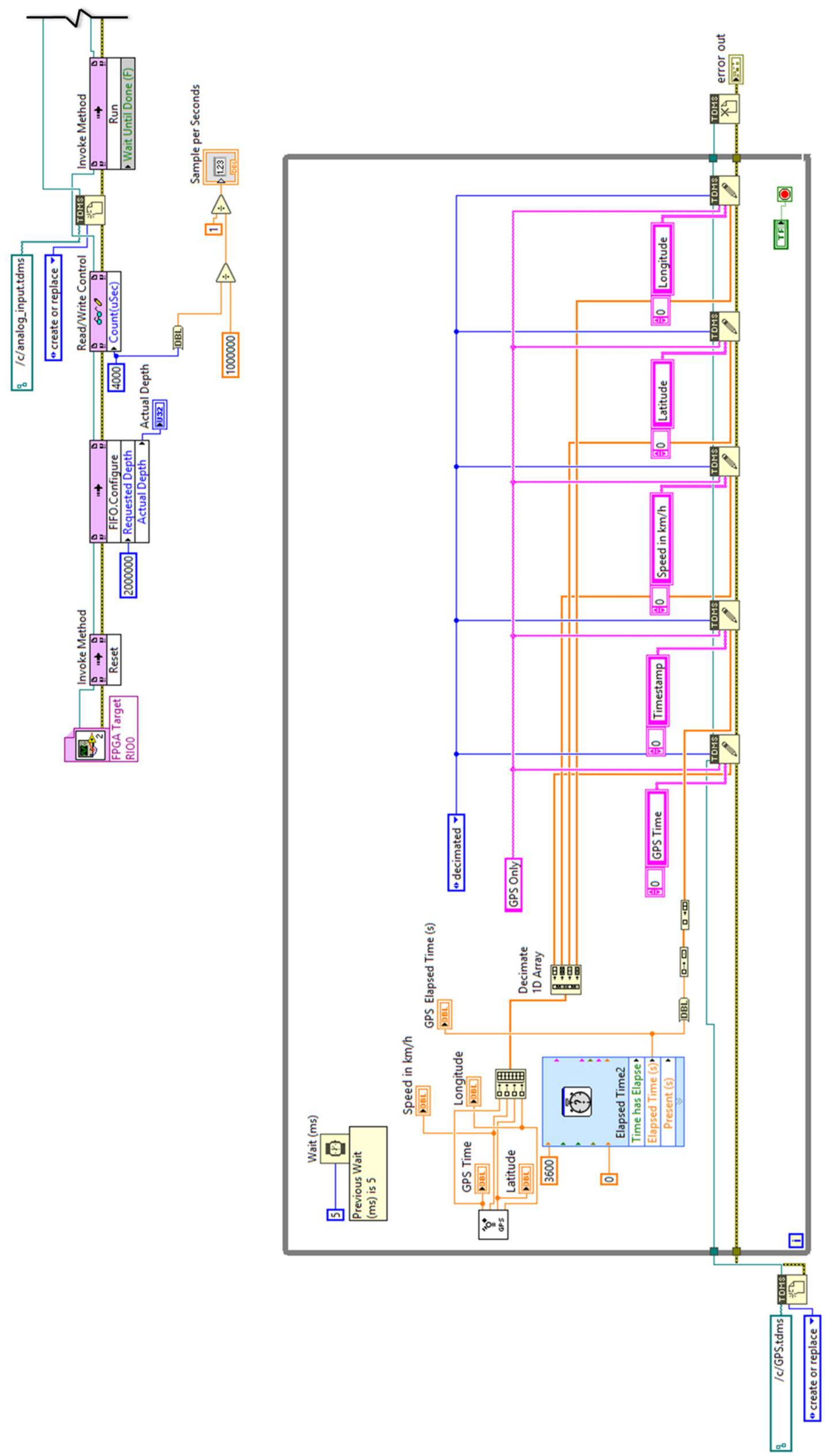
Researcher's contact e-mails: j.karjanto@tue.nl
n.yusof@tue.nl

