THE INVESTIGATION OF INTERACTION MECHANISMS WITH IN-VEHICLE INFOTAINMENT SYSTEMS (IVIS)

Ayse Leyla Crossland [Eren], BEng (Hons) MSc.

Thesis submitted to the University of Nottingham for
the degree of Doctor of Philosophy

December 17th 2018

ABSTRACT

Driver distraction has been a concern for the automotive industry and for researchers in the area of driving Human Factors for decades. The increasing use of touch screens in particular as a means of enabling drivers access to infotainment functions are providing more opportunities for visual demand, leading to a higher number of off-road glances and a detrimental impact on driver performance; potentially causing a risk to the driver themselves as well as other road users. This thesis reports on five separate driving simulator studies which focus on identifying various design characteristics of in-vehicle touch screens that contribute to off-road glances. It also aims to investigate the interaction mechanisms used by drivers whilst driving that achieve non-visual interaction with the in-vehicle display.

In study one, twenty participants took part in a driving simulator study which investigated the effects of various design characteristics of an in-vehicle touch screen (button location, size and contrast level) on driver glance behaviour whilst driving. The results of this study showed that larger buttons resulted in fewer off-road glances. The results also highlighted that across all conditions the proportion of zero glance interactions was between 10 and 45 per cent showing that participants were able to perform the button selection task without taking their eyes off the road at times.

In study two, the effects of the number of items displayed on an in-vehicle touch screen on driver glance behaviour whilst driving were investigated in a simulator study with sixteen participants. The results showed that a higher number of items presented on the touch screen resulted in more glances being made away from the road. The proportion of zero glance interactions was between 12 and 24 per cent, varying based on the number of buttons displayed which indicated that participants took their eyes off the road to look at the touchscreen for most interactions, but vision was not needed for all successful target selections. Observations made of the behaviours of the participants when interacting with the touch screen and feedback they gave helped in identifying two possible interaction mechanisms for non-visual interaction; namely, peripheral vision and muscle memory.

In study three, twenty-five participants completed a driving simulator study which aimed to identify the interaction mechanisms adopted by those who were able to perform the button selection task non-visually. Two interaction mechanisms (peripheral vision and muscle memory) were tested with different sized buttons presented on the touch screen display. The results showed that participants were able to interact with larger buttons using only peripheral vision which resulted in them being able to keep their eyes on the road ahead. In contrast, muscle memory appeared to have little impact on results.

In study four, the relationships between driving complexity and the two interaction mechanisms investigated in study three were examined in another driving simulator study that involved twenty participants. The two interaction mechanisms were also compared to foveal vision to investigate how successful participants were in completing a button selection task on an in-vehicle touchscreen. The results of the study showed that although driving complexity did not impact participants’ performance, there was a considerable difference between the interaction mechanisms. In particular, a muscle memory-based interaction resulted in considerably worse task and driving performance compared to peripheral and foveal vision interactions.

In the final study, twenty participants took part in a driving simulator study in which a peripheral vision friendly interface (based on the design elements identified from the literature and the first two studies) was tested with either peripheral vision interaction or natural interaction. In the natural condition, participants were asked to interact with the touch screen as they would in a real on-road driving environment. The results of this study showed that the driving performance when interacting with the display using peripheral vision showed similarities to the performance when participants were interacting with the touch screen naturally.

In conclusion, in contrast to previous literature on the investigation of the role of peripheral vision in a driving context, this thesis investigates the role of peripheral vision in interaction with in-vehicle displays. The work highlights that peripheral vision as an interaction mechanism with in-vehicle touch screens can result in successful ‘blind interactions’ allowing drivers to keep their eyes on the road whilst driving to decrease the possibility of driver distraction caused by visual demands placed on the driver. It also shows that there are clear design elements of in-vehicle touch screens that can be used in aiding peripheral vision interaction, for example the number of items and the location of the items displayed on the screen as well as the contrast levels of the display. Future work should focus on testing in-vehicle infotainment systems present in vehicles to identify which aspects could be redesigned to support peripheral vision interaction in a real-driving environment.

PUBLICATIONS

Over the course of this research the author has published the following papers based on studies reported in the thesis:

1. **Eren, A. L.**, Burnett, G., Large, D., 2015. Can in-vehicle touch screens be operated with zero visual demand?: An exploratory driving simulator study. Proceedings of the 4th International Driver Distraction and Inattention Conference. Sydney, Australia, 9-11 November.
2. **Eren, A. L.**, Burnett, G., Harvey, C., Large, D., 2017. Exploring two interaction mechanisms for in-vehicle touch screens: Peripheral Vision and Muscle Memory. Proceedings of the 5th International Driver Distraction and Inattention Conference. Paris, France, 20-22nd March
3. **Eren, A.L.,** Burnett, G., Large, D.R. and Harvey, C., 2018 (in press). Understanding the effects of peripheral vision and muscle memory on in-vehicle touchscreen interactions. IET Intelligent Transport Systems.
4. **Crossland, A.L.,** Burnett G., Large D. R. and Harvey C., 2019 (in press). The impact of interaction mechanisms with in-vehicle touch screens on task performance. Proceedings of Ergonomics and Human Factors. Stratford, 29th April – 1st May.

ACKNOWLEDGMENTS

I would like to thank my supervisors, Dr Gary Burnett, for taking me on as his PhD student and giving me this opportunity, Dr David Large, for being there whenever I doubted myself and Dr Catherine Harvey, for always providing the different perspective I needed for my research.

I would also like to thank my fellow PhD colleagues whom I had the privilege to share my journey with. This has not been an easy process and there were a lot of instances where I was close to giving up on all the hard work. It was the conversations I have had with you along the way that has kept me sane and made me realise I am not alone in this process.

I would like to thank the participants who took part in my studies. If it was not for them, I would not have been able to collect the data that has made my work possible.

James Crossland, a lot has happened in my personal life during my PhD and you were there for most of it! Thank you for your patience over the last three years and for providing me with endless Excel support.

Finally, I would like to dedicate this PhD to my mother. Being raised by an engineer mother has had a significant influence on the way I see the world. A perspective which I would not have been able to get from any educational institution. If it was not for her support and her faith in me, I would not be where I am today. Thank you, Mum, for making all this possible for me.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

HCI	Human-Computer Interaction
HMI	Human-Machine Interface
HUD	Head-up Display
HVAC	Heating, ventilation and air conditioning
IVIS	In-vehicle Information System
MRT	Multiple Resource Theory
Satnav	Satellite Navigation
ADAS	Advanced Driver Assistance System
USP	Unique Selling Point
RT	Reaction Time
SDLP	Standard Deviation of Lane Position
SDS	Standard Deviation of Speed
TEORT	Total Eyes off Road Time

1 CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

There has been a significant increase in in-vehicle technologies over the last decade, including new forms of display such as touch screens and head up displays (HUDs) (Becker, Hanna and Wagner, 2014). In-vehicle infotainment systems (IVIS) are defined as "*the collection of features and functions in vehicles that allow motorists to complete tasks unrelated to driving while operating the vehicle*" (Strayer *et al.*, 2017, p. v). These systems make use of audio/video interfaces, touchscreens and keypads for drivers and passengers to interact with. IVIS were first introduced to cars in the 1930s starting with the in-car radio. The 2000s became an introduction to connected and smart cars for the automotive industry (O'Brian, 2015). The interactive nature of these new systems gradually increased, allowing drivers to perform a greater number of secondary tasks in addition to driving. The way drivers are able to interact with the systems also changed due to the gradual replacement of physical dials and knobs with touch screen surfaces. Moreover, it is apparent that touch screen sizes within vehicles are rapidly growing in size (Rümelin and Butz, 2013).

As people are becoming more 'connected' in every aspect of their lives, car manufacturers are creating in-vehicle systems that facilitate the drivers' need to be connected even when they are driving. In 2016 BMW released their 7 series which allows drivers to answer/reject calls, interact with the map and adjust the audio using gesture control (BMW, 2016). Similarly, Audi's Audi Connect infotainment system provides access to more connected features such as WiFi and social media (Audi, 2018). Another car manufacturer Tesla offers a 17-inch touch screen in all of their models as a standard on which they offer over-the-air updates to introduce new features and functionality as they are released (Tesla, 2018). Car manufacturers now aim to design in-vehicle infotainment systems that are more seamless and sophisticated which they believe will significantly improve the driving experience. The extent of the functions the new systems offer is significantly greater than those that were made available on traditional displays. In addition to functions available on traditional displays (e.g. temperature control, navigation and audio entertainment); the recent technologies allow drivers to perform tasks such as browsing the web, bringing the desktop browsing experience into the vehicle and checking vehicle dynamics and performance whilst driving. It is estimated that by 2020 globally the car infotainment market will be worth 35.2 billion US dollars (Global Industry Analysts, 2018) and that 98 per cent of new cars sold will have access to the internet (Statista, 2015).

Whilst conventional displays are limited to the initial design (i.e fixed physical controls) and are not capable of updates, touch screens offer various advantages such as dynamic controls which can be changed depending on the functions that are desired to be added to the system (McGookin, Brewster and Jiang, 2008). They are also capable of presenting numerous functions on one display (Lee & Kantowitz, 2005). This for example makes navigation easier for drivers by presenting real-time information on traffic, incidents, delays and potential hazards on the road in advance (May, Ross and Osman, 2005).

As a result of all the advancements in the design of in-vehicle systems it is important for driving researchers to gain a better understanding of the impact of these changes on display design and consequently on the way drivers adapt their behaviours when interacting with the new technologies compared to traditional displays. Even in comparison to a decade ago the technological developments in in-vehicle systems have changed the driving experience significantly. Some of the functions provided by the new systems are now becoming an integral part of the driving experience for many of the drivers rather than being presented as optional features. Many changes are implemented in legislation to adapt to the changes in the systems. For example, as the use of satellite navigation systems (SatNav) have become very common, new drivers will now be expected to use them in their driving tests to make sure they are capable of using such systems whilst driving (Driver and Vehicle Standards Agency, 2017). Governments are also investigating current Advanced Driver Assistance Systems (ADAS) to be able to update legislation to keep up with the advances in driving related technologies (Department for Transport, 2017). However, there is still a lack of change in existing design guidelines to accommodate the changes in technology.

1.2 TOUCH SCREENS IN DRIVING AND OTHER DOMAINS

The first touch screen was purportedly introduced in 1965 by E.A. Johnson to support air traffic controllers (Orphanides and Nam, 2017). Johnson believed that a touch screen connected to a computer could be used as a keyboard (Johnson, 1965). Following that in 1971 touch screens were introduced to the public domain via automated teller machines (ATMs) and information kiosks. In 1983 Hewlett-Packard (HP) aimed to offer an intuitive technology by combining the touch screen technology with personal computers (Caprani, O'Connor and Gurrin, 2012). Due to the various domains where touch screens are used and the many users who interact with them there has been a considerable amount of research on interface design for touch screens and its various design characteristics such as button size and spacing and their effect on user performance (Sesto *et al.*, 2012).

Touch screens overall have several advantages and disadvantages. According to Shneiderman (1991), compared to other devices a touch screen is the fastest pointing device as well as providing an easier hand-eye coordination compared to mice or keyboards. When picking from several choices on a visual display, the use of touch screens requires little thinking and facilitates direct manipulation which is easy to learn. He also suggests that touch screens do not require extra workspace unlike some other pointing devices. Specifically in a driving context, touch screens allow direct inputs onto the display (Taveira and Choi, 2009). As the displays in the vehicle are within the reach of the driver this provides a style of interaction during which the eyes see what the hands do (Dul and Weerdmeester, 2003). According to Rogers et al., (2005) this results in increased user acceptance. Pointing gesture interaction is also considered to be more intuitive and easier to learn by novice users (Greenstein, 1997; Rydström *et al.*, 2005). On the other hand, there are some disadvantages particularly in relation to the way users interact with touch screens such as; the possibility of the users' hand obscuring the screen and the user not having enough flexibility with the screen's position which may result in arm fatigue (Shneiderman, 1991; Bhalla and Bhalla, 2010).

1.3 DRIVER DISTRACTION

Although touch screens in vehicles may improve the driving experience in many ways as noted above, one of the major – and potentially most concerning - disadvantages of the use of in-vehicle touch screens is the potential for distraction when used whilst driving (Burnett, Summerskill and Porter, 2004). The lack of tactile feedback for touch screens can result in a higher mental load (Rümelin and Butz, 2013). Especially for secondary tasks where they may not be immediate feedback in other ways (e.g. volume going up, air conditioning fan speed slowing down) without tactile feedback from the screen it is difficult for the driver to know whether or not they have made a successful selection. There is ongoing research looking at ways to introduce tactile feedback onto in-vehicle touch screens (Akamatsu, MacKenzie and Hasbroucq, 1995; Richter *et al.*, 2010). Although tactile feedback may help with certain aspects of the interaction to decrease visual demand, it still does not lead to interaction with the IVIS without any visual demand (Bellotti *et al.*, 2005). In-vehicle touch screen displays also allow for more visual information to presented to the driver at a given time which can result in visual distraction (Kujala, 2013). It is widely known that visual distraction is a key cause of car incidents and crashes (Klauer *et al.*, 2006). According to NHTSA in 2013 10 per cent of fatal crashes, 18 per cent of injury crashes, and 16 per cent of all police-reported motor vehicle traffic crashes in the US were reported as distraction-affected crashes (NHTSA, 2013). In 2015, in the UK, 27 per cent of recorded fatal crashes that resulted in one or more deaths have been as a result of failure to look, and a further 7 per cent has been a result of in-vehicle distractions, distractions outside the vehicle and phone use (Department for Transport, 2016). According to NHTSA in 2015, in the US, 3,477 were killed and 391,000 were injured as a result of driver distraction (NHTSA, 2015). In 2016, 9.2 per cent of total fatalities were distraction related fatalities (NHTSA, 2017).

Driving is known to be a highly visual task (Owsley *et al.*, 1999). Drivers typically spend approximately 90 per cent of their time looking at the road ahead when driving (Burnett and Joyner, 1997). Hence it is crucial that drivers keep their eyes on the road ahead whilst driving. Driver distraction has been a major part of driving research for years. Even before in-vehicle infotainment displays and mobile phones existed, driver distraction was a concern (Brown, Tickner and Simmonds, 1969) and driver distraction is now a globally acknowledged road safety issue (Regan, Lee and Young, 2009). Driving is a complex task and anything that is not related to the primary task of driving has the potential to cause distraction for the driver. With the increase in the implementation of IVIS and the amount of information accessible to the driver within the vehicle, it is important now more than ever to focus on finding solutions to mitigate driver distraction caused by in-vehicle displays.

1.4 EXISTING DESIGN PRINCIPLES FOR IN-VEHICLE SYSTEMS AND TOUCH SCREENS

Although there has been an increase in the use of touch screens in vehicles, there is still a lack of Human Factors design guidelines for the new technology

(Harvey, Stanton, Pickering, Mike McDonald, *et al.*, 2011a; Feng, Liu and Chen, 2017a). The guidelines and recommendations that do exist are mainly based on traditional display and control design and do not consider the new touch screen displays specifically. Compared to touch screen display interaction, traditional knobs and dials provide the potential for non-visual interaction (Burnett and Porter, 2001). This is because of the user's ability to get used to where the buttons are placed with the help of proprioception and muscle memory as well as the existence of tactile feedback during the interaction (Lauber, Follmann and Butz, 2014). However, touch screens do not provide an equivalent form of tactile feedback and also require more precise hand-eye coordination (Stevens *et al.*, 2002). Moreover, there are various tasks that might be more difficult to perform using touch screens compared to traditional interfaces that use push-buttons and dials – for instance, data entry and selection on a continuous scale. Due to the lack of tactile feedback from touch screens, the drivers are not able to perform touch screen tasks relying on the feel and location of the target buttons and, as a result, are encouraged to take their eyes off the road to look at the screen in order to locate the target (Burnett and Porter, 2001; Rydström *et al.*, 2005).

There are existing guidelines on the design of traditional displays that incorporate buttons and dials (SAE 2119, 1997; Stevens *et al.*, 2002; ISO 2575, 2010). Due to the nature of traditional displays/controls, these existing guidelines tend to focus on buttons and dials or lightly touch on brief guidelines for earlier versions of in-vehicle touch screens. The capabilities of the screens used in cars have significantly improved since the early 2000s. A set of guidelines were produced by Stevens et al., in 2002 to address the safety (including distraction) of in-vehicle information systems. These guidelines focus on input controls, visual displays and auditory information as well as system assessment and driver dialogue management. However, the section dedicated to touch screen controls is very brief and the authors highlight the fact that the generations of touch screens available at the time the guidelines were written were not suitable for use in vehicles due to the lack of tactile feedback resulting in high visual demand and drivers taking their eyes off the road for longer periods. However, they suggest the following guidelines if touch screens are used in-vehicles. The guidelines state that "*they should be simple to use and suitable for the function they serve, should work with light positive pressure for activation*" and "*provide auditory control activation feedback*" (Stevens *et al.*, 2002, p. 22). Another set of guidelines produced by Campbell et al., (2004) focus specifically on icons for in-vehicle displays with no mention of touch screens.

There have been efforts in research to identify design guidelines and recommendations for the new touch screen interfaces. A number of studies conducted by various researchers have attempted to address some of the issues around the use of touch screen displays in cars. For example, a study conducted by Kujala and Saariluoma (2011) investigated the effects of two different touch screen menu structures – grid and list layout – the number of items displayed on the screen and the scrolling method that is used to go through the list of items – arrow buttons, swipe and kinetic – on glance behaviour. Their results showed that as the number of items displayed on the screen increased, glance duration significantly increased. Another two studies conducted by Kujala and Salvucci (2015) and Salvucci and Kujala (2016) showed that the number of off-road glances significantly increased when there were a larger number of items displayed on the screen. There are also guidelines that encourage limiting interaction with in-vehicle touch screen displays due to their contribution to driver distraction based on the reasons mentioned above. For example, the NHTSA guidelines state that the IVIS should be designed in a way so that the driver does not take their eyes off the road ahead for more than 2 seconds at a time and the total glance off road time for any given task is not more than 12 seconds (NHTSA, 2013). Nevertheless, there is still a gap in driving research specifically focusing on display design for touch screens and design factors such as size of buttons, location of buttons and contrast levels of displays.

1.5 VISUAL DEMAND OF IN-VEHICLE SYSTEMS

As highlighted above, the visual demand caused by the introduction in-vehicle touch screens can have a detrimental impact on driver performance. In order to address this issue, it is important to explore ways to design interfaces which decrease the visual demand required from the driver when interacting with such systems. To do so, there is a need to better understand the ways drivers currently interact with in-vehicle touch screens.