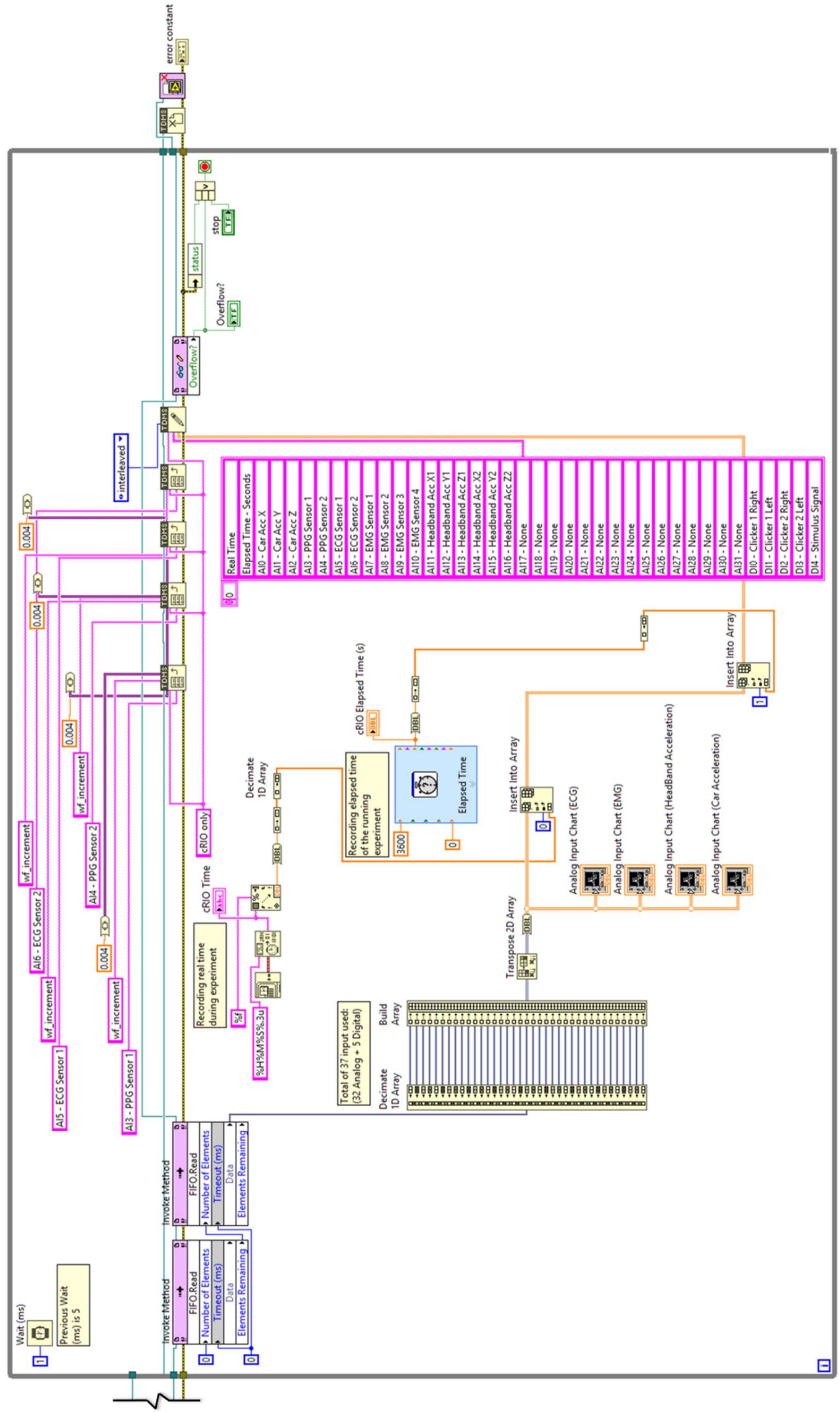
Faculty Advisor 's contact e-mails: j.m.b.terken@tue.nl
f.l.m.delbressine@tue.nl
g.m.w.rauterberg@tue.nl

Appendix 4: The field-programmable gate array (FPGA) program inside LabVIEW software (block diagram view)



Appendix 5: The real-time (RT) program inside LabVIEW software (block diagram view)




error constant
Wait (ms)
Previous Wait (ms) is 5
Invoke Method
FIFO.Read
Number of Elements
Timeout (ms)
Data
Elements Remaining
Invoke Method
FIFO.Read
Number of Elements
Timeout (ms)
Data
Elements Remaining
AI5 - ECG Sensor 1
wf_increment
AI6 - ECG Sensor 2
wf_increment
0.004
AI3 - PPG Sensor 1
wf_increment
0.004
AI4 - PPG Sensor 2
wf_increment
0.004
0.004
interleaved
cRIO only
Overflow?
status
stop
Recording real time during experiment
%H%M%S%3u
%d
cRIO Time
Decimate 1D Array
Recording elapsed time of the running experiment
3600
Elapsed Time
cRIO Elapsed Time (s)
Total of 37 input used: (32 Analog + 5 Digital)
Decimate 1D Array
Build Array
Transpose 2D Array
Insert Into Array
Insert Into Array
Analog Input Chart (ECG)
Analog Input Chart (EMG)
Analog Input Chart (HeadBand Acceleration)
Analog Input Chart (Car Acceleration)
Real Time
Elapsed Time - Seconds
AI0 - Car Acc X
AI1 - Car Acc Y
AI2 - Car Acc Z
AI3 - PPG Sensor 1
AI4 - PPG Sensor 2
AI5 - ECG Sensor 1
AI6 - ECG Sensor 2
AI7 - EMG Sensor 1
AI8 - EMG Sensor 2
AI9 - EMG Sensor 3
AI10 - EMG Sensor 4
AI11 - Headband Acc X1
AI12 - Headband Acc Y1
AI13 - Headband Acc Z1
AI14 - Headband Acc X2
AI15 - Headband Acc Y2
AI16 - Headband Acc Z2
AI17 - None
AI18 - None
AI19 - None
AI20 - None
AI21 - None
AI22 - None
AI23 - None
AI24 - None
AI25 - None
AI26 - None
AI27 - None
AI28 - None
AI29 - None
AI30 - None
AI31 - None
DI0 - Clicker 1 Right
DI1 - Clicker 1 Left
DI2 - Clicker 2 Right
DI3 - Clicker 2 Left
DI4 - Stimulus Signal

Appendix 6: Motion Sickness Susceptibility Questionnaire Short-Form (MSSQ-Short)

1. Please State Your **Age** .... Years.   *2.* Please State Your Sex (tick box) **Male** [1] **Female** [2]

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Appendix 7: Motion Sickness Assessment Questionnaire (MSAQ)

***Instructions.* Using the scale below, please rate how accurately the following statements describe your experience**

Not at all	Severely
1——2——3——4——5——6——7——8——9	
1. I felt sick to my stomach (G)	9. I felt disoriented (Q
2. I felt faint-like (C)	10. I felt tired/fatigued (S)
3. I felt annoyed/irritated (S)	11. I felt nauseated (G)
4. I felt sweaty (P)	12. I felt hot/warm (P)
5. I felt queasy (G)	13. I felt dizzy (C)
6. I felt lightheaded (C)	14. I felt like I was spinning (C)
7. I felt drowsy (S)	15. I felt as if I may vomit (G)
8. I felt clammy/cold sweat (P)	16. I felt uneasy (S)

Note. G; Gastrointestinal; C: Central; P: Peripheral; SR; Sopite-related.

Appendix 8: Original Situational Awareness Rating Technique (SART)

SITUATION AWARENESS RATING TECHNIQUE (SART; Taylor, 1990)

Instability of Situation
How changeable is the situation? Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

1 2 3 4 5 6 7

Complexity of Situation
How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

1 2 3 4 5 6 7

Variability of Situation
How many variables are changing within the situation? Are there a large number of factors varying (High) or are there very few variables changing (Low)?

1 2 3 4 5 6 7

Arousal
How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

1 2 3 4 5 6 7

Concentration of Attention
How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focussed on only one (Low)?

1 2 3 4 5 6 7

Division of Attention
How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focussed on only one (Low)?

1 2 3 4 5 6 7

Spare Mental Capacity
How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?

1 2 3 4 5 6 7

Information Quantity
How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

1 2 3 4 5 6 7

Familiarity with Situation
How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1 2 3 4 5 6 7

Appendix 9: Modified SART

NOTE: The questions in this part always refer to the **<u>autonomous riding experience (10 minutes when you were driven around inside the car),</u> NOT** to the instructed task, except when indicated otherwise.

a. Do events turning to the right or left occur unexpectedly?
   Not at all 1 2 3 4 5 6 7 *Very much*

b. How complex is the situation: Is it hard to understand what is happening?
   Not at all 1 2 3 4 5 6 7 *Very much*

c. How many variables (e.g. speed of the car, forces felt inside the car, etc.) are changing in the situation?
   Few 1 2 3 4 5 6 7 *Many*

d. Are you able to anticipate and keep up with the changing situation?
   Not at all 1 2 3 4 5 6 7 *Very much*

e. Can you concentrate on both watching the video and acquiring the information regarding the situation?
   Not at all 1 2 3 4 5 6 7 *Very well*

f. Are you concentrating on many aspects of the situation (high) or only on one aspect (low)?
   Low 1 2 3 4 5 6 7 *High*

g. How much mental effort does it take to acquire the information regarding the situation?
   Very little 1 2 3 4 5 6 7 *Very much*

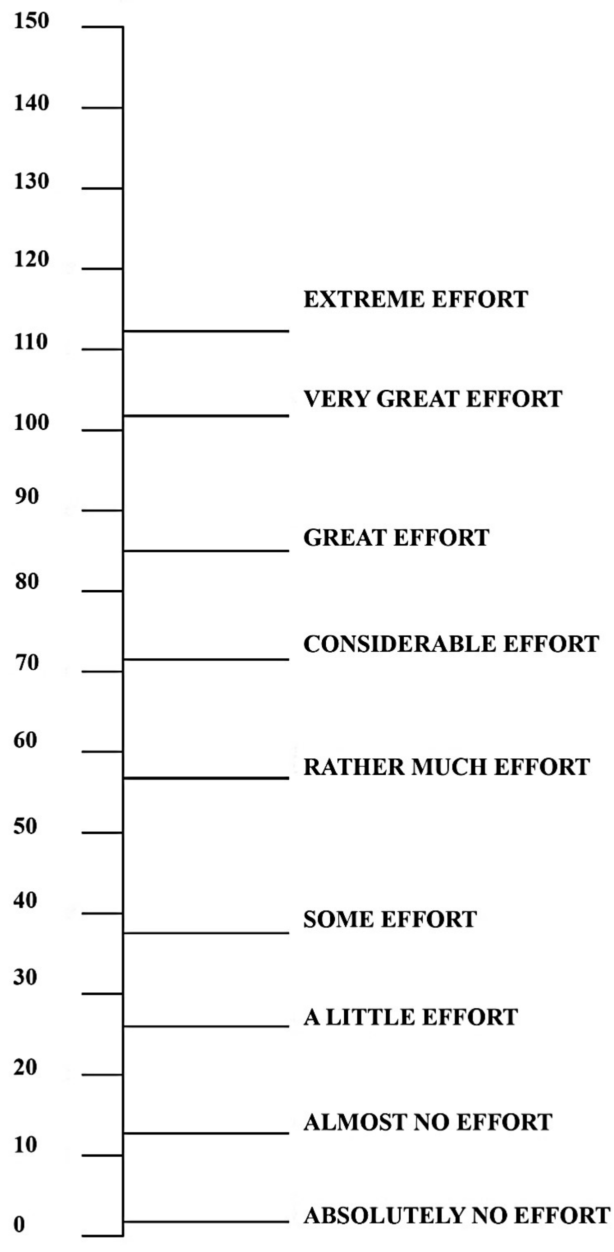
h. How much information did you gain about the situation?
   Do you gain a great deal of information (high) or very little information (low)?
   Very little 1 2 3 4 5 6 7 *Very much*

i. How useful is the information you gained about the situation?
   Not useful at all 1 2 3 4 5 6 7 *Very useful*

j. How familiar are you with the situation? Do you have a lot of related or relevant experiences (high) or is it totally new experience (low)?
   Low 1 2 3 4 5 6 7 *High*

Appendix 10: Rating Scale Mental Effort (RSME)

Instruction: Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task you have just finished.



Appendix 11: User Experience Questionnaire (UEQ)

Instruction: How do you find the peripheral information prototype?