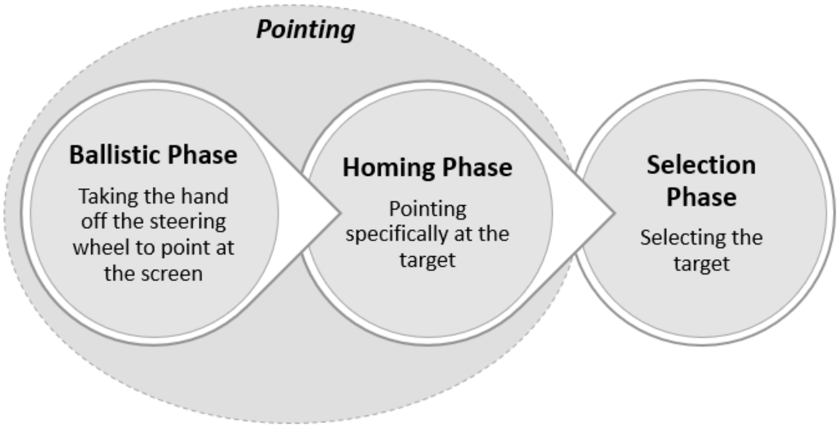


Figure 1. Stages of a target selection task on an in-vehicle display

Drivers follow a certain process when performing a target selection task on an in-vehicle display which comprises of three visual stages as seen in Figure 1. The process starts with the driver initiating the 'aiming' phase of the interaction process which starts with the driver taking their hand off the steering wheel followed on by moving their hand closer to the desired target on the display. Aiming movements comprise of two phases according to Woodworth (1899); *initial impulse phase* and *current control phase*. During the initial impulse phase (also referred to as the 'ballistic' phase), the hand/finger is brought to the vicinity of the target. This is followed by the current control phase (also referred to as the 'homing' phase) during which proprioception is used to make necessary adjustments in the movement to successfully touch/press the target (Elliott *et al.*, 2001; Biswas and Langdon, 2012). Following the 'aiming phase' the driver makes their selection by pressing the button – or in the case of touch-screens, touching the display. Research shows that people have a natural tendency to direct their gaze at the target they are going to select as they start moving their hand towards the target and they keep their gaze on the target until they actually make the selection (Desmurget *et al.*, 1998; Neggers and

Bekkering, 2000; Gribble *et al.*, 2002; Crawford, Medendorp and Marotta, 2004).

If the vehicle is stationary when the driver is completing a target selection task, then they would be expected to be looking at the display for all three stages of the process as there is no other task that requires their visual attention. However, in a driving context the driver needs to be able to keep their eyes on the road as much as possible to safely perform the longitudinal and lateral vehicle control task, whilst also being aware of hazards. Hence it is important to identify approaches and methods to address the visual distraction issues for each step of this process to discourage the driver to take their eyes off the road.

It is important to focus on aiming for non-visual interaction rather than just focusing on low visual demand. Literature shows that any off-road glances made by the driver whilst driving could have a detrimental effect on driving performance (Burnett and Joyner, 1997; Hatfield and Chamberlain, 2005; Funkhouser and Chrysler, 2007; Salvucci *et al.*, 2007; Chisholm, Caird and Lockhart, 2008). Hence decreasing visual demand caused by in-vehicle displays does not necessarily solve the issue of drivers taking their eyes off the road to interact with these displays. Whereas the focus of non-visual interaction is that foveal vision should not be required at all during the interaction with the display. Following on from that, it is also important to consider - if non-visual interaction is facilitated - how this type of interaction currently arises naturally, when drivers interact with certain in-vehicle controls whilst driving (Burnett and Porter, 2001). It is crucial to understand how drivers achieve non-visual interaction, so systems could be designed in a way that can accommodate this type of interaction to allow drivers to achieve successful zero glance interactions. Other non-visual modalities do exist such as haptic and auditory feedback and have been widely studied however these modalities have their own limitations such as annoyance (Absar and Guastavino, 2008; Adell, Várhelyi and Hjälmdahl, 2008; Politis, Brewster and Pollick, 2014), social disturbance (Ege, Cetin and Basdogan, 2011; Väänänen-Vainio-Mattila *et al.*, 2014) and negative effect on driving performance (Christiansen *et al.*, 2011). A breakdown of these modalities is provided in the literature review (section 2.5.2) discussing the advantages and disadvantages of each of them in detail.

1.6 RESEARCH AIM AND QUESTIONS

The overall aim of this research is to understand the underlying mechanisms that will facilitate non-visual interaction with in-vehicle touchscreens. To enable the overall aim to be addressed, the work aims to answer the following research questions that address various aspects of the overall aim.

> RQ1. What are the design characteristics of in-vehicle touch screens that can help in achieving non-visual interaction?
>
> RQ2. What are the interaction mechanisms adopted by drivers to achieve non-visual interaction when interacting with in-vehicle displays?
>
> RQ3. What is the relationship between the design characteristics and interaction mechanisms in a driving environment?

1.7 STRUCTURE OF THESIS AND SYNOPSIS

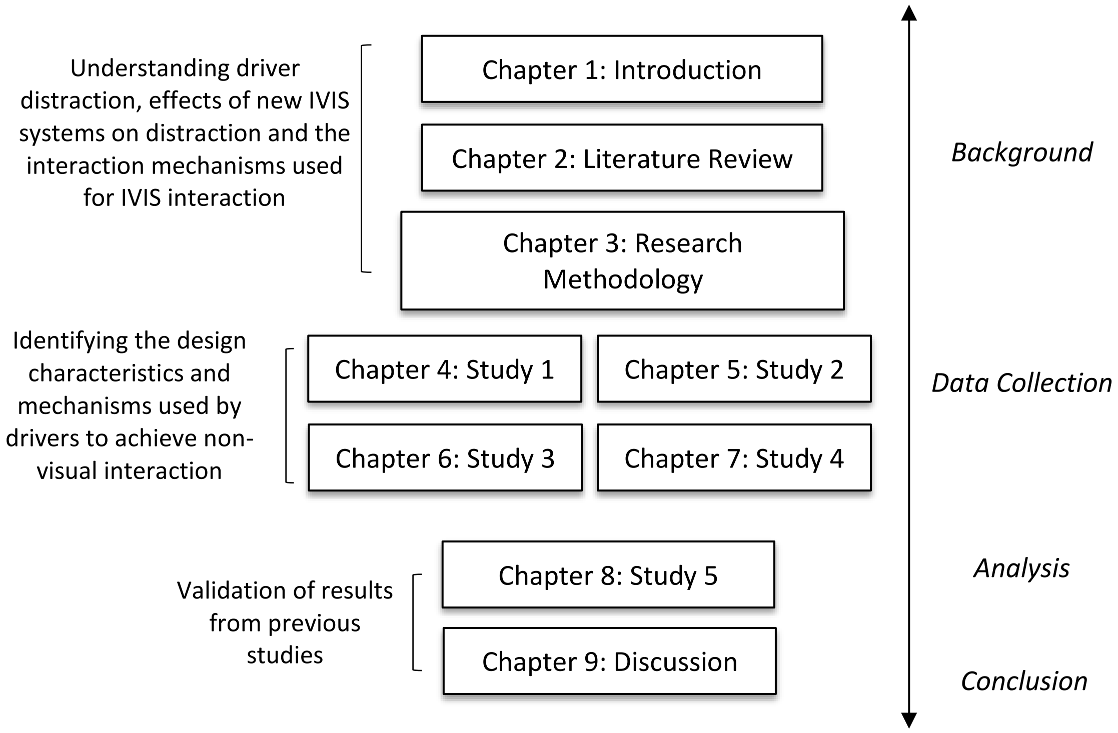


Figure 2. Outline of thesis

The structure of the thesis is shown in Figure 2, outlining each chapter. Chapter one introduces the research, including the rationale, aims and objectives, research questions, research setting and an outline of the thesis.

Chapter two is a literature review of the work surrounding driver distraction (definition and types). It focuses on visual distraction caused by the visual demand posed on the driver by secondary tasks, especially in-vehicle displays. It highlights the role of vision in driving detailing the differences between the use of foveal and peripheral vision in a driving context. This chapter also discusses muscle memory as a mechanism for interacting with in-vehicle displays, as well as some of the design elements that are relevant to in-vehicle display design.

Chapter three describes the methodological approach taken in this research focusing on the use of driving simulation in research. The chapter outlines some of the equipment used in the user trials conducted as part of this research and the reasons of choosing these specific tools and methods. It also describes the measures that were collected during the user trials.

Chapter four details a driving simulator study involving 24 participants which aimed to observe the effects of button location, button size and contrast level displayed on an in-vehicle touch screen on glance behaviour whilst driving, in order to understand the visual demand caused by these specific design elements. Results highlighted that button size had a significant impact on the number of off-road glances, resulting in higher glance frequency for smaller buttons.

Chapter five describes a driving simulator study involving 16 participants which aimed to observe the effects of the number of buttons displayed on an in-vehicle display on glance behaviour whilst driving. Results showed that the number of buttons displayed on the screen had a significant effect on the number of off-road glances. Both studies detailed in chapters four and five also highlighted that some participants in certain conditions were able to perform the button selection task on the touch screen completely non-visually in a natural way.

Chapter six describes a study involving 25 participants which aimed to understand the interaction mechanisms needed to achieve non-visual interaction. This study observed the effects of two different interaction mechanisms (muscle memory and peripheral vision) combined with three different button sizes on secondary task time. Results showed that secondary task time was significantly lower when participants were using peripheral vision to complete the button selection task when compared to muscle memory.

Chapter seven describes a driving simulator study involving 20 participants which aimed to observe the relationship between driving complexity and three different interaction mechanisms when interacting with the in-vehicle display. Results of this study highlighted that relying on muscle memory resulted in significantly poorer secondary task performance compared to peripheral and foveal vision. It showed that the results from peripheral and foveal vision interaction were similar.

Chapter eight details the final driving simulator study involving 20 participants which aimed to compare peripheral vision and natural interaction with a peripheral vision friendly display. Natural interaction involved participants interacting with the in-vehicle display as they would in a real driving environment. The results highlighted the similarities between peripheral vision and natural interaction in terms of the time taken to complete the target selection task or the number of errors made during the target selection task.

Chapter nine discusses the main findings of the research and relates them back to existing research in this area. It revisits the research aim and questions introduced in chapter one and recounts the findings from the studies back to these. Overall contributions of the work are highlighted, and limitations are discussed.

2 CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The concepts discussed in the first chapter are detailed in this literature review drawing on existing literature not just in driving research but other research areas that are relevant to the ideas covered in this thesis. Driver distraction is defined with a focus on visual distraction. The contributors to visual distraction are outlined with a focus on in-vehicle displays. The relationship between the driving and secondary task and the effects of distraction caused by secondary tasks on driving performance and glance behaviour are detailed. The design characteristics that have the potential to contribute to non-visual interaction as well as the potential interaction mechanisms that are adopted by drivers for non-visual interaction are discussed.

2.2 DRIVER DISTRACTION

In a driving context the primary task is considered as the driving task which includes controlling the vehicle by steering and changing speed. As this is the main task the driver needs to be engaging with in a driving context it is important that they are focused on the primary task for road safety reasons. Any other task that is not driving related – mainly the functions that are made available via the IVIS – are considered to be secondary tasks (Geiser, 1985; Wierwille, 1993b; Richter *et al.*, 2010). Hence for the purposes of this thesis the tertiary tasks defined by Geiser will be referred to as secondary tasks.

The primary task of driving entails multi-tasking. It is a task that requires a lot of visual attention from the driver to be focused on the road ahead. It also requires the driver to be aware of their surroundings such as other road users including other vehicles on the road, cyclists and pedestrians. It comprises of the driver checking their mirrors continuously to obtain information about their surroundings. Drivers use their hands to steer which contributes to the directional movement of the vehicle and they use their feet to control the speed which contributes to the longitudinal control of the vehicle. Figure 3 shows the three hierarchical categories of driving. The control category represents the positioning of the vehicle on the road in terms of lanes. Manoeuvring consists of the vehicle's position on the road in relation to other road users such as drivers, pedestrians etc. And finally the navigation category entails choosing a destination and navigating to it (Reyes and Lee, 2004).

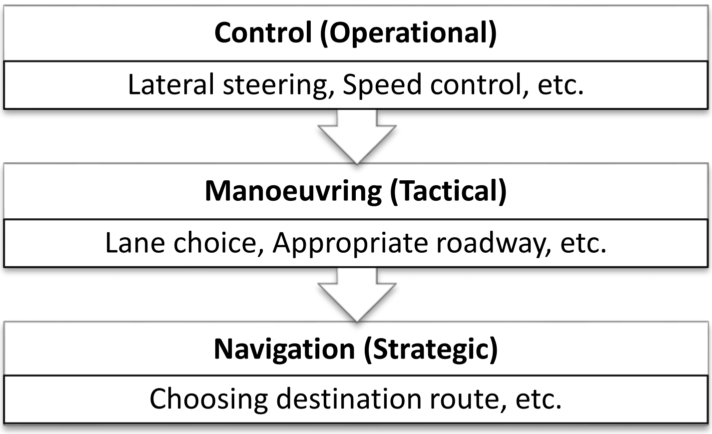


Figure 3. Three hierarchical categories of driving [diagram based on (Michon, 1993; Koppinen, 2000)*]*

As suggested by Wierville there are five types of secondary task the driver can perform in the vehicle and these are based on the demand required from the driver by the task (Wierwille, 1993b). These are;

- Manual only – these tasks are performed by hand and could be performed non-visually after enough practice (e.g. opening the window),

- Manual primarily – these tasks require vision to a certain extent to find the control and determine its present state before making any adjustments,
- Visual only – these tasks are mainly visual and used for gathering information without any manual input from the driver,
- Visual primarily – these tasks although rely on vision they also require manual input from the driver,
- Visual – manual – these tasks require the driver to gather information visually and then use this information to perform a manual input or sequential manual inputs (Pickering, Burnham and Richardson, 2007).

Secondary tasks have the potential to result in driver distraction if they are using the same resources required by the driving task. As discussed previously driver distraction is a major contributor to road accidents. It is also an issue researchers and car manufactures have been working on addressing for decades. There are various definitions of driver distraction in the literature. In 2005, Pettitt, Burnett and Stevens provided the following definition for driver distraction based on existing literature and accident statistics which is the definition used in this thesis.

"*Driver distraction occurs when:*

- *A driver is delayed in the recognition of information necessary to safely maintain the lateral and longitudinal control of the vehicle (the driving task) (Impact)*
- *Due to some event, activity, object or person, within or outside the vehicle (Agent)*

- *That compels or tends to induce the driver's shifting attention away from fundamental driving tasks (Mechanism)*
- *By compromising the driver's auditory, biomechanical, cognitive or visual faculties, or combinations thereof (Type)."* (Pettitt, Burnett and Stevens, 2005, p. 11)

There are four types of distraction; visual, auditory, cognitive and physical (biomechanical). Visual distraction is caused by the driver taking their eyes off the road and focusing their attention on another target for an extended period (e.g. adjusting the radio). Auditory distraction is caused by the driver focusing their attention on auditory signals rather than the road ahead. Physical distraction is a result of the driver taking their hands off the steering wheel for extended periods of time to physically interact with another target. And finally cognitive distraction includes any thoughts that absorb the driver's attention to the point that they are no longer able to navigate through the road environment safely (Pettitt, Burnett and Stevens, 2005; Regan, Lee and Young, 2009).

There are numerous existing studies that explore cognitive and visual distraction in driving due to secondary tasks. In some cases, different types of distractions can occur simultaneously, caused by the same secondary task. Different types of distractions are not necessarily exclusive, as shown in a number of studies in the literature. For example, a source of distraction that may result in physical distraction may also simultaneously result in cognitive distraction. A study was conducted by Sonnleitner et al., observing the effects of an auditory secondary task on drivers' mental demand. The study was conducted on a non-public test track and two measures were recorded; provoked reaction to brake lights and brain activity. The results showed that brake reaction times and brain activity were significantly higher while participants drove with the auditory secondary task (Sonnleitner, et al., 2014). The use of a mobile phone whilst driving (although this has been made illegal in several countries and people use hands free instead) is a good example of the combination of multiple types of distraction. It could cause drivers to take their eyes off the road, their hands off the steering wheel and their cognitive attention off the road. There is evidence showing that the use of a mobile phone when driving can cause distraction which may result in longer reaction times, inability to keep in the correct lane and an overall reduction in awareness (World Health Organisation, 2011). The effects of driver distraction on driving performance have been clearly established in driving research. A study conducted by Engstrom et al., aimed to investigate the effects of visual and cognitive demand on driving performance in simulated and real motorway driving. The results showed that visual demand resulted in reduced speed and increased lane deviation. On the other hand, although cognitive demand did not have an effect on speed it resulted in reduced lane keeping variation and increased gaze concentration toward the centre of the road (Engström, Johansson and Östlund, 2005). A driving simulator study conducted by Horberry et al. (2006), observed the effects of two different in-vehicle tasks (auditory and visual-manual) in two different driving environments (simple and complex) among two groups of drivers (younger and older). The results of the study showed that both in-vehicle tasks had a negative effect on driving performance for both driving environments and age groups with the visual-manual task being more distracting than the auditory task. This is due to the visual-manual task sharing more resources with the primary task of driving compared to the auditory task due to its visual nature (Wickens, 1984, 2008). Other researchers have also shown that if the driver is performing a secondary task that is as highly visually demanding as the driving task, detriments to driving can occur such as a decrease in lateral control (Engström, Johansson and Östlund, 2005; Jamson and Merat, 2005; Törnros and Bolling, 2005).

Driver distraction is not only caused by demanding secondary tasks within the vehicle but could also be caused by the road environment. One of the contributors to this is roadside advertisements. A study conducted by Horberry (1998) showed the effects of visual advertisements on the roadside on glance behaviour. The results showed that drivers took their eyes off the road to look at the ‘visual clutter’ 14 per cent of the total driving time. In their literature review of the effects of roadside adverts Cairney and Gunatillake (2000) identified that road safety played a part in the regulations for roadside adverts. Ho et al., (2001) showed that the effects of roadside adverts could have an increased negative effect on older drivers by leaving them with a decreased visual and cognitive capacity to associate with the driving task. Although it is not just older drivers that may be affected by the distracting effects of visual clutter in the road environment. A study conducted by Horberry et al., (2006) investigated the relative effects of in-vehicle distraction and roadway visual clutter and the interaction between the two causes of distraction on three different age groups (young, mid-age and older drivers). They observed the effects of these causes of distraction on driving performance, response to hazards and perceived mental workload. The results of their study showed that the detriment of the secondary in-vehicle task was similar during different levels of visual clutter. They also showed that older drivers drove at lowers speeds during high visual clutter.

A driving simulator study conducted by Haigney et al., (2000) investigated the effects of interacting with a hands-free mobile phone whilst driving on driving performance. Their results showed that interacting with the mobile phone resulted in decreased mean speed and standard deviation of accelerator travel. Another driving simulator study conducted by Rakauskas et al., (2004) investigated the effect of having a naturalistic conversation using a mobile phone on driving performance. Their results showed a decrease in mean speed and an increase in speed variability. A study conducted by Chiang et al., (2004) found a decrease in speed in situations during which the driver was interacting with the navigation system. Kass et al. (2007) conducted a study which showed that the use of cell phones had a detrimental effect on driving performance for both novice and experienced drivers. As discussed by Horberry et al., (2006) the decrement in speed could be caused by either the drivers lowering their expectations of their driving performance whilst engaging in a secondary activity or them allocating more attention to the secondary task than the primary task of driving that their driving performance suffers. Increasing the distance between the car ahead and their own vehicle – following distance – can also be an indication of distraction. Two studies conducted by Strayer and colleagues investigating the effects of hands-free phone conversation on driving performance showed that the distance from the lead vehicle increased – especially during heavy traffic conditions - (Strayer, Drews and Johnston, 2003) and that the following distance increased by 12 per cent (Strayer and Drews, 2004). Jamson et al., (2004) conducted a driving simulator study during which they asked drivers to interact with a speech-based system to process emails. Their results showed that the headway from the vehicle in front increased when they were interacting with the system. These three studies showed that although the secondary demanding task increased headway distance, this distance still was not enough to avoid collisions (Young and Regan, 2007).