	1	**2**	**3**	**4**	**5**	**6**	**7**	
annoying	○	○	○	○	○	○	○	enjoyable
not understandable	○	○	○	○	○	○	○	understandable
creative	○	○	○	○	○	○	○	dull
easy to learn	○	○	○	○	○	○	○	difficult to learn
valuable	○	○	○	○	○	○	○	inferior
boring	○	○	○	○	○	○	○	exciting
not interesting	○	○	○	○	○	○	○	interesting
unpredictable	○	○	○	○	○	○	○	predictable
fast	○	○	○	○	○	○	○	slow
inventive	○	○	○	○	○	○	○	conventional
obstructive	○	○	○	○	○	○	○	supportive
good	○	○	○	○	○	○	○	bad
complicated	○	○	○	○	○	○	○	easy
unlikable	○	○	○	○	○	○	○	pleasing
usual	○	○	○	○	○	○	○	leading edge
unpleasant	○	○	○	○	○	○	○	pleasant
secure	○	○	○	○	○	○	○	not secure
motivating	○	○	○	○	○	○	○	demotivating
meets expectations	○	○	○	○	○	○	○	does not meet expectations
inefficient	○	○	○	○	○	○	○	efficient
clear	○	○	○	○	○	○	○	confusing
impractical	○	○	○	○	○	○	○	practical
organized	○	○	○	○	○	○	○	cluttered
attractive	○	○	○	○	○	○	○	unattractive
friendly	○	○	○	○	○	○	○	unfriendly
conservative	○	○	○	○	○	○	○	innovative

Principles and elaborations

1. Honesty and scrupulousness

Principle

Academic practitioners are honest and forthright about their research and its applications. Scientific and scholarly activities are performed scrupulously and should remain unaffected by the pressure to achieve.

Definition

Researchers are called upon to be open and nuanced about margins of uncertainty and other limits on the interpretation and applicability of their own research and that of their fellow practitioners. Communication regarding research results should be dispassionate and realistic. The actions of an academic practitioner are scrupulous when they are performed with the dedication and precision that a proper exercise of the profession requires.

Elaboration

1.1. Academic practitioners know that the ultimate aim of science is to establish facts and they therefore must present the nature and scope of their results with the greatest possible precision. Accordingly, they do not prevaricate about their findings or about attendant uncertainties. Scrupulousness also entails the presentation of doubts and contraindications.

1.2. Every academic practitioner demonstrates respect for the people and animals involved in scientific teaching and research. Research on human subjects is exclusively permitted if the persons concerned have freely given informed consent, the risks are minimal and their privacy is sufficiently safeguarded. Research involving animals is only permitted if the statutory permits have been granted and in conformity with the relevant legislation.

1.3. Accurate source references provide a clear indication of the intellectual provenance of cited and paraphrased text. This also applies to information gathered from the Internet and from anonymous sources. The texts and research results of others are never reproduced without a reference.

1.4. Authorship is acknowledged. Rules common to the academic discipline are observed.

1.5. Academic practitioners do not republish their own previously published work or parts thereof as though it constituted a new contribution to the academic literature. When republishing previously published findings, they indicate this with a correct reference to the source or by another means accepted within the discipline. In many disciplines it is permissible and even customary to reprint short texts from works published with or without co-authors without a source reference when it concerns brief passages of introductory, theoretical or methodological explanation.

1.6. Scrupulousness is expressed through precision and nuance in academic instruction and research, in publishing research results and in other forms of knowledge transfer.

Appendix 13: Informed consent form used in Chapter 5

Participant ID: Date:

TU/e Technische Universiteit Eindhoven University of Technology

EINDHOVEN UNIVERSITY OF TECHNOLOGY (TU/e)

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of the Project: Comfort in autonomous car's riding experience

Researcher: Juffrizal Karjanto and Nidzamuddin Md. Yusof

Faculty Supervisor: Jacques Terken, Frank Delbressine and Matthias Rauterberg

I. Purpose of this Research/Project

This research is done as part of a project (comfort in autonomous driving/riding). This experiment aims to determine the effectiveness of peripheral means in enhancing situation awareness and mitigating motion sickness in autonomous riding experience.

II. Procedures

a) Participants will answer a set of pre-experiment questionnaire prior to starting the experiment.

b) Then, participants will be seated in the car, an autonomous test vehicle, and a pulse sensor will be placed at one of the fingers on the left hand while a clicker with two indicators will be held on the right hand.

c) The participant will wear the seat belt and watch a video for the whole experiment.

d) The phase of the experiment is as follows:

   1. A 5-Minutes phase where the car is stationary and the participant watching the video.
   2. A 10-Minutes phase where the car is driven autonomously and the participant continue watching the video.
   3. A final 5-Minutes phase where the car is stopped and the participant continue watching the video.

e) The experiment is done after the participant have answered the post-experiment questionnaire and after a debriefing of the experiment.

III. Risks

Please notify the researchers (**by pushing the white button on the desk**) if you cannot continue with the experiment.

Participant ID: Date:

TU/e Technische Universiteit Eindhoven University of Technology

IV. Benefits

Your participation in the study would provide the information that will help evaluate role of haptic/visual means in situation awareness and motion sickness development in autonomous riding experience.

Your personal benefits are independent of the benefits of this study. You are entitled to contact the researchers of this study at a later time for a summary of the research results.

V. Extent of Anonymity and Confidentiality

As a participant of this study, you will be ensured confidentiality. Any data associated with you will be assigned a numbered code. This study is being conducted solely for research and development purposes, and the resulting data and interpretations will also be a part of the researchers' academic work. In addition, the whole activities during the experiment will be recorded for the purpose of observation analysis and will not be shared or exposed to personnel other than the researchers for this particular experiment.

VI. Freedom to Withdraw

Participation in this study is entirely voluntary and you have the right to withdraw from the study at any time you wish.

VII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities: perform experimental tasks, and answer the questionnaire to the best of my ability.

VIII. Subject's Permission

I have read this consent form and conditions of this experiment. I am aware of the potential risks in the experiment. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

Date: ______________________________

Participant's signature: ______________________________

Should I have any pertinent questions about this research or its conduct, I may contact:

Researcher's contact e-mails: j.karjanto@tue.nl
n.yusof@tue.nl

Faculty Advisor's contact e-mails: j.m.b.terken@tue.nl
fdelbres@tue.nl
g.w.m.rauterberg@tue.nl

Appendix 14: Autonomous Driving Test Ride Quality (ADTQ)

How do you rate the **overall quality** of the autonomous driving?
(On the scale of 1 = very unrealistic, to 10 = very realistic)

1	2	3	4	5	6	7	8	9	10

Appendix 15: Reading Performance Questionnaire for Control-condition

My Undersized Load

1. When picking up her blueberry and blackberry bushes and apple, peach and pear trees, she felt embarrassed as she brought a truck to pick up those that only in a little bundle. But the man behind her was even more embarrassed as he brought a ____________
    a. Bicycle
    b. Trailer
    c. Wheelbarrow
    d. Caravan

Old Trick, New Dog

2. In Florida, the dog was not afraid because there are no rocks over there, just a lot of ________
    a. Water
    b. Mud
    c. Sand
    d. Fire

Mechanical Kid

3. Why Jimmy, when asked by his grandparent, wanted to be a machine?
    a. Machine is cool
    b. Parts of in the machine can be upgraded
    c. Parts of the machine can be replaced
    d. Machine is awesome

My Hurry-up Hairdo

4. Busy in getting herself and her two children ready for the church has made the lady forgot that _________ were still on her hair.
    a. Hair combs
    b. Hair extensions
    c. Hair curlers
    d. Hair straighteners

A Ride in Oklahoma

5. A lady, who left Tokyo to live in a small town in Oklahoma, pulled "what she thought was a taxi" in order to get a ride home. Later, when she realised that she actually rode a _______
    a. Police car
    b. Ambulance
    c. Fire truck
    d. Caravan

Funny Dad: The World's Most Practical Dad

6. Mary bought her dad a personal safe in a shape of ________ with a false bottom so that he can now keep his money in the workshop. But instead, he put still put his money in his underwear drawer.
    a. A glue can
    b. A paint can
    c. A spray can

d. An oil can

The Dumbest Police Calls in America

7. One of the dumbest calls received by a policeman in America was that a report about a woman and her son was attacked by a ______ and the ______ would not allow her to take her son to the hospital.
    a. Dog
    b. Bird
    c. Cat
    d. Mouse

Gator Mystery

8. What do you call an alligator in a vest?
    a. Navigator
    b. Investigator
    c. Interrogator
    d. Litigator

Big Mouth

9. New to the United States, a woman was eager to meet people. So one day she struck up a conversation with the only other woman in the gym. Pointing to two men playing ___________ in a nearby court, I said to her, "There's my husband." Then I added, "The thin one—not the fat one."
    a. Badminton
    b. Racquetball
    c. Table tennis
    d. Basketball

Missing Number

10. A guy with his friend wants to watch a movie and found that the show supposed to start at ____ o'clock, but the theatre is missing that specific number and instead of putting a set of different number to show the movie's showing time.
    a. 7
    b. 5
    c. 9
    d. 8

No kidding

1. What do you call an iPhone that isn't kidding around?
   a. Siri-us Black
   b. Dead Siri-ous
   c. Siri-us Star
   d. Numb Siri-ous

The Most Confusing Password

2. A guy was in a couple's home trying to fix their Internet connection. The husband called out to his wife in the other room for the computer password. What was the password?
   a. Start123
   b. 1Start23
   c. 123abc
   d. ABC123

Sergeant Nimrod

3. To place an address on an important letter, an army security misspelt Sergeant Gary last name as _______?
   a. Toohard
   b. Tootough
   c. Toolittle
   d. Toosmall

Deployment

4. When the Air Force deployed a soldier overseas, his daughter's friend asked her where he was headed. "My dad is going to __________," my daughter said. "Oh, my God!" her friend shrieked. "What did he do?"
   a. Pirate Bay
   b. Guantanamo Bay
   c. Bengal Bay
   d. Ha Long Bay

Locked Out

5. What key won't open any door?
   a. A monkey
   b. A donkey
   c. A mickey
   d. A turkey

My Son's #1 Concern

6. When my three-year-old was told to pee in a cup at the doctor's office, he unexpectedly got nervous. With a shaking voice, he asked ______
   a. "Do I have to throw it?"
   b. "Do I have to drink it?"
   c. "Do I have to consume it?"

d. “Do I have to play with it?”

With Pointed Fangs I…

7. With pointed fangs I sit and wait; with piercing force I crunch out fate; grabbing victims, proclaiming might; physically joining with a single bite. What am I?
    a. A cobbler
    b. A butler
    c. A stapler
    d. An assembler

Payday

8. A friend had a waitressing position open at his diner and asked job seekers to fill out an application. Under "Salary Expected," a woman wrote _______
    a. Thursday
    b. Friday
    c. Saturday
    d. Sunday

Chemistry in the Soup Kitchen

9. While volunteering in a soup kitchen, a woman found an attractive single man. But she always figured that a man that she met is a married man. This time the guy is single, but he is a _____
    a. Soldier
    b. Priest
    c. Minister
    d. Lieutenant

Bad Work Excuses

10. Thinking of skipping work? Don’t try these real excuses. They didn’t work the first time. Which one is not coming from the provided text?
    a. My false teeth flew out the window while I was driving down the highway.
    b. My favourite football team lost on Sunday, so I needed Monday to recover.
    c. I received a threatening phone call from the electric company and needed to report it to the FBI.
    d. My cat is getting married.