The unsuccessful distribution of bandwidth that is required by the primary and secondary tasks is what results in driver distraction. Multiple resource theory (MRT) can aid in understanding this (Wickens, 2008). According to MRT two tasks that compete for the same resource can cause issues as the bandwidth may not be enough within that source to sustain both tasks simultaneously. If a visually demanding secondary task is performed whilst driving – which is known to be a highly visual task (Burnett and Joyner, 1997) – the secondary task will have a detrimental effect on driving performance as both tasks the driver is engaging in require visual attention (Koch, 2004). This will also impact the performance of the secondary task as the attention is shared between the primary and secondary task (Sanders and McComick, 1993).

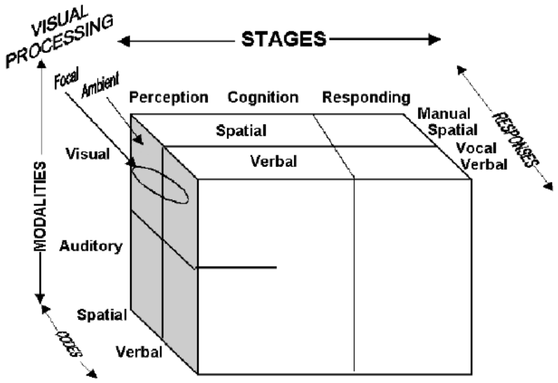


Figure 4. Multiple Resource Theory (Wickens, 2008)

As seen in Figure 4 there are three resources that are considered by MRT to be limited in capacity; processing stages, response and modality. Task performance is best when the overlap in the resources required is minimum. For example, according to MRT, as driving is a highly visual task, any auditory or audio-visual secondary task would be less detrimental to the driving task than a purely visual secondary task (Parkes and Coleman, 1990; Lui, 2001). This is due to the competition for bandwidth within the same resource. When the driver is performing a purely visual task whilst driving, it is the high demand on a single resource that results in a degradation of potentially both the driving and secondary task performance. When performing two tasks simultaneously humans reduce attention on one task whilst attending the other task to compensate for the limitation of bandwidth. However it is important to remember any secondary task that may not require the same resource as the driving task could still have a detrimental effect on driving performance as all tasks require a certain amount of central processing (Regan, Lee and Young, 2009).

There are many studies in literature that discuss the effects of visual distraction on a number of measures such as driving performance, glance behaviour and secondary task performance. Visual distraction in a driving context is experienced if the driver is expected to or has chosen to perform a secondary task that poses visual demand and consequently is competing for resources with the driving task. ISO defines visual demand as the "*degree or quantity of visual activity (determined by e.g. number of glances, total glance time) required to extract information from an object to perform a specific task"* (ISO 15007-1, 2014, p. 3). The visual demand imposed on the driver by the IVIS inherently result in distraction, by creating situations for the driver during which they are required to time share their visual resources between driving and the secondary tasks. A way to measure the visual demand placed on the driver by the IVIS is the use of eye movement measures such as glance frequency and mean glance duration (Schall *et al.*, 2012; ISO 16673, 2017). It has been established in literature that during visual secondary task performance the driver's gaze moves between the driving and secondary task (Wierwille, 1993a; Sodhi, Reimer and Llamazares, 2002) and the more visually demanding the secondary task is the higher number of switches of the glance between the driving and secondary task (Antin *et al.*, 1990; Sodhi, Reimer and Llamazares, 2002; Chiang, Brooks and Weir, 2004; Victor, Harbluk and Engström, 2005). A review of the literature conducted by Metz in 2009 showed that glance frequency of off-road glances ranged between 2.2 and 13.8 depending on the visual complexity of the secondary task (Metz, Schömig and Krüger, 2011). Other studies in literature propose various thresholds for mean glance duration can range from 1.6s (Wierwille and Tijerina, 1998), 2s (Zwahlen, Adams and DeBals, 1987; Klauer *et al.*, 2006) and at times even 4s (Ito and Miki, 1997) which is higher than the mean glance duration threshold set by the NHTSA guidelines (NHTSA, 2013).

When interacting with secondary tasks and driving simultaneously drivers try to compensate for the extra demand which they cope with by changing their driving behaviour. This is the drivers' attempt to free up more resource by reducing the demand from the primary task to be able to cope with the demands of the secondary task which usually requires the same resources as the primary task. It has been discussed in literature that when visual attention is diverted from the road ahead the driver struggles to give tracking response (steering wheel angle) and as a result may weave between lanes or completely move away from the lane they are in (Godthelp, Milgram and Blaauw, 1984). Studies have also shown that increased visual demand has a decremental effect on lane keeping (Zwahlen, Adams and DeBals, 1987; Greenberg *et al.*, 2003; Tsimhoni, Smith and Green, 2004; Boyle *et al.*, 2013; Bao *et al.*, 2015; Pavlidis *et al.*, 2016) which evidently result in the driver trying to correct lane keeping errors by performing larger steering movements which are more disruptive than normal driving (Macdonald and Hoffmann, 1980). Studies have also shown that high visual demand results in slower speeds (Curry, Hieatt and Wilde, 1975; Antin *et al.*, 1990; Haigney, Taylor and Westerman, 2000; Burns *et al.*, 2002; Rakauskas, Gugerty and Ward, 2004; Strayer and Drews, 2004) which has been interpreted as the driver's attempt in reducing the demand of the driving task to be able to attend to the secondary task. There is also evidence to show that visual-manual secondary tasks can have a degrading effect on headway control (Strayer, Drews and Johnston, 2003; Jamson *et al.*, 2004), braking behaviour (Harbluk, Noy and Eizenman, 2002; Lansdown, Brook-Carter and Kersloot, 2004), response to hazards on the road (Greenberg *et al.*, 2003; Horrey and Wickens, 2004a) and an increase in crash risk or accidents (Wierwille and Tijerina, 1998; Horrey and Wickens, 2007).

Some of the studies in literature that focus on the effects of visual distraction on driving performance, glance behaviour or secondary task performance at times include a cognitive distraction element to them due to the tasks the drivers are asked to perform. An example is a study conducted by Engstrom et al., (2005) which compared the effects of cognitive and visual load by comparing subjective and objective driving performance and glance behaviour data from simulated and motorway driving. Their results showed that visual and cognitive load had different effects on driving performance as visual demand resulted in reduced speed and increased variation in lane keeping. Jamson and Merat (2005) investigated the effects of two tasks that required interaction with the IVIS – visual (which was to create more visual demand for the driver) and auditory (which was the create more cognitive demand for the driver) – on various aspects of the driving performance. Their study took place in a high-fidelity driving simulator and 48 participants were asked to follow a lead car in the simulator. They also presented their participants with various driving complexities. Their results showed that participants reduced their driving speed during both secondary tasks to compensate for the extra demand and the visual task had a greater adverse effect on speed. The authors also highlighted the importance of driving performance measures when it comes to assessing in-vehicle display design. They highlighted that reduced driving performance – such as shorter time-to-collision and slower response to hazards - whilst interacting with secondary tasks can be an indication of the negative effects of the design of IVIS (Jamson and Merat, 2005).

As visual distraction is a contributor to road accidents it is crucial to understand the impact of IVIS design on the visual demand caused by such systems. In-vehicle displays, especially the newer ones are designed to be highly visually demanding due to the increased size of the displays, the increase in the functions provided to the driver whilst driving and the lack of physical buttons and dials. Understanding the different elements of display design that contribute to visual demand can help designers choose less visually demanding elements for their designs which allow the driver to keep their attention on the road ahead. As stated by Harvey and Stanton (2012), there are a number of guidelines provided for IVIS design (Stevens *et al.*, 2002; Bhise, Dowd and Smid, 2003; Japan Automobile Manufacturers Assosciation, 2004; Commission of the European Communities, 2008) however there are no set industry standards. Particularly in the recent years as developments in in-vehicle technologies have progressed and touch screens in vehicles have become a common display type, there is especially a lack of guidelines or checklists specific to the utilisation of touch screens in vehicles. An example of one of the existing guidelines is one produced for Transport Research Lab (TRL) by Stevens et al., (2002) which have a small section on touch screen specific controls and state that touch screens at the time of the guidelines being written were not appropriate for mobile use and should not be used in a vehicle due to the distraction they might cause the driver. Another set of guidelines produced by the Japan Automobile Manufacturers Association (JAMA) (2004) do not specifically discuss interface design for in-vehicle touch screens but provide general guidelines about how information should be presented (both auditory and visual) with a focus on more traditional displays in vehicles and highlight that the information presented should not be distracting. Similarly a set of guidelines prepared by the Alliance of Automobile Manufacturers (AAM) (2006) focus on design guidelines for more traditional displays.

Nevertheless, there is a considerable amount of research investigating the different design aspects of displays in general outside of the driving context which are discussed in more detail in section 2.4 of this chapter. It is useful to consider these findings when designing touch screen displays for vehicles as there is some learning that can be adopted when designing in-vehicle interfaces.

2.3 DRIVING SAFETY

There are numerous studies in literature discussing the implications of HMI design on driving safety highlighting the potential negative consequences of poor HMI design. However, there are also other factors that contribute to driving safety (Figure 5). These have been discussed by various researchers identifying different elements that contribute to driving safety risks. In 2006, Elvik suggested that there are four universal laws of accident causation; learning, rare events, complexity and cognitive capacity (Elvik, 2006). These are aspects associated with risk and are important to the causality of driving safety.

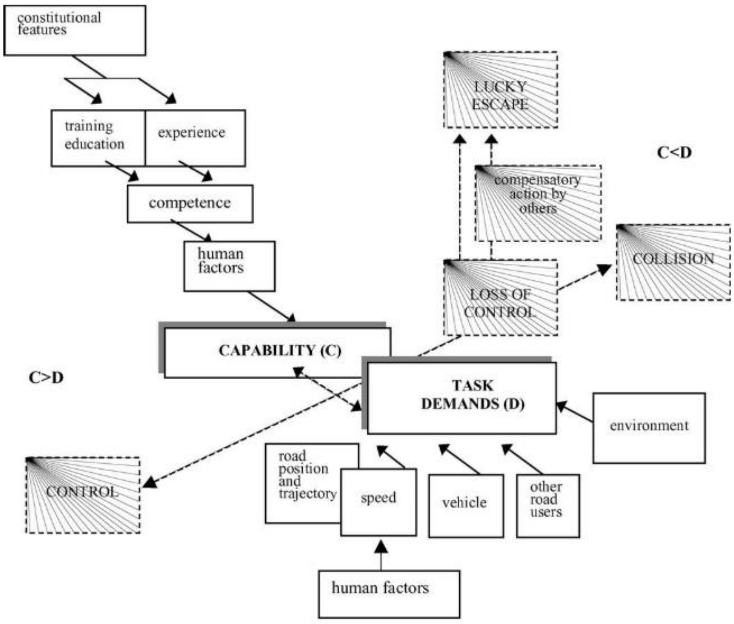


Figure 5. Task Capability Interface Model (Fuller, 2005)

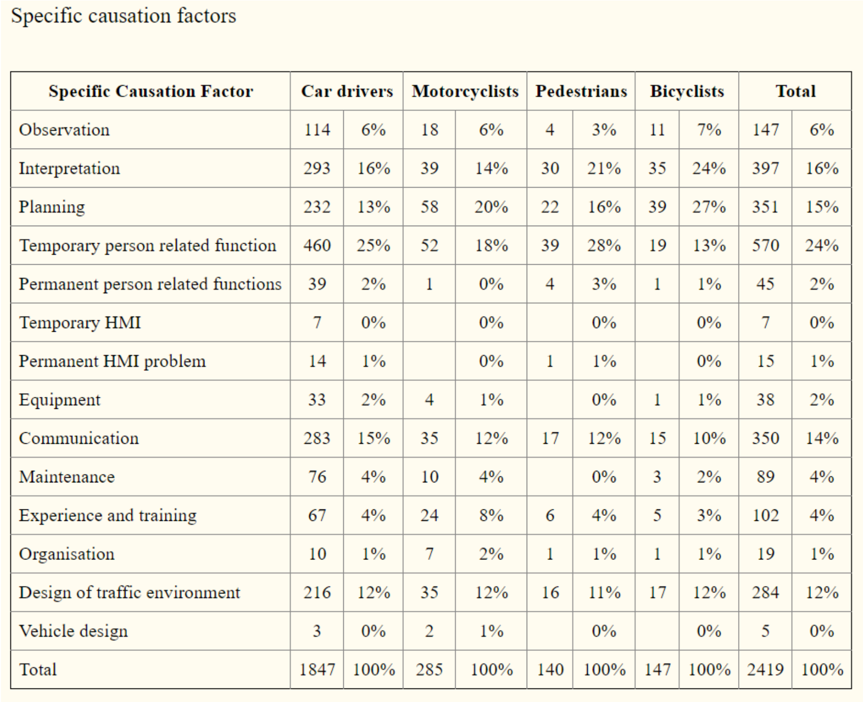
In the context of driving, scenarios that are more likely to result in accidents indicate that the driver’s mental workload could be in critical condition (Wong and Huang, 2009). In-vehicle systems that drivers can interact with whilst driving could contribute to this issue. In-vehicle displays allow drivers to perform additional task activities and result in a decrease of the spare capacity available for the primary task of driving (Horberry *et al.*, 2006). There are various functions of such systems, such as navigation, that may allow the driver to allocate their mental resources appropriately by providing information in advance (Fuller, 2005) . However, these systems still have the possibility of resulting in increased workload and have a negative impact on driving safety.

In 1931, Heinrich developed an early model of accident causation based on industrial accidents. This model outlined the chain of events in the context of industrial accidents where each step depends on the previous event creating a domino effect (Heinrich, 1931). The idea behind this theory is that the removal of an event from the chain would stop the consequent events from happening and ultimately would prevent the accident from happening. The five accident causation factors identified by Heinrich are; 1) social environment/ancestry, 2) fault of the person, 3) unsafe acts, mechanical and physical hazards, 4) accident and 5) injury. Heinrich’s model has influenced road safety management over the years and contributed to the understanding of the causes of road accidents.

Other accident causation models have been suggested following on from Heinrich’s such as Haddon’s matrix which includes road user, vehicle and infrastructure (Haddon, 1999). There are limitations in the application of a systems-based approach to road safety accidents in terms of its sample size.

Industrial accidents tend to be on an individual event basis. However, traffic accidents happen in larger numbers and need to be generalised for the wider population.

A method developed by Hollnagel called Cognitive Reliability and Error Analysis Method (CREAM) defines an accident as “an unsuccessful interaction between the person, technology and organisation” (Hollnagel, 1998). Although this method is intended to be applicable across various domains, in 2002 Ljung adapted CREAM to the road safety domain and developed Driver Reliability and Erorr Analysis Method (DREAM) (Ljung, 2002). Another method that was developed based on DREAM was SafetyNet Accident Causation System (SNACS) by Thomas et al., who applied their method to the active road users involved in 997 crash investigations (Thomas *et al.*, 2013). Figure 6 shows the list of causation factors identified which highlights the contribution of HMI related issues among other factors.



Specific causation factors

Specific Causation Factor	**Car drivers**		**Motorcyclists**		**Pedestrians**		**Bicyclists**		**Total**	
Observation	114	6%	18	6%	4	3%	11	7%	147	6%
Interpretation	293	16%	39	14%	30	21%	35	24%	397	16%
Planning	232	13%	58	20%	22	16%	39	27%	351	15%
Temporary person related function	460	25%	52	18%	39	28%	19	13%	570	24%
Permanent person related functions	39	2%	1	0%	4	3%	1	1%	45	2%
Temporary HMI	7	0%		0%		0%		0%	7	0%
Permanent HMI problem	14	1%		0%	1	1%		0%	15	1%
Equipment	33	2%	4	1%		0%	1	1%	38	2%
Communication	283	15%	35	12%	17	12%	15	10%	350	14%
Maintenance	76	4%	10	4%		0%	3	2%	89	4%
Experience and training	67	4%	24	8%	6	4%	5	3%	102	4%
Organisation	10	1%	7	2%	1	1%	1	1%	19	1%
Design of traffic environment	216	12%	35	12%	16	11%	17	12%	284	12%
Vehicle design	3	0%	2	1%		0%		0%	5	0%
Total	1847	100%	285	100%	140	100%	147	100%	2419	100%

Figure 6. Specific causation factors (Thomas *et al.*, 2013, p. 16)

Figure 5 outlines the task capability interface (TCI) model by Fuller (2005). This model shows that task difficulty is dependent on the relationship between the demands of the driving task and the capability of the driver. The difficulty level of the task is considered to be low when capability exceeds demand. When capability equals demand, this indicates that the task difficulty is high, and the driver is at their limit of their capability. Finally, the demand exceeding capability suggests that the task has become too difficult for the driver to complete successfully resulting in a loss of control and potentially leading to a road accident. An increase in task demand means and increase in task difficulty which ultimately challenges road safety. As a result, any secondary task that the driver can perform using an in-vehicle system introduce an additional task, resulting in an increase in demand that could exceed the driver's capability. In 1996, Violanti and Marshall reported that the use of mobile phones whilst driving increases the probability of a collision by 500% (Violanti and Marshall, 1996). It is also important to consider the fact that mobiles phone at the time would have offered less functionality to the user, limiting the number of actions the driver could perform compared to today's driver. In Fuller's model task complexity is different to task difficulty; the task is considered to be simple even if it is a complex task if the driver's capability exceeds the task demands of the said task.

At the point of the driver's capability is less than the demand of the task which eventually could lead to a collision, the actions of other road users could positively impact a negative scenario which may result the driver in avoiding a collision. Consequently, the driver could also change their behaviour at this point to avoid a collision. Wickens and Hollands (1999) suggest that as a result of the demand exceeding capability, the driving performance may gradually deteriorate during which the driver may start dropping lower priority elements of the driving task such as checking mirrors. Furthermore, gradually lower priority aspects of the task may also start suffering such as looking at the road ahead.

2.4 DRIVING COMPLEXITY

It has been established in literature that driving complexity can have an influence on secondary task performance (Strayer, Drews and Johnston, 2003; Young and Regan, 2007). In addition to having a direct effect on secondary task performance, the complexity of the driving environment can also reduce the effectiveness of peripheral vision as a viable mechanism to undertake secondary tasks if foveal vision is demanding. A study by Janelle et al., was conducted to assess the effect of increased task demands on peripheral target detection while playing a racing video game. The result showed that in competitive racing (in comparison with less stressful driving conditions) there was a decrease in peripheral target detection (Janelle, Singer and Williams, 1992).

The results of a study conducted by Jahn et al., (2005) showed that drivers driving in a city centre during which they had to deal with complex driving environments and were subjected to visual clutter were slower in responding to the Peripheral Detection Task (PDT) compared to driving in urban and rural areas where there are fewer vehicles on the road (Jahn *et al.*, 2005; Patten *et al.*, 2006). A series of on-road studies conducted by Lee & Triggs (1976) aimed to investigate the effect of driving complexity on the ability to detect peripheral light stimuli placed at near (30 degrees) and far (70 degrees) in the vehicle. The results showed that there was a significant decrementing effect of difficulty of the driving task and the complexity of the driving environment on the performance of the peripheral visual detection task for both angles used in the trial (Lee and Triggs, 1976).