The Camper's Second Opinion

1. Two campers are hiking in the woods when one is bitten on the _______ by a rattlesnake. The other looked for a doctor, and the doctor suggested to take a knife, cut a little X where the bite is, suck out the poison and spit it on the ground. But he refused to do so and gave a second opinion.
    a. Stomach
    b. Mouth
    c. Buttocks
    d. Armpit

Chicken Scratch

2. At the wedding reception, the father of the bride, who is a doctor, stood to read his toast, which he had scribbled on a piece of scrap paper. Later, he explained, "I'm sorry. I can't seem to make out what I've written down." Looking out into the audience, he asked, "Is there a________ in the house?"
    a. Nurse
    b. Surgeon
    c. Pharmacist
    d. Neurologist

Scared Dog

3. My sister-in-law, a truck driver, had decided to get a dog for protection. As she inspected a likely candidate, the trainer told her, "He doesn't like _______ “. One day she was approached by two ________ in a parking lot, as the _______ got closer, the dog ran under the nearest car.
    a. Cats
    b. Dogs
    c. Men
    d. Women

Canine Division

4. After lunging through the doorway, the dog froze and backed out. The sheriff was puzzled until he investigated further. Then he noticed the sign on the building: “________.”
    a. Post Office
    b. Veterinarian Office
    c. Hospital
    d. Cemetery

Lunatic

5. Like to hunt for fossils, a hobbyist found the petrified bones of a _______. But his wife is not impressed and said “I’ve heard of many a _______ bringing a nut home,” she remarked, “but this is the first time I’ve heard of a nut bringing a _______ home.”
    a. Chipmunk
    b. Flying Fox
    c. Squirrel
    d. Marsupial

Scared of Insects

6. A nine-year-old daughter of the author is not afraid of snake and frog but scared of ________
    a. Ants
    b. Butterfly
    c. Lizard
    d. Dragonfly

Uninvited

7. The prison warden is upset as one of his convict (prisoner) is running away with his ________
    a. Wife
    b. Best friend
    c. Daughter
    d. Fellow warden

Changing Species

8. A hypnotist was visiting the aquarium during feeding time and claimed to hypnotize the shark into a/an _________
    a. Alligator
    b. Alpaca
    c. Armadillo
    d. Elephant

Magic Cat

9. The author worked at a boarding kennel where people leave their dogs and cats while on vacation. One day, she was surprised to see the cat suddenly at her feet. To her surprise, the cat's name is ________
    a. David Blaine
    b. Harry Houdini
    c. David Copperfield
    d. Criss Angel

Bad Kitty

10. What's the worst kind of cat?
    a. Catalogues
    b. Catholics
    c. Caterpillar
    d. Catastrophe

Appendix 18: Informed consent form used in Chapter 6

Participant ID: Date:

TU/e Technische Universiteit Eindhoven University of Technology

EINDHOVEN UNIVERSITY OF TECHNOLOGY (TU/e)

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of the Project: Comfort in autonomous car's riding experience

Researcher: Juffrizal Karjanto and Nidzamuddin Md. Yusof

Faculty Supervisor: Jacques Terken, Frank Delbressine and Matthias Rauterberg

I. Purpose of this Research/Project

This research is done as part of a project of comfort in autonomous driving/riding. This experiment aims to determine the effectiveness of peripheral means in mitigating motion sickness in autonomous riding experience.

II. Procedures

a) Participants will answer a set of pre-experiment questionnaire prior to starting the experiment.

b) Before going to the car, an autonomous test vehicle, participants need to attach the ECG electrodes on their body, based on the instructions given.

c) Then, participants will be seated in the car. The ECG electrodes cable will be attached to the ECG microcontroller box and the headband accelerometer will be worn on the head.

d) The participant will wear the seat belt and do the reading as a task for the whole experiment.

e) The phase of the experiment is as follows:

1. A 5-Minutes phase where the car is stationary and the participant reading the texts on the tablet.
2. A 15-Minutes phase where the car is driven autonomously and the participant continue reading the texts on the tablet.
3. A final 5-Minutes phase where the car is stopped and the participant continue reading the texts on the tablet.

f) The experiment is done after the participant have answered the post-experiment questionnaire and after a debriefing of the experiment.

III. Risks

If motion sickness happens to occur and you wish to stop the experiment, please notify the researchers. (**By pushing the white button on the desk**)

Participant ID: Date:

TU/e Technische Universiteit Eindhoven University of Technology

IV. Benefits

Your personal benefits are independent of the benefits of this study. You are entitled to contact the researchers of this study at a later time for a summary of the research results.

V. Extent of Anonymity and Confidentiality

As a participant of this study, you will be ensured confidentiality. Any data associated with you will be assigned a numbered code. This study is being conducted solely for research and development purposes, and the resulting data and interpretations will also be a part of the researchers' academic work. In addition, the whole activities during the experiment will be recorded for the purpose of observation analysis and will not be shared or exposed to personnel other than the researchers for this particular experiment.

VI. Freedom to Withdraw

Participation in this study is entirely voluntary and you have the right to withdraw from the study at any time you wish.

VII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities: perform experimental tasks, and answer the questionnaire to the best of my ability.

VIII. Subject's Permission

I have read this consent form and conditions of this experiment. I am aware of the potential risks in the experiment. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

Date: ____________________________

Participant's signature: ____________________________

Should I have any pertinent questions about this research or its conduct, I may contact:

Researcher's contact e-mails: j.karjanto@tue.nl
n.yusof@tue.nl

Faculty Advisor's contact e-mails: j.m.b.terken@tue.nl
fdelbres@tue.nl
g.w.m.rauterberg@tue.nl

Summary

Autonomous vehicles raise numerous complex challenges in the forthcoming years as automated driving technology evolves. They enable a transition of humans drivers to eventual passengers that can perform non-driving tasks, such as reading, socializing with other passengers, watching movies, or working. Such activities usually tend the automated vehicle users' focus off the road, which leads to an incapability to predict the immediate movement of the automated vehicle. This lack of outside visual information substantially reduces situation awareness of the users.

Situation awareness is defined in various ways of concept, depending on the theoretical and methodological approaches. In a simple way, situation awareness is "knowing what is going on around you". In the context of autonomous vehicle riding experience, situation awareness would involve the user being aware of what is happening in the environment and surroundings of the autonomous vehicle while performing non-driving related tasks. Furthermore, autonomous vehicle users will be subjected to experience certain forces, which are induced by braking, cornering and accelerating of the vehicle. They normally try to compensate for the feeling of forces acted on their body by visually understanding the situation and act accordingly. However, when they have no ability to foresee the direction of movement of the vehicle, they cannot act accordingly and motion sickness symptoms, such as physical discomfort, dizziness, and nausea, might occur.

Motion sickness is a result of a conflict between the passenger's vestibular and visual inputs, diminished ability to foresee the direction of movement of the vehicle and deprivation of control over one's movements. In addition, an aggressive driving manner involving multiple occurrences of acceleration and braking is more probable to cause motion sickness. Previous studies found that autonomous vehicle user would prefer a defensive or much less induced acceleration driving styles. Yet, engaging in non-driving related tasks, even with that kind of driving style, can cause motion sickness since human bodies are not habitual to the low-frequency oscillation of movement, especially in an urban area with many junctions and corners.

The general idea to overcome this situation is using human senses to provide sufficient situation awareness to predict or anticipate the action of the automated vehicle and act accordingly on time. In this dissertation, experimental and analytical methods of research are described and discussed in order to investigate the research goal:

To mitigate the motion sickness by proposing an enhancement of the situation awareness of the autonomous vehicle users while engaging in non-driving related tasks.

Two specific main research questions and one methodological research question were proposed to address this goal:

a) *Ds information displays can help to enhance situation awareness while engaging in non-driving related tasks?*
b) *Does increasing the situation awareness help to mitigate motion sickness in an autonomous vehicle?*
c) *How to conduct our study in a real-world environment?*

We discussed the type of driving styles that human drivers normally drove and explained how these driving styles could be related to autonomous driving styles. Then, a new test platform was designed and developed to be used for our study. This test platform called Mobility Lab was specially developed to replicate an autonomous car of the future for research on the experience of comfort. An evaluation has been made to assess its capability to conduct studies on the real road.

Two main experiments were conducted to attempt to enhance the situation awareness by means of the haptic cue. The first experiment involved a vibrotactile display that was designed to be used on the forearm to provide information about the vehicle's immediate manoeuvre. Based on the results, the level of situation awareness was found to increase with the display, but there was no change for the level of motion sickness. The second experiment involved an iteration of the vibrotactile display with an extension of the movable plate that actively moves or pushes the users' upper body to the sides when the vehicle is turning to any direction, either to the left or the right. As a result, the level of situation awareness was increased while the level of motion sickness was decreased.

In general, this study explores the possibilities of increasing riding comfort experience in an autonomous vehicle. The findings from this study imply that the future interior of an autonomous vehicle should be designed with the idea of how to reduce motion sickness with different kind of non-driving related tasks.

List of Publications

Karjanto, J., & **Yusof, N. M.** (2015). Multi-Dimensions Motivational Factors in Autonomous Driving. In *3rd Workshop on User Experience of Autonomous Vehicles at AutoUI'15*.

Yusof, N. M., & Karjanto, J. (2015). Comfort Determination in Autonomous Driving Style. In *3rd Workshop on User Experience of Autonomous Vehicles at AutoUI'15*.

Md. Yusof, N., Karjanto, J., Terken, J., Delbressine, F., Hassan, M. Z., & Rauterberg, M. (2016). The Exploration of Autonomous Vehicle Driving Styles: Preferred Longitudinal, Lateral, and Vertical Accelerations. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - Automotive'UI 16* (pp. 245–252). New York, USA: ACM Press. https://doi.org/10.1145/3003715.3005455

Karjanto, J., **Yusof, N. M.**, Terken, J., Hassan, M. Z., Delbressine, F., van Huysduynen, H. H., & Rauterberg, M. (2017). The identification of Malaysian driving styles using the multidimensional driving style inventory. In *MATEC Web of Conferences* (Vol. 90, p. 1004). EDP Sciences. http://doi.org/10.1051/matecconf/20179001004

Karjanto, J., **Yusof, N. M.**, Terken, J., Delbressine, F., Hassan, M. Z., & Rauterberg, M. (2017). Simulating autonomous driving styles: Accelerations for three road profiles. In MATEC Web of Conferences (Vol. 90, p. 1005). EDP Sciences. http://doi.org/10.1051/matecconf/20179001005 **(Best Presenter Award)**

Md. Yusof, N., Karjanto, J., Kapoor, S., Terken, J., Delbressine, F., & Rauterberg, M. (2017). Experimental Setup of Motion Sickness and Situation Awareness in Automated Vehicle Riding Experience. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct - AutomotiveUI '17* (pp. 104–109). New York, USA: ACM Press. https://doi.org/10.1145/3131726.3131761 **(Honourable Mention Award)**