A driving simulator study conducted by Cantin et al. (2009), aimed to observe the effects of driving complexity on mental workload and the differences between young and older drivers. They asked participants to drive on rural and urban roads and the driving task consisted of driving on straight roads, approaching junctions and overtaking other vehicles. Participants also completed a baseline drive. Participants were asked to perform a secondary task which was verbally reacting to an auditory stimulus that was presented to them. The authors used the reaction time (RT) as an indicator of mental workload. The results of the study showed that the RT during the baseline drive was similar for both young and older drivers. The RT also increased as the driving complexity increased for both groups of drivers. However, overall older drivers took longer to react to the auditory stimulus than young drivers during all driving conditions (Cantin *et al.*, 2009).

Glance behaviour also changes based on driving complexity. It has been shown that when drivers are driving on roads with curves their gaze focus more on the centre of the road – which is the future path region - compared to normal driving (Land & Lee, 1994; Wann & Swapp, 2000). A study conducted by Senders et al. (1967), showed that as driving complexity increases drivers focus more on the driving task which is observed in changes in their behaviour such as decreasing speed, glancing at the centre of the road more frequently or longer glances towards the centre of the road. Changes in driving complexity and the demand of the driving task also result in changes in the glance behaviour of drivers when performing in-vehicle tasks (Wierwille, Antin, Dingus, & Hulse, 1988). Drivers spend less time looking at in-vehicle displays and more time looking at the road ahead as driving complexity increases due to the increase in the demand of the primary task of driving (Wierwille, 1993a, 1993b).

2.5 ELEMENTS OF DISPLAY DESIGN

There are various elements of display design that have been discussed in literature in terms of their effects on the performance of the task being performed using the display. Due to the differences in the nature of traditional displays that incorporate physical buttons and touch screens there have been efforts in identifying elements of display design that best work with touch screen displays.

2.5.1 Display Size

The size of a touch screen has been identified as an important factor for interaction alongside how precise the user is required to be to select a target and how the items on the screen should be displayed (Caprani, O’Connor and Gurrin, 2012). Display size impact the breadth and depth of the menus presented on the screen. Larger displays allow for more options to be displayed on the same screen at a given time but could result in providing the driver too many options at once and create visual clutter. Although smaller displays may be able to provide the same number of features as a larger display; as the screen has less space to present all the options at once, the levels of menus the driver needs to go through the reach the target option increase. Whatever the size of the display is, it is imperative that the content on the screen is easily visible to the user. This seems to be an issue on smaller screens compared to larger displays and designers are pushed to compromise between the various design elements to be able to design a user-friendly interaction but also be able to fit all the necessary information on the display. This is particularly a concern for in-vehicle touch screens as the number of functions made available to the driver are increasing with the introduction of new technologies to vehicles.

2.5.2 Visual Density

There have been efforts to investigate the effects of different design elements on usability outside of the driving context. A study conducted by Ziefle (2010) investigated the effect of visual density - using two font sizes of 8pt and 12pt - and preview size - displaying 1 option on the screen at a time compared to displaying 5 options. The author’s focus was on older users aged between 55 and 73 years old. The results showed that effectiveness and efficiency was worse for the 1-option condition compared to the 5-option condition. The best combination identified in terms of performance was the 5-option preview with the 12pt font size. They highlighted the importance of the layout of target items as well as the need for larger items which aid accurate target selection. A similar point has been highlighted by Lee and Zhai (2009) who showed that buttons smaller than the width of a finger result in reduced task performance.

2.5.3 Target Size and Spacing

Target size has also been established as another important design factor to consider when designing displays. It is established that the larger the size of the target is the better pointing performance will be (Fitts, 1954). A study conducted by Caprani et al., (2012) investigated the effect of target size on task performance comparing specifically younger and older display users. The results of the study showed that smaller target sizes resulted in poorer target accuracy and increased task time. It is also suggested by the authors that when designing interfaces consistency in grouping items for easier navigation of the screen is important to avoid clutter. Various researchers investigated the optimal button size specifically for touch screen interaction. Some stated that the ideal button size is at least 20 mm square (Waloszek, 2000; Chung *et al.*, 2010) and some suggested that wider buttons (20 x 31.75 mm) are preferred by users. Lee and Zhai (2009) recommended 10 mm as a minimum size for a touch screen button. However, it has been stated by others that this size should be bigger (11.43 mm) for older users (Jin, Plocher and Kiff, 2007). Button spacing is also considered to be a design characteristic that aids usability. In the same study Jin et al, stated that for older users, button spacing should be between 3.17mm and 12.7 mm for better task performance. Although Fitts Law focuses on pointer inputs it has been established that the same principle applies to touch input hence touch screen displays (Sasangohar, MacKenzie and Scott, 2009).

1954 Fitts developed a “rule” for pointer inputs called the Fitts Law which states that as the size of a target that a user is required to interact with increases, the time it takes to interact with the said target decreases. There are various recommendations in literature regarding target sizes displayed on touch screens. These vary from 19mm (Monterey Technologies Inc., 1996), 22mm (Greenstein, 1997) and 16-20mm (Dandekar, Raju and Srinivasan, 2003) –

which is the average size of an adult’s fingertip. Jin et al., (2007) also investigated the effects of number of buttons, spacing between the buttons and manual dexterity on reaction time with a focus specifically on older adults. The results showed that small buttons resulted in poor levels of accuracy and slower reaction times. On the other hand, increased accuracy plateaued after a certain point for larger buttons.

2.5.4 Visual Appearance of Targets

Other research has focused on the effects of colour as a design feature and identified that it supports faster search times compared to size, brightness and shape (Carney, Campbell and Mitchell, 1998). Christ (1984) showed that the discriminating effects of colour decreased in time as a result of learning. In 1975, Christ also analysed a number of studies that were conducted on the effects of colour on visual search. An important finding in this evaluation was the fact that people were quicker in identifying colour than other characteristics of items displayed on screens such as size, brightness or shape (Christ, 1975). Nordgren (2007) has highlighted that it is important to be consistent with the choice of colours for targets as well as using the user’s prior knowledge when it comes to the selection of a colour for a target (e.g green for confirm and red for cancel) (Avsar, Fischer and Rodden, 2016).

2.5.5 Number of Targets

The number of items displayed on a screen have been identified as an important design factor by a number of researchers in different domains. A study conducted by Wolfe (1997) showed that the more items displayed on the screen the less efficient the search task became. Nothdurft (2000) also showed that the density of the items displayed on a screen impacts visual behaviour. The results of their work showed that with higher densities visual search becomes slower. On the other hand if the items on the screen are too close to each other, this could also result in longer search task times as it becomes harder to identify between different targets (Vlaskamp and Hooge, 2005).

2.5.6 Grouping

There also has been work carried out showing the advantage of showing all menu options at the same time (Maguire, 1999; Ziefle, 2010) and differentiation of different menu groups based on shape and style (Waloszek, 2000). Similarly, guidelines around reconfigurable systems specifically within aviation outline that frequently used buttons/switches should be assigned the same task for each sub-level (Calhoun, 1978). Another guideline provided by Little and Hannen (1993) suggest that there should be buttons providing a high-level access to smaller subsets. It is also suggested that buttons with similar functions should be grouped together (McDonald, Dayton and McDonald, 1988; Seidler and Wickens, 1992).

Although there is a lack of research specially focusing on the design elements of in-vehicle touch screen displays there have been efforts in identifying different types of interaction that are more suitable for the nature of using touch screens whilst driving.

2.6 INTERACTION WITH IVIS

2.6.1 Input Methods

There are various input methods that can be used in the vehicle such as direct touch, gesture, speech and physical input devices. These methods have different effects on secondary task performance, driving performance and distraction. Interfaces that incorporate direct touch are the ones that usually present the equivalent of physical buttons on the touch screen which requires the driver to physically select the button on the screen by touching the screen. There are some technologies that also use touch gestures which incorporate direct touch with gestures. This is a type of interaction that users commonly come across when interacting with smartphones and it involves gestures such as swiping to move between screens or pinching for zooming in and out. Other types of gestures include mid-air gestures during which the user is not required to physically touch the display to complete their interaction. Physical input devices for interaction with in-vehicle displays could come in the form of rotary controls and touch pads. Rotary controls allow drivers to manipulate what is displayed on the screen remotely with the movement observed on the screen mimicking the movement of the rotary control (e.g. turning the rotary control right would turn the volume up and turning it left would turn the volume down). Touch pads are also used to allow the drivers to hand write to interact with certain functions on the display such as inputting a destination postcode to the satnav. Finally, the use of speech has also been incorporated into vehicles when interacting with the IVIS. This allows the user to give instructions to the system verbally that allow the driver to keep their hands on the steering wheel. There has been considerable amount of work in the driving research area that focuses on these different types of interactions with in-vehicle touch screens outlining the advantages and disadvantages of each method. In the more recent in-vehicle technologies it is common to see a combination of these types of interaction.

A study conducted by McLaughlin et al., (2009) investigated the effect of direct and indirect input on attentional demand. Their results showed that instances during which the input device attributes do not match the requirements of the task being performed an increase in attentional demand is observed. They also found that when the input device matches the task it significantly benefits older adults as they are likely to experience age-related attentional decline. A driving simulator study was conducted by Kujala (2013), investigating the effects of three different touch screen scrolling methods (button, swipe and kinetic) on distraction. Their dependant variables were driving performance (lane keeping), gaze behaviour and subjective ratings. The results of their experiment showed that the effect of kinetic scrolling on gaze behaviour was worse compared to button and swipe methods as well as not allowing for resumability as much. Kinetic scrolling also resulted in increased subjective workload compared to button and swipe methods (Kujala, 2013).

With the increasing concerns of distraction of IVIS speech-based interfaces provide an alternative in order to tackle the visual demand imposed on the driver by the system. Although these may provide certain advantages, they are still not the solution to decreasing distraction from in-vehicle displays as distraction is also associated with interfaces that use speech as an input. There has been research showing that speech-based interaction has the potential to cause distraction. Research conducted by Goodman et al., (1999) reviewed crash data from NHTSA regarding mobile phone use whilst driving and identified that conversation as opposed to dialling, hanging up or reaching for the phone was the main factor to contribute mobile phone related crashes. An experiment conducted by Lee et al. (2001), used a car following task to evaluate the effects of speech-based email system on drivers' reaction to a lead braking vehicle. The results showed that participants were 30 per cent slower in reacting to the lead vehicle braking event when interacting with the speech-based system. They have emphasised that a delay in response to that extent could have safety implications on the driving task. Another study conducted by Jamson et al., (2004) also used a speech-based email system and found that the secondary task resulted in longer headways but showed reduced anticipation of braking requirements and shorter time to collision. Participants were also found to be less reactive when they were interacting with the speech-based system. Maciej et al., (2009) also conducted a study investigating the effects of speech-based interfaces on reducing distraction. They compared three tasks; audio, phone with name selection and address entry with the navigation system using speech and manual control. They also compared these to a baseline driving condition during which there was no IVIS interaction. The dependant variables were gaze behaviour, driving performance (Lane Change Task (Mattes, 2003)) and subjective distraction. The results of their experiment showed that although driving performance was better when using speech systems compared to manual systems, it still was not as good when compared to the baseline condition (Maciej and Vollrath, 2009). A more recent study focusing on the IVIS design of ten different model year 2015 vehicles also showed that voice-based interactions with in-vehicle systems can result in cognitive distraction and that they should not be used extensively whilst driving (Strayer *et al.*, 2016).

A study conducted by Bach et al., (2008) assessed three different types of interaction with an in-vehicle touch screen; tactile, touch and gesture interaction with 16 participants. The results of their study showed that gesture interaction resulted in longer fixations and more glances away from the road. They established that touch interaction resulted in quicker and more efficient interaction. And overall tactile interaction was better than touch and gesture interaction. Ahmad et al., (Ahmad *et al.*, 2016) designed a predictive display concepts which aimed to decrease the demand caused by in-vehicle displays which incorporates free hand pointing gestures. Their system predicts what the user will be selecting on the screen as the user starts pointing at the screen and aids the target selection process. They recruited 20 participants and assessed their system under various driving conditions. Their results showed that systems such as theirs can have a significant positive effect on driver workload and could reduce effort and task time for in-vehicle touch screen tasks.

Other research in literature have also identified other limitations of gesture interaction. A study conducted by Sauras-Perez et al., (2014) analysed the variability of the gestures used for interacting with secondary tasks in a vehicle. During their study in order to identify some common gestures for commonly performed tasks using the audio functions, they introduced participants with the actions and asked them to perform a gesture to represent the action. They found that there was a high variability in the gestures performed by the participants which highlights another issue with gesture interaction. When there are assigned gestures to certain functions this could lead to user acceptance issues as well as driver distraction (Sauras-Perez, Taiber and Smith, 2014).

A number of studies have investigated the use of remote controllers to interact with in-vehicle displays as an alternative to touch or gesture interaction. A study conducted by Rogers et al., (2005) compared direct touch interaction and rotary controllers to interact with a number of in-vehicle tasks. Their results showed that the use of rotary controllers was more appropriate for more repetitive tasks compared to direct touch interaction A study conducted by Harvey at al., compared indirect and direct input when interacting by asking participants to use a touch screen (direct) and a rotary controller (indirect) to perform a number of in-vehicle tasks. Their results showed that whilst completing the secondary tasks – such as climate control – participants took less time when using direct touch interaction. Direct touch also had a higher usability rating compared to the rotary control. This was due to the issue of translation of movement when using the rotary controller. The touch screen afforded direct input as drivers were able to touch the required target directly. On the contrary, the rotary controller requires translation of movement from inputs to the controller to movements of the cursor towards an on-screen target. However, other authors have shown that remote controllers could be more useful for in-vehicle display interaction if they incorporate a haptic adjustable surface (Spies *et al.*, 2009).

A driving simulator study conducted by Burnett et al., (2011) compared the use of a touchpad, touch screen and a rotary controller when performing secondary in-vehicle tasks. The results highlighted that the rotary controller was the least preferred input method resulting in the worst secondary task performance compared to touch screen and touchpad. However, the touchpad and the touch screen were found to be useful for different type of tasks. For example, the authors found that touchpads were more suitable for simple commands to bypass complex menu interactions whereas touch screens were more suitable for simple menu selection tasks. Another study conducted by Lauber et al., (2014) compared the use of hand gestures and rotary controllers when interacting with an in-vehicle displays. The results of their study showed that driving performance was better and subjective workload was lower when participants were interacting with the rotary controller compared to using hand gestures.

2.6.2 Output Methods

Similarly, to the input methods used to interact with in-vehicle displays, there are also a number of different output methods that can be used within in-vehicle display design to give feedback to the driver about their interaction which are; haptic feedback, auditory feedback and visual feedback. Depending on the system some of these output methods may be used in combination providing multimodal feedback to the driver. Out of the three feedback methods, visual feedback is the one that is most likely to interfere with the driving task as driving itself is a highly visual task. As a result, researchers have investigated the possibility of using auditory and/or haptic feedback to be able to decrease the visual demand caused by in-vehicle displays. Providing feedback to the driver when they are interacting with an in-vehicle display whilst driving is particularly important if the task they are performing may not have an obvious and immediate outcome. For example, if the driver is turning the volume up for the audio being played in the vehicle, this would have an immediate effect and the driver can assess whether their interaction was successful based on hearing the increase in the volume. However, some interactions may not have immediate feedback, and these are the ones that can particularly benefit from one or more of the three feedback methods discussed in this section.

A study conducted by Lee et al., aimed to show the benefit of multimodal feedback when driving and performing a secondary touch screen task simultaneously. They used trimodal sensory feedback which consisted of auditory, tactile and visual feedback. Their results showed that participants were able to complete the secondary task quicker when presented with tri-modal feedback compared to no feedback. Another similar study conducted by Pitts et al., involved participants driving in a simulator whilst using a touch screen for a secondary task and performing the Lane Change Task as a part of their driving task. The data collected on subjective preferences showed that participants preferred multimodal feedback compared to visual feedback only as it made their interaction easier.

Another type of non-visual feedback from touch screens other than auditory feedback is haptic feedback and this type of feedback consist of; vibrations, pressure sensitive systems, remote tactile feedback and electrovibrations (Rümelin and Butz, 2013). Haptic feedback has been investigated as a way to reduce visual demand posed by in-vehicle touch screens on the driver. Due to the nature of touch screens not providing any tactile feedback, providing haptic feedback is seen as a way to give an indication to the driver about their interaction with the display. The advantage of haptic feedback is that it can benefit from muscle memory and does not necessarily require confirmation visually and audibly; hence has the potential to decrease eyes-off-road time. As mentioned before the changes in IVIS and the move towards touch screens in vehicles resulted in the loss of tactile feedback from the in-vehicle displays. Drivers are used to receiving tactile feedback from the IVIS when they are interacting with them. Evidence shows that drivers are able to perform IVIS tasks quicker with fewer errors with increased usability when tactile feedback is a part of the interaction (Banter, 2010).

A driving simulator study conducted by Martens and Winsum (2001) aimed to examine the effects of the use of a driver support system on driving performance, workload and user acceptance whilst driving. They also used peripheral vision as a means to measure workload using the Peripheral Detection Task (PDT) (Martens and van Winsum, 2000). The driver support system used tactile and speech warnings which was compared to a no warning condition. Participants were asked to respond to hazards on the road driving on both rural roads and motorways. Their results showed that tactile feedback performed better than speech warnings when used for critical situations that required a response from the driver. For both methods of delivery of the driver support system message - tactile and speech – they observed short lasting increases in workload compared to the no warning condition.

Richter et al., (2010) designed a touch screen device with haptic feedback called HapTouch to be used in a vehicle. The aim of this device was to allow the user to interact with the screen and manipulate certain elements of the screen using the sense of touch. They conducted a study to assess the impact of their design on the driver’s visual attention, driving performance and task error rate. They particularly focused on the benefits of using tactile feedback when interacting with the smaller items on the touch screen. They showed that the existence of tactile feedback had a positive impact on error rates and task time. Similarly Carter et al., (2013) designed a system called Ultrahaptics[1] which provides haptic feedback on touch screens. Their system "*employs focused ultrasound to project discrete points of haptic feedback through the display and directly on to users' unadorned hands"* (Carter *et al.*, 2013). The authors also suggest that such system can be used in a driving environment where it is important for the driver to keep their eyes on the road.

Other studies also highlighted the benefits of introducing haptic feedback to touch screens. Haptic feedback does not always necessarily have to be something built into the screen. Pielot et al. (2012), used the edges and corners of the smart phone screen in their study to guide the interaction with the phone. Another study conducted by Rumelin et al., showed that haptic feedback improves task time by providing an easier interaction with the screen (Rümelin and Butz, 2013).

Lee and Zhai (2009) also conducted a study comparing various feedback (no feedback, audio, haptic and audio and haptic together) to be used with soft buttons. Their results showed that the existence of audio or haptic feedback increased task performance significantly compared to not having any feedback at all. However, there was no difference in having both types of feedback together. Cao et al., (2010) also conducted a study to investigate two different ways to deliver what they called informative interruption cues (IIC) using

---

[1] https://www.ultrahaptics.com/

auditory and haptic feedback. Their results showed that although both methods of feedback were easily learned and detected; haptic feedback had less impact on driving performance and participants were able to identify the haptic feedback more accurately than auditory feedback.

Consideration of both input and output methods when drivers are interacting with in-vehicle displays is essential as highlighted in the previous work carried out; as the selection of these methods have an impact on both driving performance and secondary task performance. It also impacts the way drivers interact with the in-vehicle display.

2.7 TOUCH SCREEN INTERACTION MECHANISMS

Although there has been a significant amount of research on the different types of interaction with in-vehicle touch screens there is still a lack of research in understanding the behaviour adopted by the driver when interacting with these displays. The focus so far as outlined in the previous sections have been on introducing new types of interaction. However, there are other interaction mechanisms that have not been considered in terms of driving and interaction with IVIS.

Drivers interact with the visual aspect of in-vehicle touch screens in three ways. They use their foveal vision, so they take their eyes off the road to look at the touch screen. They use peripheral vision, so they keep their eyes on the road ahead and are still able to obtain information about the road scene using foveal vision but are also able to detect items in their peripheral vision. And finally, they use muscle memory, so for certain tasks that they are used to performing they may be able to keep their eyes on the road ahead and know where to place their hand on the controls without looking at the touch screen.

2.7.1 Foveal and Peripheral Vision

Vision is a significant part of driving and its main role in driving is to provide information to the driver for them to be able to control the vehicle as well as identifying other road users. As stated by Broström, "*to maintain lateral control, the driver's eyes constantly scan the road environment for directional cues from far road information such as vanishing point, tangent points, and near road lane edges*" (Land, 2006; Broström, 2015, p. 16). As seen in Figure 7 there are two independent visual activities in driving; vision for action and vision for identification. Both of these activities require input from foveal and peripheral vision (Goodale and Milner, 2005). Vision for action is used to control the vehicle and vision for identification is used for gathering information regarding the driving scene. Peripheral and foveal vision both support motor control and object recognition (Broström, 2015).

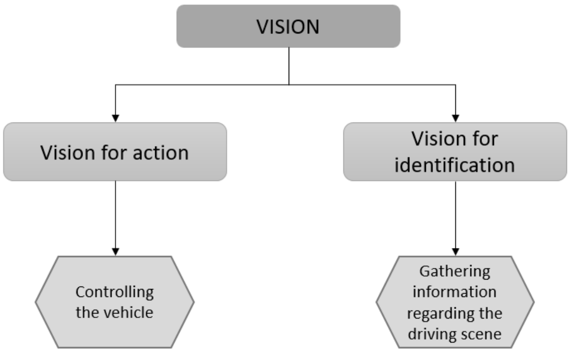


Figure 7. Vision in driving (adapted from Goodale and Milner 2004 and Land 2006)

Certain aspects of driving require both peripheral and foveal vision such as maintaining lateral control (Donges, 1978). The visual information that is captured by the driver is translated into a steering wheel movement or the pressing of the gas or brake pedal to manipulate the vehicle and according to Land (2006) this translation takes about a second. As a result Land highlights the importance of vision in driving as the movements performed by the driver as a part of the driving task start with the driver acquiring information relevant to the movement visually (Land, 2006).

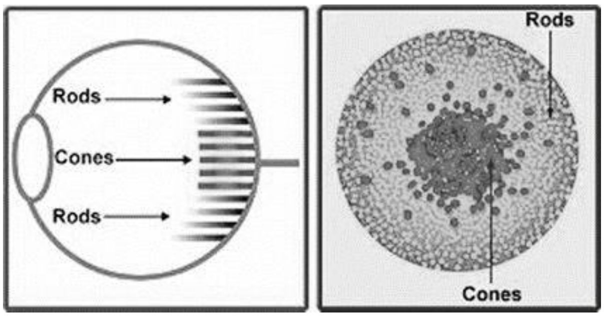


Figure 8. Rods and cones in the retina (Iris Tech, no date)

There are anatomical and neurological differences between peripheral and foveal vision. For example, peripheral vision is more sensitive to movement and less sensitive to detail and colour in comparison to foveal vision. The difference that results in this is where the rods and cones are located within the retina. The rods are the visual perception cells that respond to movement and the cones are the cells that respond to colour. As seen in Figure 8, there are more rods in the periphery of the retina than cones compared to the centre of the retina (Costanza *et al.*, 2006). Due to its sensitivity to movement peripheral vision is particularly useful for orientation and navigation (Wickens and Hollands, 1999). The differences between peripheral and foveal vision results in the two types of vision to be useful for different things. Tasks that are usually performed using peripheral vision are not affected by changes in acuity and eccentricity as these are provided by foveal vision. It has been proven by research that it is possible for people to process visual scenes quicker than make an eye movement. It has also been shown that one can gather basic information regarding a scene in less than 100ms (Oliva and Torralba, 2006; Greene and Oliva, 2009) and this is heavily reliant on peripheral vision. One also does not need to be attending to objects within a scene in order to gather basic information regarding a scene (Fabre-Thorpe, 2011) and can still gather the necessary information when their attention is divided between two tasks (Fei Li *et al.*, 2002).

There is evidence in driving research that foveal vision is imperative for hazard detection in driving (Horrey, Wickens and Alexander, 2003). According to Horrey et al., "*the primary functions of the focal visual system are visual search, object recognition, and other tasks requiring high visual acuity, including reading text*" (Horrey, Wickens and Consalus, 2006). Although recent studies also show that peripheral vision can be used in processing hazards and help in directing the gaze towards the location of the hazard (Huestegge and Böckler, 2016). Recognising that driving is a highly visual task, increases in eyes-off-road time or the number of off-road glances is therefore likely to result in detrimental effects on driving performance (e.g. a driver's ability to detect any hazards that may appear on the road). Research also shows that it is difficult to detect targets that are located within peripheral vision when the visual attention required in the foveal field is demanding (Williams, 1985, 1995; Miura, 1986; Horrey, Wickens and Consalus, 2006). So, driving tasks that are more visually demanding may result in drivers requiring their foveal vision on the driving scene and may make it difficult for them to use their peripheral vision to achieve other tasks. This can be described as the visual tunnelling phenomenon. However, this is not necessarily always caused by an increase in the visual demand in the driving scene but can also be impacted by an increase in cognitive demand (Dirkin and Hancock, 1985; Olsson and Burns, 2000).

Peripheral vision has been explored within a driving context by many researchers. Existing experiments focus on understanding how drivers use their peripheral vision to aid the driving task. Some examples focus on the use of peripheral vision to detect driving related tasks such as lane keeping and headway detection. For example, a driving study conducted by Summala et al., asked novice and experienced participants to drive on a straight road and only use peripheral vision for lane keeping whilst performing another task using their foveal vision (Summala, Nieminen and Punto, 1996). The results showed even though initially the novice drivers' performance was poor this was improved by practice and time. Another study carried out by Lamble et al., examined the effect of a visually demanding in-vehicle task on the driver's ability to detect the decelerating car ahead using peripheral vision (Lamble *et al.*, 1999). Mourant & Rockwell (1970) also verified that drivers use peripheral vision for lane keeping, monitoring the vehicles and road signs around them. They showed that this allowed drivers to use foveal vision for dealing with any visually high demanding situation. Another study conducted by Bhise & Rockwell (1971) aimed to investigate "*the role of extra-foveal and foveal vision in the visual information acquisition process of the driver, and the effect of driver's visual information acquisition behaviour on his driving performance"* (Bhise and Rockwell, 1971). The results of the study conducted on the road showed that participants did not need foveal vision when maintaining lane position and headway and were able to use their peripheral vision. On the other hand, for critical driving related tasks such as speed monitoring they needed their foveal vision. They also demonstrated that participants were able to successfully perform the car following using their peripheral vision.

Other than driving peripheral vision has been researched as a part of other actions such as identifying the average size of a group of similar items which is called ensemble perception. Ensemble perception is not possible without peripheral vision although can be achieved without foveal vision (Wolfe *et al.*, 2017). Although peripheral vision is capable of gathering a great deal of information where it lacks is the ability to gather information for individual items. A study conducted by Sweeny et al., (2013) showed that peripheral vision can be used for obtaining mean pedestrian heading. So, peripheral vision allows the driver to gain an understanding of the average size of a group of pedestrians but does not help with obtaining information about the individuals in the group of pedestrians.

It is particularly challenging to identify items with peripheral vision when visual clutter is present. Peripheral vision struggles in identifying the difference between items that are near each other, although it is still able to detect the items (Bouma, 1970; Whitney and Levi, 2011). So, the closer the items on the touch screen are the more difficult it becomes for the driver to identify between them. This is an important point to highlight as without visual crowding the visual acuity in the periphery is sufficient for one to be able to read isolated small texts (Anstis, 1974). However, once clutter is introduced this task becomes impossible. Another study conducted by Nuthmann and Malcolm (2016) showed that colour has a different role within foveal and peripheral vision. They showed that colour was used in peripheral vision to localise a target whereas it was used to verify a target in the foveal vision.

A study conducted by Lenneman et al., (2009) investigated the effects of foveal and peripheral visual demand on driving. Participants were asked to perform two tasks at once; driving in a simulator and a foveal or peripheral secondary task. Their results showed that although the driving performance deteriorated during the foveal secondary task, it was not affected by the presence of a secondary peripheral task. They also identified that the effect of the foveal secondary task was specifically on the foveal component of driving such as maintaining headway and not the peripheral component of the task such as lane keeping (Weinstein and Wickens, 1992; Lenneman *et al.*, 2009).

Birnholtz et al., (2010) stated that using peripheral vision could help with attention management. They conducted a study to show that displays that exploit peripheral vision can improve attention management. They argue like some other authors that presenting information in the peripheral vision of a person can reduce distraction (Maglio and Campbell, 2000).

However, there is a gap in research exploring the use of peripheral vision to achieve other tasks apart from the driving task. Especially for interaction with in-vehicle touch screens. Peripheral vision has been considered as an interaction mechanism in other contexts over the years such as aviation and interaction with various displays (Malcolm, 1984; Chapman and Underwood, 1998; Grudin, 2001). Peripheral displays are particularly useful in the aviation domain and has been used since late 1950s (Stokes, Wickens and Kite, 1990). The first peripheral displays introduced in aviation were to help with landing of aircrafts. The aim of these displays was to get the attention of the operator as they were focusing on the information displayed on other areas of the aircraft instruments. A simulator study conducted by Nikolic and Sarter in 2001 "*compared the effectiveness of foveal feedback and two implementations of peripheral visual feedback for keeping pilots informed about uncommanded changes in the status of an automated cockpit system".* The results showed that both peripheral vision implementations resulted in higher detection rates and faster response times compared to foveal feedback. They also suggested that this theory could be applied to other dynamic environments to help with attention allocation (Nikolic and Sarter, 2001). Studies conducted by Brown, Holmquist and Woodhouse (1961) showed that the use of peripheral displays in aviation were particularly useful for providing redundant information for tracking tasks.

Outside aviation, researchers have suggested using peripheral displays in other domains such as a way of interacting for people with disabilities. Ebrahimi and Kunov developed a wearable peripheral display which was embedded into glasses for deaf people to wear which aimed to help them in lip reading. Their device resulted in better lip-reading performance (Ebrahimi and Kunov, 1991). A study conducted by Somervall et al., (2002) aimed to understand how effective users can be in identifying items presented on a peripheral display whilst engaging in a highly demanding foveal activity. Their independent variables were the number of items displayed on the peripheral display, how long the items were displayed for and the type of task they were required to perform using the peripheral display. They asked participants to identify certain aspects of the items being displayed such as shape and colour and recorded how successful they were in identifying these characteristics. Their showed that it is possible to successfully identify items in the periphery even when engaged in a highly demanding foveal task. They also showed that certain characteristics of the peripheral display can help in achieving successful interaction with the display. The results showed that the more cluttered the peripheral display, the longer it takes for users to identify the items being displayed. They also showed that items that are similar that are grouped together were easier to identify peripherally than those that were presented on their own (Somervell *et al.*, 2002). Therefore, it is not uncommon to make use of peripheral vision for interaction with displays.

2.7.2 Muscle Memory

The terms muscle memory and motor learning are used interchangeably in this thesis as it has been in other work in the literature (Hassanpoor, Fallah and Raza, 2012). A number of definitions for muscle memory are identified from literature. According to Taber (2016) muscle memory, i.e. motor learning, is *“the process of developing a motor plan for a particular skill”* (Shusterman, 2011; Hassanpoor, Fallah and Raza, 2012). Another definition of muscle memory provided by the Medical Dictionary is that “*muscle memory* is *any of the processes related to the acquisition and retention of skills associated with movement. They are influenced by practice, experience, and memory*” (Medical Dictionary, no date). Zaharis et al. (2010, p. 194) also stated that *“muscle memory is fashioned over time through repetition of a given suite of motor skills and the ability through brain activity to inculcate and instil it until they become automatic”*.

In a driving context, muscle memory would, in theory, enable a driver to move their hand directly from steering wheel to an in-vehicle control without the need for vision. It is easier to develop muscle memory when using traditional hard in-vehicle controls as the driver may learn the approximate location of the button and then use tactile cues (i.e. touching the buttons and receiving physical feedback) to help calibrate the finer movements as well as differentiate one target from another (Burnett and Porter, 2001). This is not possible with touch screen displays as they lack tactile feedback to confirm successful selection (Stevens *et al.*, 2002; McGookin, Brewster and Jiang, 2008). Layouts may also be dynamic, which means that button locations could change between different menu screens. This makes it more difficult for the driver to develop muscle memory for specific locations on a touch screen display. However, it is possible that some muscle memory will develop to guide a driver’s hand from steering wheel to touch screen and possibly to a specific area of the screen where they recall a particular button being located, based on repeated and regular use. This will contribute to reducing button selection times with practice and lead to reductions in the need for vision over time. Previous literature suggests that vision is important in learning; however, it becomes less important for well-learned tasks (Proteau *et al.*, 1987).

Muscle memory has been explored in the context of interface design but has been seldom applied in the driving domain. While driving, the driver builds up muscle memory as they gain experience with physical actions. Actions that are essential to driving – such as changing gear, indicating, steering, keeping the distance to the car in front and lane keeping – therefore become more ‘automatic’, i.e. the driver does not necessarily need to think consciously about every action before executing them (Charlton and Starkey, 2011).

In relation to interface design, the potential benefits of muscle memory have been explored. Van Dam (1997) highlighted the development and use of muscle memory in his discussion about WIMP GUIs (graphical user interfaces based on windows, icons, menus, and a pointing device, typically a mouse). He suggests that multilevel radial menus (Figure 9) would allow users to exploit muscle memory without having to look at the menu.

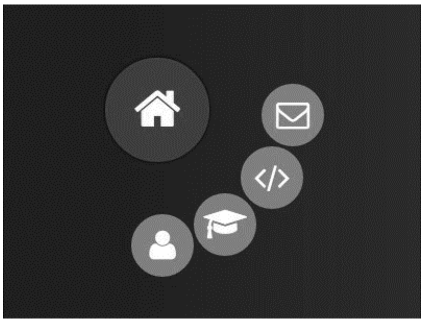


Figure 9. Example of a multilevel radial menu (https://www.jqueryscript.net/tags.php?/circle%20menu/)

Other examples of the use of muscle memory are inputting a password, touch typing, or playing the piano. When people are required to put in their password in various scenarios (e.g. ATMs, touch screen mobile phones and laptops) many people are able to recall the spatial locations of numbers on a keypad and put in their password without having to think about it but rather typing their password in ‘automatically’. Similarly, touch typists can type using a keyboard without having to look at the letters on the keyboard as they build a mental model of the physical keyboard through repetition. A study conducted by Krol et al., investigated the use of a one-time password entry method called Vernitski Authentication Grid (VAG) by observing the time taken to complete the password entry task and by receiving subjective feedback from participants. The VAG required participants to *“enter their password in pairs of characters by finding where the row and the column containing the characters intersect and entering the character from this intersection”*. The results of the study showed that the task time decreased over time with practice. It also showed that participants were quicker in entering their password when using a touch screen tablet than using a PC (Krol *et al.*, 2015). McLean suggested that interface design could benefit from muscle memory by structuring frequently completed/patterned tasks into stylised or abbreviated gesture. It was argued that this would help reduce cognitive workload (Maclean, 1999). Symth and Kirkpatrick proposed a set of design principles for haptic interaction techniques which included “*use vision for controlling novel tasks, and haptics for controlling routine tasks. Maintain sufficient consistency in the environment that haptic feedback is effective and muscle memory is allowed to develop*” (Smyth and Kirkpatrick, 2006, p. 374).

During attempts to identify less visually distracting ways to interact with a touch screen some authors have identified that muscle memory might have played a part in interacting with their proposed interaction method. For example, a study conducted by Ecker et al. (2009) aimed to asses a pie menu structured interface and highlighted in their results that the pie menu structure allowed the user to familiarise themselves with the system and use muscle memory to locate the icons which enabled blind interaction.

Alongside muscle memory and peripheral vision proprioception should also be considered in relation to interaction with in-vehicle displays. Proprioception is described as “*the sense of the relative location and orientation of body parts, providing information about one’s own movement*” (Schmidt and Lee, 1999).

For example, using proprioception one can compare the actual position of a hand with where the hand needs to be in relation to the in-vehicle display and adjust the movement of the hand in order to successfully interact with the screen. Wolpert and Flanagan (2001) states that humans have the ability to mentally visualise the movement of their limbs. They create an internal model which is developed over time based on the predicted behaviour of the limb and the outcome of the action. Desmurget et al., (2000) state that "*motor prediction is useful in sensorimotor control because it enables state estimation, which allows for faster movements than using sensory feedback alone".* They also highlight that there have been studies in literature showing that it becomes harder for people to estimate the location of their arm if they are not able to see it. Hence it is suggested that proprioception degrades it not calibrated by vision. However, a series of experiments conducted by the authors during which participants only relied on proprioception to locate their hand showed different results to other studies in literature. The results of their set of experiments highlighted that proprioception does not degrade quickly when people are not able to see their arm. Proprioception has also been established be a key component in muscle memory (Sherrington, 1907). A study conducted by Hocherman (1993) investigated people's ability to reach a number of targets without visual guidance and found that people could successfully achieve reaching these targets without relying on visual guidance. Another study conducted by Soechting and Flanders (1989) showed that people were able to accurately reproduce directions when reaching targets however made significant errors in distance when they had no visual guidance. Crossman and Goodeve (1983) also established that when there is no visual guidance available proprioception can be a viable alternative for detecting accuracy errors.

In relation to displays in vehicles, Rumelin and Butz (2013) found that proprioception can aid in finding target areas on large screens. Using their peripheral vision drivers can still see their hand moving towards the target and hence can increase proprioception without having to take their eyes off the road to potentially confirm that their finger is on the target they aim to select.

2.8 SUMMARY OF CHAPTER

It is evident from literature that driver distraction, especially visual distraction has been a major issue for drivers and it continues to be an issue due to the developments in in-vehicle technologies. Visual distraction is caused by visual demand and can have serious consequences impacting driver performance as a result of drivers being encouraged to take their eyes off the road.