Karjanto, J., **Md. Yusof, N.**, Wang, C., Delbressine, F., Rauterberg, M., Terken, J., & Martini, A. (2017). Situation Awareness and Motion Sickness in Automated Vehicle Driving Experience. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct - AutomotiveUI '17* (pp. 57–61). New York, USA: ACM Press. https://doi.org/10.1145/3131726.3131745

Terken, J., Levy, P., Wang, C., Karjanto, J., **Yusof, N. M.**, Ros, F., & Zwaan, S. (2017). Gesture-Based and Haptic Interfaces for Connected and Autonomous Driving. In I. L. Nunes (Ed.), *Advances in Human Factors and System Interactions: Proceedings of the AHFE 2016 International Conference on Human Factors and System Interactions, July 27-31, 2016, Walt Disney World®, Florida, USA* (pp. 107–115). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-41956-5_11 **(Best Paper Award)**

Karjanto, J., **Md. Yusof, N.**, Wang, C., Terken, J., Delbressine, F., & Rauterberg, M. (2018). The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving. *Transportation Research Part F: Psychology and Behaviour*, *58*, 678–692. https://doi.org/10.1016/j.trf.2018.06.046

Karjanto, J., **Yusof, N. M.**, Terken, J., Delbressine, F., Rauterberg, M., & Hassan, M. Z. (2018). Development of On-Road Automated Vehicle Simulator for Motion Sickness Studies. International Journal of Driving Science, 1(1), 1–12. https://doi.org/10.5334/ijds.8

Md. Yusof, N., Karjanto, J., Terken, J., Delbressine, F., & Rauterberg, M. (2019). Gaining Situation Awareness through a Vibrotactile Display to Mitigate Motion Sickness in Fully-Automated Driving Cars. *Transportation Research Part F: Psychology and Behaviour*. (In reviewing process)

Karjanto, J., **Md. Yusof, N.**, Terken, J., Delbressine, F., & Rauterberg, M. (2019). Reading in fully automated driving: a study of visual and haptic peripheral information system in mitigating motion sickness. *Applied Ergonomics*. (In reviewing process)

Karjanto, J., **Md. Yusof, N.**, Terken, J., Delbressine, F., & Rauterberg, M. (2019). Level of Motion Sickness Based on Heart Rate Variability When Reading Inside a Fully Automated Vehicle. *2019 IEEE International Conference on Cybernetics and Computational Intelligence*. (In reviewing process)

Md. Yusof, N., Karjanto, J., Terken, J., Delbressine, F., & Rauterberg, M. (2019). User Experience of an Early Autonomous Vehicle's Trajectory Information Using Visual and Haptic Modalities on Occupants. *2019 IEEE International Conference on Cybernetics and Computational Intelligence*. (In reviewing process)

Student Supervision

Project Report, Faculty of Industrial Design, TU/e

AWAIR: A Tangible Interface Communicating Situational Awareness in Autonomous Vehicles (Miguel Cabral Guerra and Jose Gallegos Nieto, 2016)

SAS: Situation Awareness System (Donovan Lewis, 2016)

Can patterns help in communicating what an autonomous vehicle is going to do? (Rosa van Koningsbruggen, 2016)

Bachelor End Project, Faculty of Electrical Engineering, TU/e

Experimental Analysis of Motion Sickness and Situation Awareness in Future Autonomous Vehicles (Shivam Kapoor, 2017)

A Thorough Research on Motion Sickness Reduction in Autonomous Vehicles Using Visual Stimuli (Alberto DeMartini, 2017)

Quantifying perception of comfort for autonomous vehicles occupants in combination with physiological measures (Diego Parrondo Ojanguren, 2018)

Estimation of Passenger State from Camera Data for Autonomous Driving Experiments (Thomas Marinissen, 2018)

Master Graduation Project, Faculty of Industrial Design, TU/e

COMRADE: Intelligent Driving eXperience (Sergej Gilliammo Zwann, 2016)

Motion sickness mitigation in autonomous vehicles (Nakul Shetty, 2017)

Master Graduation Project, Faculty of Mechanical Engineering, TU/e

Quantifying the perception of comfort by autonomous vehicle occupants on the basis of physiological correlates of perceived comfort (Hielke Wils, 2018)

Curriculum Vitae

Nidzamuddin Md. Yusof was born on 15 September 1982 in Johor, Malaysia. He received his Bachelor Degree (Dipl.-Ing) in Mechanical Engineering from Fachhochschule Gelsenkirchen (University of Applied Science Gelsenkirchen), Germany in 2009. As a graduate student, he worked at Arex Precision Manufacturing (Malaysia) Sdn. Bhd. as a production engineer. His professional life at the Universiti Teknikal Malaysia Melaka (UTeM) began in 2009 as a tutor in the Department of Design and Innovation, Faculty of Mechanical Engineering (FKM). In 2012, he completed his Master of Innovation and Engineering Design from Universiti Putra Malaysia (UPM), Malaysia, and one intellectual property was officially registered and secured. Upon completion of his study, he was appointed as a lecturer and became an active member at the Centre for Advanced Research on Energy (CARe), UTeM.

In 2014, he started a PhD project in the Department of Industrial Design at the Eindhoven University of Technology (TU/e), Netherlands, fully funded by Malaysian Ministry of Education (MoE) and UTeM. The research was focusing on the Comfort in Autonomous Riding Experience, of which the results are presented in this dissertation. In 2016, his PhD research received Best Presenter Award in the International Conference on Automotive Innovation and Green Energy Vehicle (AIGEV) and Best Paper Award in the International Conference on Applied Human Factors and Ergonomics (AHFE). In 2017, he received Honourable Mention Award for Work-in-Progress in the International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI).

Since 2019, he resumed his position as a lecturer at UTeM and continuing his research focusing on human factor inside autonomous vehicles.