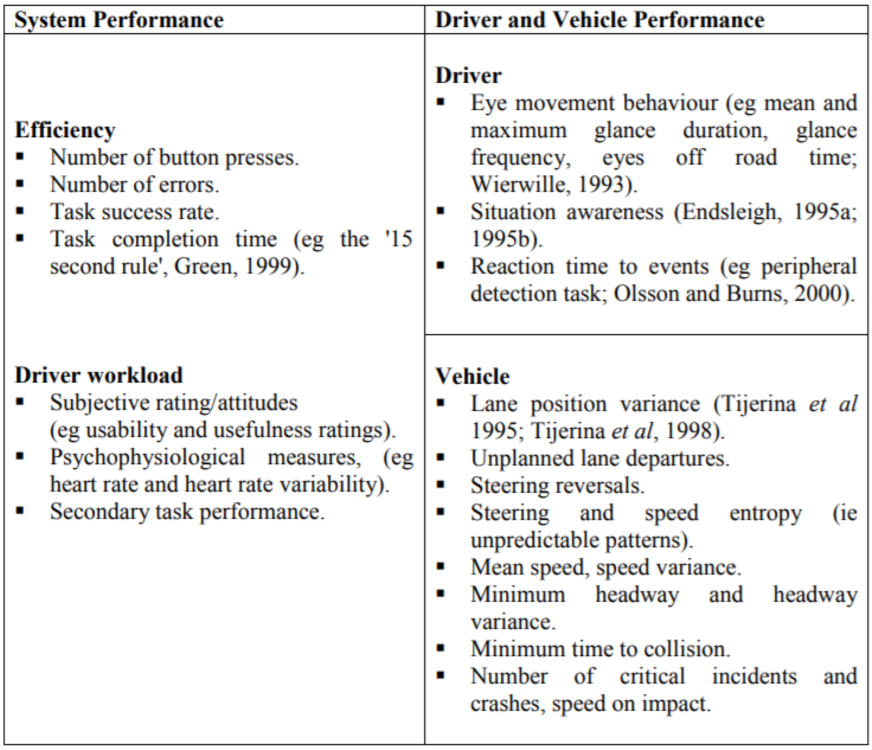
It is clear that there is a significant amount of work in driving research that aims to find ways to decrease visual demand caused by in-vehicle displays by incorporating multimodal interaction methods in interaction with these displays. It is also clear that vision plays a big role in driving as driving is a highly visual task. Both peripheral and foveal vision play a part in information gathering when driving. There have been many studies showing the differences between the two types of vision and their contribution to driving. It is also apparent that peripheral vision can provide the driver with information foveal vision may not be able to.

When designing interfaces there are many design elements to consider that can contribute to visual demand caused by in-vehicle displays. Although there is not as much research when it comes to the newer in-vehicle displays that are found in cars these days there are many studies looking at display design that in-vehicle touch screen display design can benefit from to achieve lower levels of visual demand.

3 CHAPTER 3: RESEARCH METHODOLOGY

3.1 CHAPTER OVERVIEW

This chapter discusses the methods that have been used in the user trials conducted as a part of this thesis such as driving simulator studies, eye tracking, driving and secondary task performance measures and questionnaires (Figure 10). It also reveals the reasons for choosing these measures and their relevance to visual demand, workload and distraction. The equipment that is detailed in this chapter has been used in all of the trials and is covered in this chapter to avoid repetition in the chapters that discuss the user trials.



System Performance	Driver and Vehicle Performance
Efficiency ▪ Number of button presses. ▪ Number of errors. ▪ Task success rate. ▪ Task completion time (eg the '15 second rule', Green, 1999).	**Driver** ▪ Eye movement behaviour (eg mean and maximum glance duration, glance frequency, eyes off road time; Wierwille, 1993). ▪ Situation awareness (Endsleigh, 1995a; 1995b). ▪ Reaction time to events (eg peripheral detection task; Olsson and Burns, 2000).
Driver workload ▪ Subjective rating/attitudes (eg usability and usefulness ratings). ▪ Psychophysiological measures, (eg heart rate and heart rate variability). ▪ Secondary task performance.	**Vehicle** ▪ Lane position variance (Tijerina *et al* 1995; Tijerina *et al*, 1998). ▪ Unplanned lane departures. ▪ Steering reversals. ▪ Steering and speed entropy (ie unpredictable patterns). ▪ Mean speed, speed variance. ▪ Minimum headway and headway variance. ▪ Minimum time to collision. ▪ Number of critical incidents and crashes, speed on impact.

Figure 10. Measures of IVIS safety and usability performance (Stevens *et al.*, 2002)

3.2 USE OF DRIVING SIMULATORS FOR RESEARCH

Simulators are used in different areas of driving related work such as; research, training and testing (Table 1). Driving research especially is an area that has benefitted greatly from the use of simulators. There are numerous driving studies in literature that have been conducted using a driving simulator. These studies investigated different aspects of the driving task such as speed (Godley, Triggs and Fildes, 2002; Bella, 2008), road environment (Horberry *et al.*, 2006) and driver workload (Cantin *et al.*, 2009; Palinko *et al.*, 2010). Driving simulators come in a variety of forms from desktop computers to moving pods and are used to create the impression of a driving vehicle on the road (Stern and Davis, 2006). There are several advantages to using a driving simulator rather than conducting an on-road experiment to assess driving performance. It is easier to control for variables and experimental conditions when conducting experiments in driving simulators such as weather, traffic densities and behaviour of other vehicles on the road (Blana, 1996). This also allows for repeatability and objectiveness. It also helps researchers ensure that their results are not affected by unknown variables. Using driving simulators allows researchers to conduct their experiments in a safe environment (Blana, 1996; Kaptein, Theeuwes and Van Der Horst, 1996; Konstantopoulos, Chapman and Crundall, 2010). A majority of the experiments discussed in this thesis consisted of participants purposely being asked to take their eyes off the road whilst driving. These studies would not have been possible to conduct in a real driving environment. Driving simulator trials also can take place in smaller office/lab settings instead of complex on-road settings. It is easier to collect data during simulator studies and they are cheaper to run (although initial costs might be higher for medium and high-fidelity simulators) compared to on road studies (Reed and Green, 1999; Bella, 2008).

Table 1. Examples of research areas for which driving simulators were used

Author(s)	Title	Investigation Area
Easa & He, 2006	Modeling Driver Visual Demand on Three-Dimensional Highway Alignments	Driver visual demand
Broughton, Switzer & Scott, 2007	Car following decisions under three visibility conditions and two speeds tested with a driving simulator	Driver behaviour in specific weather conditions
McAvoy, Schattler & Datta, 2007	Driving Simulator Validation for Nighttime Construction Work Zone Devices	Testing of positioning of road signs
Noyce & Smith, 2003	Driving Simulators for Evaluation of Novel Traffic-Control Devices: Protected-Permissive Left Turn Signal Display Analysis	Testing traffic control devices
Van Der Horst & Ridder, 2007	Influence of Roadside Infrastructure on Driving Behaviour	Research on lateral positions
Van Driel, Hoedemaeker & van Arem, 2007	Impacts of a Congestion Assistant on driving behaviour and acceptance using a driving simulator	In-vehicle driver assistance systems
Yan, Abdel-Aty, Radwan, Wang & Chilakapati, 2008	Validating a driving simulator using surrogate safety measures	Assessing traffic safety

On the other hand, there are some limitations to using driving simulators in driving research. There have been some concerns regarding simulator studies not being ecologically valid (Blana, 1996). Although one of the main concerns around using driving simulators have been the absolute and relative validity of the results collected during these experiments. A majority of researchers have carried out user trials to establish the absolute and relative validity of driving simulators by comparing them to on-road trials conducted using instrumented vehicles.

Driving simulation was chosen as the main method of this research due to the nature of the studies conducted as a part of this research. In the studies conducted participants were encouraged to interact with an in-vehicle touch screen that could potentially be distracting and risky in a real-life driving environment. There are undoubtedly safety and ethical issues with conducting these types of studies on the road.

3.2.1 Simulator Sickness (SS)

One of the main disadvantages of driving simulators is the potential for the participants to experience simulator sickness during and after a simulator session (Shechtman *et al.*, 2007). In literature SS has been defined as "*physical discomfort experienced when 'driving' a simulated vehicle that is caused by incompatible signals from visual, auditory, and motion systems"* (Classen, Bewernitz and Shechtman, 2011, p. 180). SS occurs when the motion of the simulator does not reflect the motion seen on the screen where the driving environment is presented (Hettinger *et al.*, 1990). The effects of simulator sickness are cumulative and can include symptoms such as "*discomfort, fatigue, headache, eyestrain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of head, blurred vision, dizziness, vertigo, stomach awareness, or burping"* (Hettinger *et al.*, 1990; Classen, Bewernitz and Shechtman, 2011, p. 187). It is stated in literature that this is caused by an increment in the activation of the sympathetic nervous system (Chung *et al.*, 2006). Some people are generally more susceptible to simulator sickness than others and they have the tendency to commonly experience motion sickness and not just simulator sickness in driving simulators. In order to monitor the participants during driving simulator trials a commonly used questionnaire is the Simulator Sickness Questionnaire (SSQ) developed by Kennedy et al., (1993) (Appendix 11.4) which has been used in the user trials conducted as a part of this thesis to monitor the participants during the trials.

3.2.2 Validity of Driving Simulators

Another limitation of the use of driving simulators is concerns regarding the validity of the results collected. The validity of a simulator is defined as the success in the ability of the simulator in achieving a real-world environment. There are various aspects of validity that are discussed in the context of driving simulators; behavioural, physical, absolute and relative (Blaauw, 1982; Kaptein, Theeuwes and Van Der Horst, 1996). Physical validity considers how closely the physical attributes of the real-world are replicated in the driving simulator. On the other hand, behavioural validity focuses on how close the experience of the driver when driving the simulator is to real-world driving. There is also a distinction between absolute and relative validity. As described by Bella (2008, p. 1078) "*absolute validity refers to the numerical correspondence between behaviour in the driving simulator and in the real world. Relative validity refers to the correspondence between effects of different variations in the driving situation*".

There are many studies in literature that investigate the absolute and relative validity of driving simulators. These studies compare driving data - such as lane position, steering and speed - collected in a driving simulator against data collected on a real road. Some of the studies ask participants to perform a variety of secondary tasks whilst driving. Many studies established relative validity by showing that the difference in driving performance for both the driving simulator and real road drives are the same (Wooldridge *et al.*, 1999; McGehee, Mazzae and Baldwin, 2000; Horberry *et al.*, 2006; Mayhew *et al.*, 2011). For example, a study conducted by Reed and Green (1999) showed that although the performance decrement as a result of performing a secondary task was greater in the simulator, the driving performance was worse in the conditions where there was a secondary task present compared to just driving in both real life driving and simulator. Similarly, studies also established absolute validity showing that the driving performance observed is the same in both the driving simulator and on real roads (Engström, Johansson and Östlund, 2005; McWilliams *et al.*, 2018).

Although the driving simulator used in the studies that form this work was a medium-fidelity simulator as this was available to the researcher at the time, it is possible to conduct future work using a low-fidelity driving simulator. If one is not already available setting up medium-fidelity simulator could be costly and time consuming. The nature of this research allows for other methods to be used. There are studies that have used low fidelity driving simulator setups that show that the results produced can be as valid as high-fidelity driving simulators (Wang *et al.*, 2010). There are various methods that can be used as a part of a low fidelity setup such as Lane Change Test (Mattes, 2003) and the Critical Tracking Task (CTT) (Petzoldt, Bellem and Krems, 2014). The lane change test has been established as a reliable, valid, objective, simple and low-cost method for measuring driver distraction. It has been shown to work in a low-fidelity simulator setup where the features of the primary task still resemble the driving task in terms of cognitive, motoric and postural aspects. These methods are particularly useful for researchers and designers in industry, due to requiring minimum amount of equipment and the fact that they are quick to complete. The LCT is also a part of ISO 14198 (2012) which makes it standardised and widely available.

As a part of LCT the participants are asked to perform repeated lane changes when prompted by road signs using a desktop computer setup. How well the participants perform the lane change tasks are then compared. A baseline drive is completed during which the participants would be asked to complete a single task. Following on from that the quality of the performance of the LCT would then be compared to that of the baseline when participants are completing the driving task alongside performing a secondary task such as interaction with an in-vehicle display. The differences between the quality of the lane change performance depend on the ability of the driver detecting and responding to the road signs as well as their ability to maintain lateral control. Consequently, the decrease in lateral control and poor road sign detection indicates increased distraction (Harbluk *et al.*, 2007).

The CTT was first established by Jex et al., (1966) which they described CTT as a task "*in which a human operator is required to stabilize an increasingly unstable first-order controlled element up to the critical point of loss of control"* (Jex, McDonnell and Phatak, 1966, p. 138). It is suggested that the increase in workload should result in earlier loss of control. It is also suggested by Petzoldt et al., (2014) that other than being used to assess the demand of the secondary task, the CTT can also be used as a surrogate to the driving task as it shows similarities to certain aspects of the driving task. They suggest that CTT is closely related to the operational level of driving (Michon, 1993) covering the skills required for steering, acceleration and braking. They also suggest that CTT is similar to the task of keeping a safe headway distance from a vehicle whose speed fluctuates which has also been incorporated in some of the studies as a part of this research. Petzoldt et al. (2014), conducted a series of experiments to reinforce their suggestions in terms of the role of CTT in driving research when testing for distraction caused by IVIS. The results of the experiments showed that CTT was able to identify the differences between cognitive and visual distraction as well as the differences in demand of the secondary IVIS tasks. They also found that the results of CTT correlated with the subjective workload measures recorded (Petzoldt, Bellem and Krems, 2014).

3.3 EYE TRACKING

One of the main methods used to identify visual demand is observing glance behaviour using eye tracking technologies (e.g. glance frequency and duration). Various researchers have used this method to assess driver fatigue (Eriksson and Papanikotopoulos, 1997; Horng *et al.*, 2004), distraction, workload (Palinko *et al.*, 2010), visual search (Duchowski, 2002). There are two types of eye trackers; remote and head-mounted. Most eye trackers comprise of an infrared light source and a camera (or multiple cameras). The light is reflected into the eye whilst the camera tracks this reflection and other ocular features such as the pupil. The rotation of the eye is then extrapolated to get information on the direction of the gaze (Eye Tracking Inc., 2011). Ultimately direction of gaze gives an insight into the users' glance behaviour. By using eye tracking glasses researchers are able to observe where a person is looking at any given time, the sequence of the movement of the eye between different areas in the visual scene and the time spent looking at these different areas. This provides HCI researchers with a way to objectively evaluate the usability of interfaces which can help inform interface design in the future (Poole and Ball, 2006).

During interaction with in-vehicle tasks drivers time share between the driving task and the in-vehicle task. As a result, their eyes continuously move back and forth between the road ahead and the in-vehicle display. The movement of the eyes represent this time sharing and is a direct indicator of visual distraction. Time sharing between tasks occurs when foveal vision is needed by both the driving task and the secondary visual task such as interacting with an in-vehicle display (Schall *et al.*, 2012). Due to these movements of the eye, measures such as glance duration, glance frequency and total task duration are used to assess visual demand of IVIS. According to Fitts et al. (1950), "*frequency and duration of eye movements should be treated as separate metrics, with duration reflecting difficulty of information extraction and frequency reflecting the importance of that area of the display"* (McCarthy, Sasse and Riegelsberger, 2004, p. 408). It has been established in literature that attention and glance behaviour are connected, and that glance behaviour gives an indication of how much attention one is paying to the driving task or the in-vehicle task (Findlay and Gilchrist, 2003). However, it is also important to consider that there may be instances where visual behaviour may not correlate with attention. These instances are when a person may be looking at something but not attending to it and is described as inattentional blindness (Strayer, Drews and Johnston, 2003; Wood *et al.*, 2003).

Glance data is also considered to provide insight into the demand of a task and levels of distraction and workload (Wierwille and Tijerina, 1998; Angell *et* *al.*, 2006). The following glance behaviour related definitions have been taken from ISO 15007-1:

- Glance – "*the maintaining of visual gaze within an area of interest, bounded by the perimeter of the area of interest; may be comprised of more than one fixation and saccades to and from it. Its duration is measured as 'glance duration'"* (ISO 15007-1, 2014, p. 2)
- Glance duration – "*time from the moment at which the direction of gaze moves towards an area of interest (e.g., the interior mirror) to the moment it moves away from it"* (ISO 15007-1, 2014, p. 4)
- Number of glances – "*count of glances to an area of interest (or set of related Areas of Interest) during a condition, task, subtask or sub-subtask. Unit [glances]."* (ISO 15007-1, 2014, p. 4)
- Total glance time (duration) – *"summation of all glance durations to an area of interest (or set of related Areas of Interest) during a condition, task, subtask or sub-subtask; Total glance time = Σ(glance duration1, glance duration2, ..., glance duration n) unit [s]"* (ISO 15007-1, 2014, p. 4)
- Glance rate (frequency) – *"number of glances per unit of time with which the glance is in an area of interest (or set of related Areas of Interest) during a condition, task, subtask or sub-subtask, where each glance is separated by at least one glance to a different area of interest; Glance rate = (Number of glances)/(duration of condition, task, subtask or sub-subtask); unit [1/s]"* (ISO 15007-1, 2014, p. 5)
- Task - *refers to a sequence of interactions undertaken to achieve a goal - glance behaviour may be measured over the duration of a task.*

There are various studies discussed in literature which choose to focus on glance frequency rather than glance duration as a number of studies show that mean glance duration does not change based on task difficulty or tasks that are more visually distracting whereas glance frequency does. In 2006 Zhang et al., conducted a driving simulator study where they asked participants to follow a lead vehicle and read a varying number of words on an in-vehicle display. The results of the study showed that although glance frequency increased as the number of words increased, mean glance duration did not vary as the participants looked at the screen for 1-2 seconds at a time and if they did not gather all the information needed they made more glances towards the screen (Zhang, Smith and Witt, 2006). It has also been established by Wierwille (1991) that the duration of the glances made away from the forward scene does not vary significantly between different drivers; however, a larger difference is observed between the frequencies of glances. A study conducted by Labiale (1996) investigated the effect of written road messages being displayed in the vehicle on driving performance. They collected glance behaviour data in the form of glance duration and frequency as well as lane position and speed data. Their results showed that mean time duration stayed stable as the complexity of the message being displayed increased. However mean glance frequency increased with increased complexity.

In this body of work glance frequency has been chosen as the eye tracking measure of interest instead of glance duration related measures. The aim of this work is to understand the interaction mechanisms that will reduce glance frequency to zero, in other words, help achieve non-visual interaction with in-vehicle touchscreens. Non-visual interaction indicates no glances made away from the road. Hence the focus of the analysis on the data collected during the user trials was not glance duration related metrics.

Equipment and procedures captured in ISO 15007-2 have been used in the trials, such as video cameras in the simulator and eye tracking glasses. The information presented in Figure 11 has been collected from participants during each trial (ISO 15007-2, 2014).

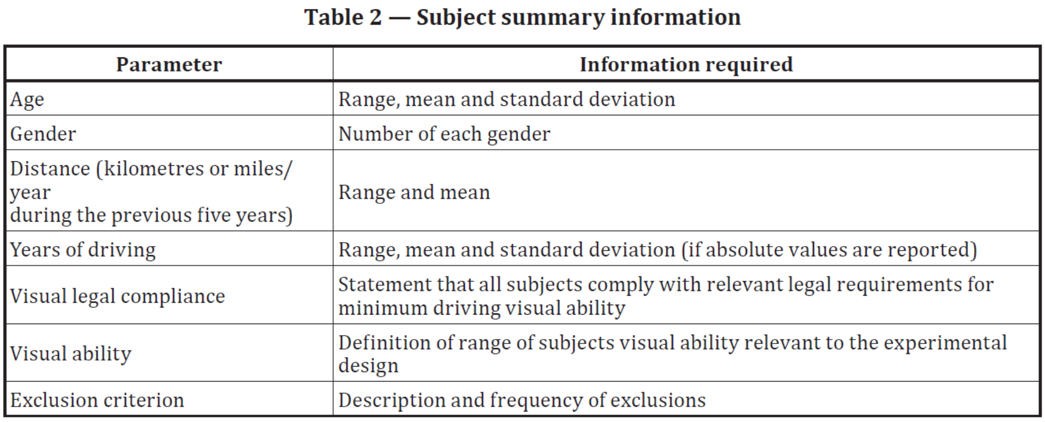


Table 2 — Subject summary information

Parameter	Information required
Age	Range, mean and standard deviation
Gender	Number of each gender
Distance (kilometres or miles/ year during the previous five years)	Range and mean
Years of driving	Range, mean and standard deviation (if absolute values are reported)
Visual legal compliance	Statement that all subjects comply with relevant legal requirements for minimum driving visual ability
Visual ability	Definition of range of subjects visual ability relevant to the experimental design
Exclusion criterion	Description and frequency of exclusions

Figure 11. Information collected from participants (ISO 15007-2, 2014, p. 7)

3.4 TASK PERFORMANCE MEASURES

Measurements related to secondary task performance are an indication of how distracted the driver is and how able they are to assign the required resources for the secondary task whilst driving. This becomes particularly difficult when the driving scenario is complex, and the demand required by the driving task is also high. Task performance can also be an indicator how easy it is for the driver to complete a task whilst driving. There are studies in literature that have used secondary task performance measures as an indicator of the level of demand imposed on the driver. Task time (time taken to complete secondary tasks) and error rates (the number of errors when performing the secondary task) are measures that indicate task performance (Jenness *et al.*, 2002;

Orphanides and Nam, 2017). As stated by Harvey et al. (2011b, p. 617) and also reiterated by other authors "*secondary task performance measures reflect the effectiveness and efficiency of the interaction with an IVIS"* (Jordan, 1998; Sonderegger and Sauer, 2009; Harvey, Stanton, Pickering, Michael McDonald, *et al.*, 2011). Productivity measures such as task time have been considered in the user trials conducted as a part of this thesis.

The instructions given to participants during each study aimed to emphasise the dual importance of speed and accuracy of the button press task and encourage natural interactions with the touch screen which could include non-visual use of the touchscreen. However, for all studies conducted the participants were reminded that the task of driving was their primary task. Specifically, the following instructions were given:

> *"Please complete each button press as quickly and as accurately as possible. Please drive as you would on a real motorway and remember that this is not a test of your abilities in any way".*

These instructions were to make sure that participants were driving as they would in a real driving environment but also, so they were aware that the secondary task was their secondary priority.

3.5 DRIVING PERFORMANCE MEASURES

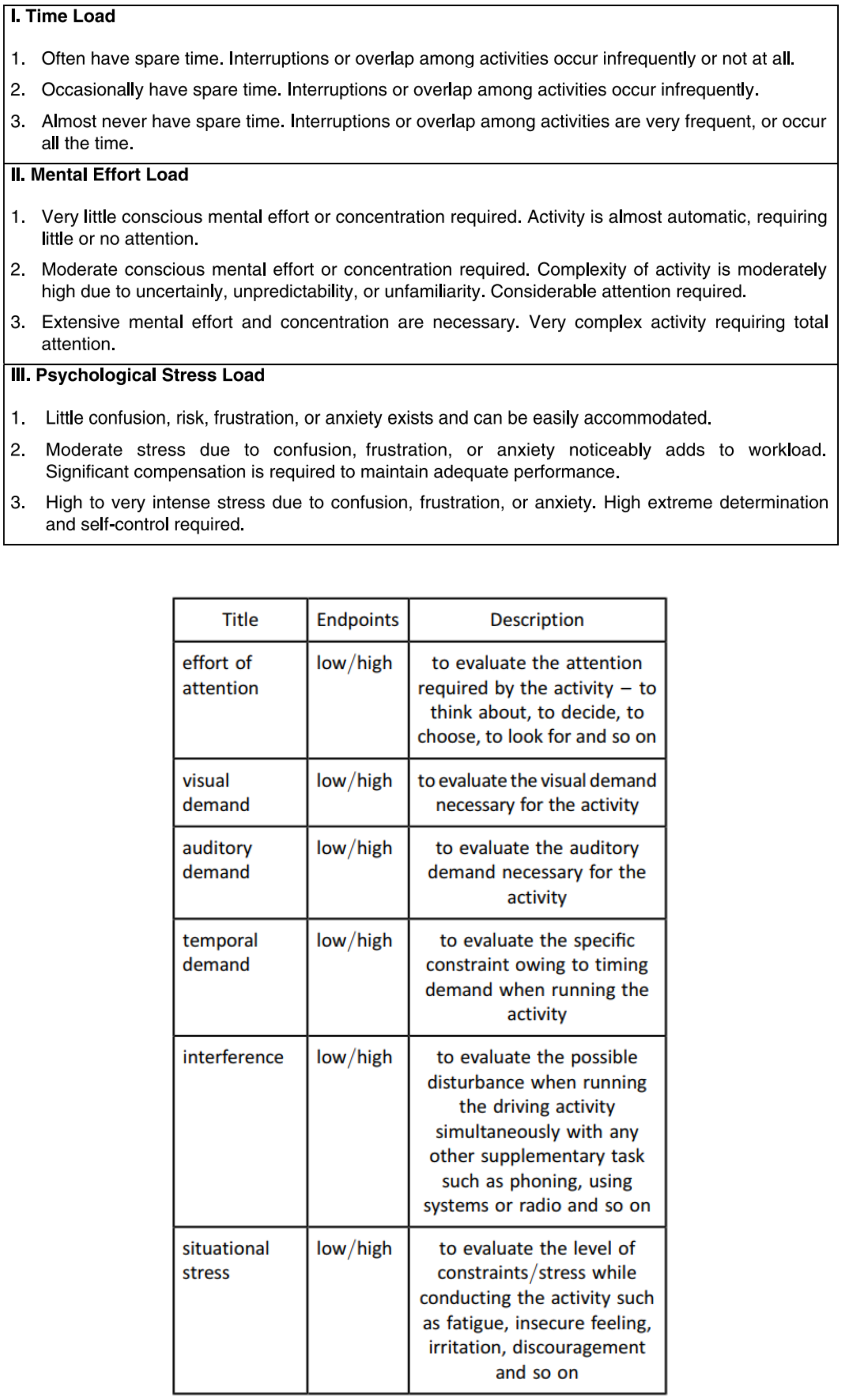
There are various measures that relate to driving performance and these can be categorised into two groups; lateral and longitudinal control measures. Lateral control measures consist of steering (Tsimhoni, Smith and Green, 2002; Ranney, Harbluk and Noy, 2005) and lane keeping/displacement

(Gellatly and Dingus, 1998; Tsimhoni, Smith and Green, 2002; Itoh *et al.*, 2004). And the longitudinal control measures consist of longitudinal acceleration (Gellatly and Dingus, 1998), longitudinal velocity (Gärtner, König and Wittig, 2001), and following distance (Ranney, Harbluk and Noy, 2005). Another measure, response time (Lee *et al.*, 2001; Ranney, Harbluk and Noy, 2005) is also an indicator of performance and measures responses to hazards on the road.

The measures that were used in the studies as a part of this thesis were standard deviation of lane position (lateral control) and standard deviation of speed (longitudinal control) which show the changes in lane position and speed which have shown to be affected by the demands of the secondary tasks. In the studies conducted, lane position was calculated as the distance of the vehicle the participants were driving, from the centre barrier within the driving scenarios. The changes in lane position indicate whether or not the secondary task has an impact on the steering and lateral control of the vehicle. The lower the standard deviation (i.e. less variability) of lane position the higher lane keeping performance (Regan, Lee and Young, 2009). Other work in literature show that as the secondary task demand increases, the standard deviation of lane position also increase (Serafin *et al.*, 1993; Siebert *et al.*, 2002; Horrey and Wickens, 2004b; Liang and Lee, 2010). Similarly, standard deviation of speed shows the variability in speed whilst performing the secondary task and driving simultaneously. Studies have shown that similar to the effects of secondary task performance on lane keeping; higher demands of secondary task result in higher variability in speed (Burns *et al.*, 2002; Ranney, 2008; Kircher *et al.*, 2014). The change in speed is also explained as a form of compensation to deal with the higher demand placed on the driver by the secondary task (Salvucci *et al.*, 2007).

3.6 SUBJECTIVE WORKLOAD MEASURES

There are different methods to evaluate subjective workload such as the Subjective Workload Assessment Technique (SWAT) (Reid and Nygren, 1988), NASA Task Load Index (NASA TLX) (Hart and Staveland, 1988), Driving Activity Load Index (DALI) (Pauzie, 2008), Cooper-Harper Scale (Cooper and Harper, Robert P, 1969) and the Bedford Scale (Roscoe, 1987; Roscoe and Ellis, 1990). The most commonly used scales in driving research are the SWAT and NASA TLX (Hendy, Hamilton and Landry, 1993). The SWAT uses three levels; low, medium and high for the measures of time load, mental effort load and psychological stress load (Figure 12). The three measures used in SWAT is based on the measures that have been hypothesised by Sheridan and Simpson (1979) who state that these measures can adequately represent subjective workload. The DALI has been developed specifically for driving research and is based on NASA TLX; although it is not as widely used as NASA TLX.



I. Time Load

1. Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.
2. Occasionally have spare time. Interruptions or overlap among activities occur infrequently.
3. Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.

II. Mental Effort Load

1. Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.
2. Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainly, unpredictability, or unfamiliarity. Considerable attention required.
3. Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.

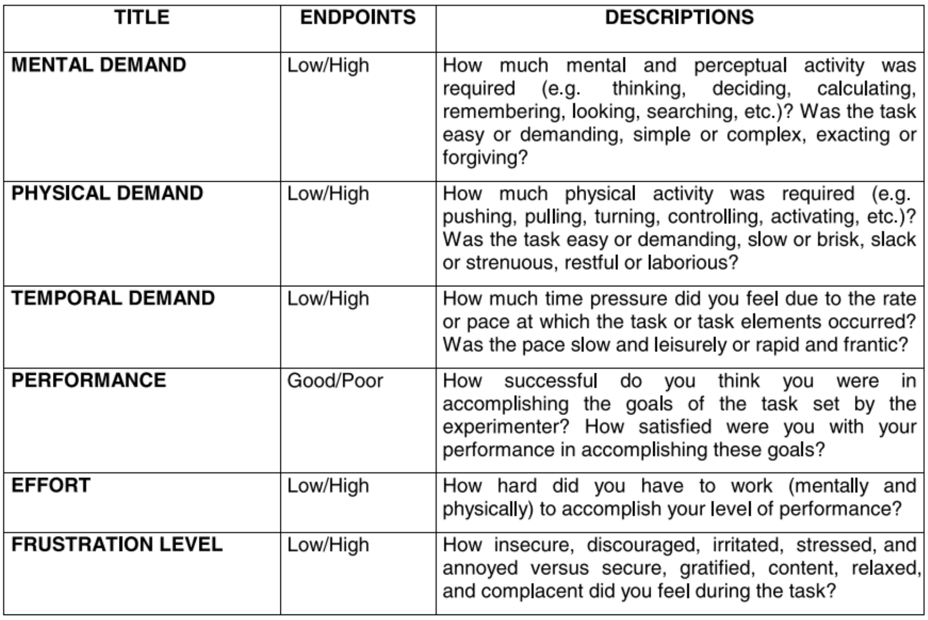
III. Psychological Stress Load

1. Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.
2. Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.
3. High to very intense stress due to confusion, frustration, or anxiety. High extreme determination and self-control required.

Title	Endpoints	Description
effort of attention	low/high	to evaluate the attention required by the activity – to think about, to decide, to choose, to look for and so on
visual demand	low/high	to evaluate the visual demand necessary for the activity
auditory demand	low/high	to evaluate the auditory demand necessary for the activity
temporal demand	low/high	to evaluate the specific constraint owing to timing demand when running the activity
interference	low/high	to evaluate the possible disturbance when running the driving activity simultaneously with any other supplementary task such as phoning, using systems or radio and so on
situational stress	low/high	to evaluate the level of constraints/stress while conducting the activity such as fatigue, insecure feeling, irritation, discouragement and so on

Figure 12. Top: Subjective Workload Assessment Technique (SWAT) rating scale dimensions (Rubio *et al.*, 2004)*; Bottom: Factors of Driving Activity Load Index (DALI)* (Pauzie, 2008)

NASA TLX has been used in driving research to measure subjective workload for many years (Lee *et al.*, 2001; Horberry *et al.*, 2006; Medenica *et al.*, 2011; Lasch and Kujala, 2012; Orphanides and Nam, 2017). It aims to break subjective workload into different categories; mental demand, physical demand, temporal demand, frustration, effort and performance (Figure 13). This scale assumes that the combination of these categories would give an indication of the workload experienced by people for most tasks. It is based on research across a variety of tasks from lab-based tasks to flying an aircraft. Most of this research aimed to answer questions regarding interface design or evaluation of interfaces. 31 per cent of the studies focused on visual and/or auditory displays, 11 per cent focused on vocal and/or manual input devices and 6 per cent focused on virtual or augmented vision (Hart and Staveland, 1988).



TITLE	ENDPOINTS	DESCRIPTIONS
MENTAL DEMAND	Low/High	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	Low/High	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	Low/High	How much time pressure did you feel due to the rate or pace at which the task or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter? How satisfied were you with your performance in accomplishing these goals?
EFFORT	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

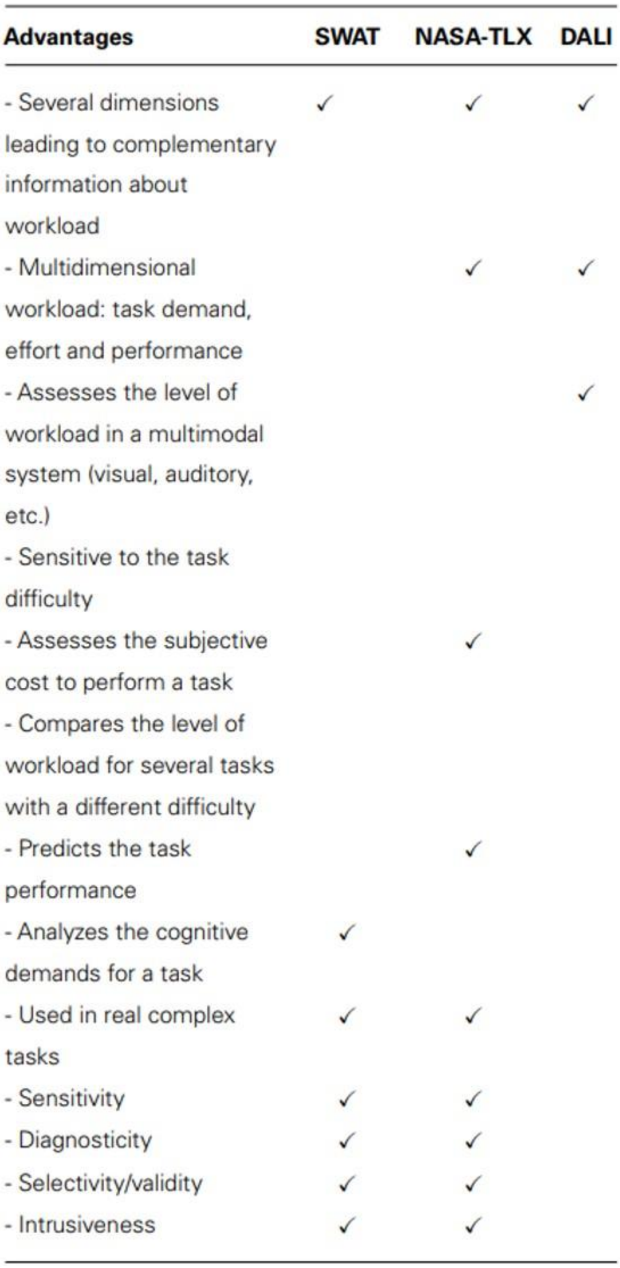
Figure 13. Rating scale definitions and endpoints from NASA TLX (Rubio *et al.*, 2004)

Paxion et al., (2014) used the seven criteria that have been identified to assess the subjective level of workload by Rubio et al., (2004) and Eggemeier et al., (1991) to compare SWAT, NASA-TLX and DALI and to identify the advantages of these three scales. The seven criteria are as follows:

1. *Sensitivity: detecting the changes of task difficulty and task demands,*

2. *Diagnosticity: identifying the changes in workload variations and the cause of these changes,*
3. *Selectivity/validity: being sensitive only to differences in cognitive demands,*
4. *Intrusiveness: not interfering with the primary task performance,*
5. *Reliability: reflecting consistently the mental workload,*
6. *Implementation requirements: including aspects such as time, instruments, and software for the collection and analysis of data, and*
7. *Subject acceptability: referring to the subject’s perception of the validity and to the usefulness of the procedure.* (Paxion, Galy and Berthelon, 2014, pp. 3–4)

The comparison can be seen in Figure 14.



Advantages	SWAT	NASA-TLX	DALI
- Several dimensions leading to complementary information about workload	✓	✓	✓
- Multidimensional workload: task demand, effort and performance		✓	✓
- Assesses the level of workload in a multimodal system (visual, auditory, etc.)			✓
- Sensitive to the task difficulty			
- Assesses the subjective cost to perform a task		✓	
- Compares the level of workload for several tasks with a different difficulty			
- Predicts the task performance		✓	
- Analyzes the cognitive demands for a task	✓		
- Used in real complex tasks	✓	✓	
- Sensitivity	✓	✓	
- Diagnosticity	✓	✓	
- Selectivity/validity	✓	✓	
- Intrusiveness	✓	✓	

Figure 14. Advantages of NASA-TLX, SWAT and DALI (modified from: (Paxion et al., 2014, p. 4)*)*

As seen in the assessment by Paxion et al., (2014) NASA TLX compared to SWAT and DALI cover more of the seven criteria used to assess these techniques. As NASA TLX has also been widely used in driving research and has shown to be a useful tool in measuring subjective workload in driving, it was chosen to be used in the studies conducted as a part of this work.

The NASA TLX questionnaire was given to participants during each trial discussed in the following chapters to gain an insight into the subjective workload experienced by participants when performing the secondary tasks whilst driving. These were also compared against the objective measures that indicate workload levels.

3.7 EQUIPMENT USED IN THE USER TRIALS

Below is the various equipment used during the user trials conducted a part of this thesis. These are both hardware and software such as; driving simulator, eye tracking equipment, software used for the driving simulator and in-vehicle display equipment. Four out of five of user trials were conducted at the University of Nottingham which is where most of the research discussed in this thesis was conducted. One of the user trials was conducted at Virginia Tech University, USA, as part of the author's visit to Virginia Tech as a visiting researcher.

3.7.1 Driving Simulators

Three different simulators were used for the driving simulator studies conducted as a part of this research. Two of these simulators were based at the University of Nottingham Human Factors Research Group (HFRG) and the third one was based at Virginia Tech University, USA.

Figure 15. Driving simulator at the University of Nottingham Human Factors Research Group (Honda)

The simulator that was used in the first two studies discussed in Chapters 4 and 5 is one of the simulators based at the HFRG (Figure 15). This is a fixed-based, medium-fidelity driving simulator which consists of the front half of a right-hand drive Honda Civic car positioned in front of a curved screen providing approximately 270° viewing angle. Three overhead projectors were used to project the driving scenario onto the curved screen. Rear and side mirror projections were also provided. An authentic steering wheel provided force feedback, and accelerator, brake and clutch pedals and indicators, situated within the car enabled the driver to interact with the car and the driving scenario. The simulated driving scenario and driving experience were created using STISIM (version 3) software[2]. A bespoke Java application is used by the STISIM software to calculate road speed which was then presented on an 8-inch LCD display fitted into the instrument panel which was used as the cluster.

---

[2] STISIM Simulator software - http://stisimdrive.com/driver-training/stisim-drive-dt-software/

Figure 16. Driving simulator at the University of Nottingham Human Factors Research Group (Audi TT)

The simulator used in the studies discussed in Chapters 7 and 8 is a medium-fidelity, fixed-based driving simulator at the HFRG (Figure 16). The simulator comprised of an Audi TT car located within a curved screen, providing 270° forward and side image of the driving scene through three overhead HD projectors. A Thrustmaster 500RS force feedback wheel and pedal set were integrated with the existing Audi steering wheel and pedals so that drivers interact with the original controls. In addition, the indicators and electrical controls remained fully operational within the vehicle. The driving scenario was created using STISIM Drive[3] (version 3) software to replicate a standard UK motorway, with speed information etc. exported dynamically to a bespoke Java application. A 7-inch Lilliput 668GL LCD screen was used as the dashboard within the vehicle to mimic the instrument cluster.

The driving simulator used in the user trial detailed in Chapter 6 was a fixed-based, medium-fidelity simulator, which is based in the COGENT Lab in the ISE department at Virginia Tech University (Figure 17). The simulator was

---

[3] http://stisimdrive.com/

formed of the front half of a left-hand drive 2014 Mini Cooper positioned in front of a curved screen providing approximately 270° viewing angle. One Epson PowerLite Pro G6900WU NL overhead projector was used to project the driving scenario onto the curved screen. The simulated driving environment was created using software called MiniSIM[4] which was developed by the National Advanced Driving Simulator and the University of Iowa.

Figure 17. Medium-fidelity driving simulator at Virginia Tech

3.7.2 Eye Tracking Equipment

The SensoMotoric Instruments (SMI) eye tracking glasses were used to track participants' eye movements (Figure 18). The glasses consisted of three cameras – one facing each eye and one facing the road scene, which allowed glance mapping for analysis. The eye tracking glasses were connected to a Lenovo laptop which had the eye tracking recording software iView by SMI with a USB cable for calibration and data recording. The glasses were calibrated using a three-point calibration before each drive for all participants.

---

[4] https://www.nads-sc.uiowa.edu/minisim/

A frame by frame analysis was used to extract information on glance frequency.

Figure 18. SMI Eye Tracking Glasses (iMotions, 2017)

3.7.3 In-Vehicle Displays

Two different touch screen laptops were used as the in-vehicle touch screen in all of the simulator studies as the in-vehicle touch screen. A 12.1" HP EliteBook 2740p tablet computer was used as the in-vehicle touch screen in the trials discussed in Chapters 4 and 5 and a 12" Microsoft Surface 3 was used for the studies discussed in Chapters 6, 7 and 8. The interfaces displayed on the touch screens were created using either PowerPoint 2013 or Matlab which allowed task times and error rates to be recorded.

Figure 19. Location of the in-vehicle touch screens in the user trials (Left: Virginia Tech driving simulator, Right: University of Nottingham driving simulator)

In the studies discussed in Chapters 4, 5, 7 and 8 the display was positioned to the left hand-side of the steering wheel (UK-based study, right-hand drive vehicle) and in the study discussed in chapter 6 it was positioned to the right-hand side of the steering wheel (US-based study, left-hand drive vehicle) (Figure 19). The positioning of the displays was based on the location of the centre console in recent vehicles (Figure 20).

Figure 20. Positioning of centre console in vehicles (Left: Mercedes (HARMAN, 2013) Right: Range Rover (CarWow, no date)*)*

3.8 SUMMARY OF CHAPTER

This chapter summarised the main methods used in the user trials discussed in this thesis. Some of the advantages and limitations of these methods have been outlined. The specific equipment used in the user trials has been described.

The next chapter discusses the first driving simulator study conducted as a part of this thesis which aimed to identify the effects of various characteristics of an in-vehicle touch screen interface (button size, location and contrast level) and their effect on secondary task performance, driving performance and glance behaviour.

4 CHAPTER 4: EFFECT OF BUTTON SIZE, LOCATION AND CONTRAST LEVEL ON GLANCE BEHAVIOUR

4.1 INTRODUCTION

When driving due to the demands of the primary task of driving the driver is required to keep their eyes on the road ahead for a majority of the time (Burnett and Joyner, 1997; Tsimhoni, Yoo and Green, 1999; Palmer *et al.*, 2017). As a result of the visual demand required by the task of driving, drivers have a limited capacity to interact with the controls on the IVIS. Hence when the driver interacts with an in-vehicle touch screen they should be able to do so without having to take their eyes off the road to the point where it will start decrementing their driving performance. In order to understand more about the potential for non-visual interaction with an IVIS, inspiration was taken from the way in which visually-impaired users interact with a touch screen and some of the learnings from touch screen display design for the visually impaired users have been incorporated into the study design.

The approach of making use of non-users in the design process has been previously discussed by Burnett & Porter (2001). Burnett & Porter argue that "*in essence, regarding the in-vehicle scene, drivers can largely be seen to be resource-limited with respect to their visual sense"* and that *"design-related benefits can be gained from considering the needs of blind people and those with low vision when developing future haptic control interfaces for vehicles"* (Burnett and Porter, 2001, p. 526). They suggest that considering users who have to overcome certain restrictions which impact their interaction with technology potentially could encourage novel designs, although they also highlight that new interfaces would still need to be tested with the real users of the system. There is also useful knowledge in previous research on designing controls for non-visual use based on work conducted for users with visual impairments (Vanderheiden, 1992; Gill, 2000).

In order to understand the design principles of displays requiring limited visual acuity, existing literature was consulted concerning the design of touch technologies for the visually impaired. The aim was to identify guidelines or approaches used in this area and explore the possibilities of implementing these in a driving environment to encourage ‘blind interactions’. It is suggested that in some respect, the limited visual acuity associated with visual impairment may be similar to the divided attention nature of interacting with an in-vehicle display while driving and thus these design principles may allow or encourage successful interaction with no vision. A number of technologies were identified that allow visually impaired users to interact with touch screen devices such as phones, tablets, and more commercial devices such as ATMs, more effectively (Brewster and Brown, 2004; Kane *et al.*, 2008; Frey, Southern and Romero, 2011). It is believed that in-vehicle touch screen design could benefit from the design principles used in touch technology design for the visually impaired. The ideal scenario whilst driving and using a touch display would be for the driver to keep their eyes on the forward driving scene at all times and still be able to perform secondary tasks accurately and efficiently. Currently, there appears to be little evidence to suggest that this has been adopted as a design principle, as in-vehicle touchscreen interfaces still gravitate towards employing interactions which demand elevated levels of visual attention and provide visually captivating feedback to drivers.

There are several design principles/guidelines for the design of touch screen devices for the visually impaired:

- _Feedback:_ As one of the main issues of interaction with touch screens for the visually impaired is the lack of tactile feedback designers use auditory feedback for the visual elements on the screen (Kane *et al.*, 2008; Su *et al.*, 2010; Oliveira *et al.*, 2011).
- _Visual appearance of targets_: Other guidelines such as the Web Content Accessibility guidelines (WCAG) (Kirkpatrick *et al.*, 2018) highlight target size (Kobayashi *et al.*, 2011), contrast (Gill *et al.*, 2013) and colour for designers to consider when designing website for the visually impaired.
- _Efficiency:_ One guideline that can be applied to in-vehicle touch screen design for the driver population is that the system should be quick and effective to learn which could also be a challenge for the designers as they would have to consider the representation of numerous functions (Kane, Wobbrock and Ladner, 2011).
- _Positioning of targets:_ Another design guideline - which was used in this study - is utilising fixed, or bounded, regions on a touch screen such as the edges and the corners of the screen. This is justified in a study carried out by Kane et al. (2011), where both visually impaired and sighted participants were asked to invent gestures that could be used to execute certain functions using a tablet PC. The results of their study showed that of the gestures created by sighted participants, 12.8 per cent of them used an edge and 24.2 per cent of them used a corner. However, blind participants created 61.1 per cent of edge gestures and

> 64.8 per cent of corner gestures. Such findings indicate that visually impaired users find it easier to use touch screens if the 'buttons' or active zones they need to acquire are closer to the edge and corners of the screen. Therefore, utilising these target areas (Sears and Shneiderman, 1991) on an in-vehicle touch screen may encourage drivers to interact with the device without having to look away from the road ahead (Kane, Wobbrock and Ladner, 2011).

Research on design considerations for touch screens in other domains have also been considered. An experiment conducted by Sun et al., (2007) has investigated the interaction of firefighters with touch screen displays. Firefighters will be subject to certain limitations in their interaction with a touch screen, caused by hazardous operating conditions, time pressure and restrictive clothing. Independent variables were button size (20x20, 30x30, 40x40, and 50x50 pixels), spacing between the buttons (0, 5, 10 and 20 pixels), type of button/icon (digit buttons, picture icons and combination) and existence of glove when interacting with the display. Their dependant variable was operator performance which was measured using task time. The results of their experiment showed that although there was no significant effect of spacing between the buttons and existence of gloves on operator performance, there was a significant effect of button type and size. Participants were faster when pressing the buttons when they were larger than or equal to 40x40 pixels. Operator performance was also significantly better for digit buttons compared to picture icons and combination. Another study was conducted by Parhi et al., (2006) that aimed to determine the optimal target sizes for one-handed thumb use of mobile handheld touch screen devices.

The two-phase study investigated a threshold for the target size for single-target (discrete) pointing tasks (e.g. activating buttons and checkboxes) and for widgets used for a sequence of taps (serial) (e.g. text entry). They also considered target location as one-handed use of the device constrained thumb movement. The results of their study showed that although participants were quicker in performing the tasks as the target size increased, they did not find any significant differences in error rates between target sizes that were larger than or equal to 9.6mm for discrete tasks and targets that were larger than or equal to 7.7mm for serial tasks. They suggested that a target size of 9.2mm for discrete tasks and 9.6mm for serial tasks were large enough for a one-handed thumb interaction with a handheld touch screen device.

Contrast is defined as "*the brightness difference of adjacent areas and determines to a large extent the ability of people to see details*" (Campbell and Maffei, 1974). Studies show that high contrast levels between a target displayed on a screen and the background makes visibility and interaction with the target easier for users. A study conducted by Harrison et al., (1995) assessed an prototype interface and found that opposing contrast levels resulted in significant improvements in visibility and distinctiveness. It is also stated by Kurniawan et al., (2006) that negative polarity (i.e. light text on a dark background) makes it easier for people with visual impairments to identify visuals displayed on websites. It has been shown in literature that "*the contrast-transfer properties of the eye's optical system are known to be nearly as good in the periphery as in the fovea*" (Wang, Thibos and Bradley, 1997; Schepers and Den Brinker, 2011, p. 321)

The study discussed in this chapter aimed to understand various characteristics of touchscreens that have an influence on glances made away from the road ahead towards the in-vehicle display. Supported by the information presented on various methods used in driving research in Chapter 3, an exploratory driving simulator study was conducted to investigate whether certain combinations of button size, location and contrast ratio for the touchscreen menu buttons could be used to achieve ‘non-visual interaction’ (during the interaction with the IVIS the driver does not take their eyes off the road). This study aimed to address the first overall research question of the thesis:

> ***RQ1. What are the design characteristics of in-vehicle touch screens that can help in achieving non-visual interaction?***

RQ1 was broken into more specific research questions which were addressed in this study which aim to gain a better understanding of the design characteristics that contribute to non-visual interaction.

RQ1.1. How does the size of the items displayed on the IVIS affect the number of off-road glances?

RQ1.2. How does the location of the items displayed on the IVIS affect the number of off-road glances?

RQ1.3. How does the contrast level of the items displayed on the IVIS affect the number of off-road glances?

4.2 METHOD

4.2.1 Participants

Twenty-four participants (15 Male, 9 Female) were recruited from the University of Nottingham staff and students through email advertisements and posters (Mean age = 30; s.d. 11.4 years). All participants held a UK driving licence, were experienced drivers (mean time with licence, 11 years; mean annual mileage, 8500 miles) and had experience using touch screen devices (e.g. tablets, mobile phones, notebooks). They owned at least one touch screen device that they interacted with on a daily basis.

4.2.2 Design

A within-subjects design was adopted, where the three independent variables were: button size, location and contrast level. Participants were asked to drive four short routes. During each drive, target buttons were randomly presented in four different sizes (small = 2x2cm, medium = 6x6cm, large = 10x10cm and extra-large = 14x14cm) (Figure 23) and in twelve different locations (4x corners, 4x sides and 4x middle) on the screen (Figure 22). Corner buttons had two, edge buttons had one and middle buttons had no sides bordering the touch screen.

The contrast level remained consistent during each drive but differed between drives. The contrast levels were calculated using the following method. First the relative luminance was calculated for colour chosen for the targets in each condition using the RGB values of these colours (seen in Table 2).

$$Relative\ Luminance\ (L) = (0.2126\ \times\ Rg) + (0.7152\ \times\ Gg) + (0.0722\ \times Bg) \qquad (1)$$

Table 2. RGB values of the colours chosen for the targets for each condition

	R	G	B
Contrast 1	255	255	255
Contrast 2	191	191	191
Contrast 3	128	128	128
Contrast 4	64	64	64
Background	0	0	0

In order to calculate the relative luminance (L) the RGB values were converted to Rg, Gg and Bg values using the following formula:

$$if\ R\ \leq 10\ then \quad Rg = \frac{R}{3294} \quad if\ not\ then \quad Rg = \left(\frac{R}{269} + 0.0513\right)^{2.4} \tag{2}$$

Once the relative luminance values were calculated for each condition these were compared with the relative luminance value of the background colour (Table 3).

$$Contrast\ Ratio = \frac{(L_1+0.05)}{(L_2+0.05)} \tag{3}$$

Table 3. Rg, Gg, Bg values, relative luminance values and contrast ratios of each condition (Relative luminance of background colour = 0)

	Rg	Gg	Bg	Relative Luminance	Contrast Ratio
Contrast 1	0.998	0.998	0.998	0.998	**20.964**
Contrast 2	0.520	0.520	0.520	0.520	**11.395**
Contrast 3	0.215	0.215	0.215	0.215	**5.302**
Contrast 4	0.051	0.051	0.051	0.051	**2.019**

The contrast levels consisted of the highest possible contrast level that was possible to achieve on the display and the lowest contrast level that still allowed for the items displayed on the screen to be visible to the driver. The two contrast levels were then chosen as two points in between the maximum and minimum point. This was also representative of what drivers may come across in real world in-vehicle touchscreens. In all conditions, a single white square button was presented on the screen at a time. The order of presentation of the screens was randomised during each drive and the order of the conditions was counterbalanced between participants.

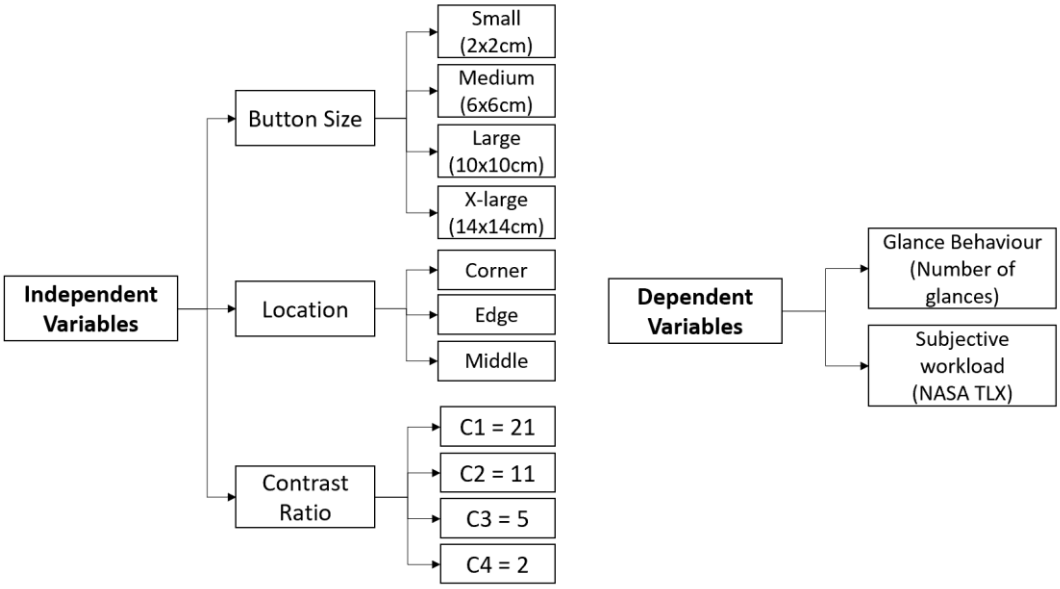


Figure 21. Independent and dependant measures

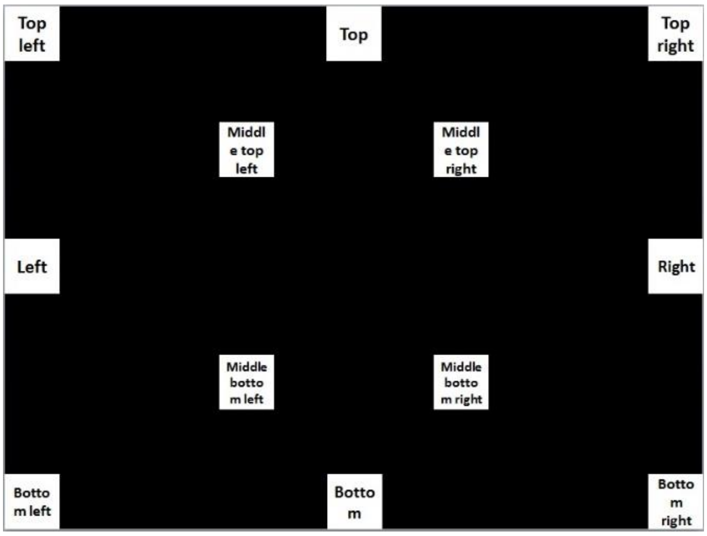


Figure 22. Different button locations presented on the display (the buttons did not have any text presented on them during the study)

For each condition, participants began with their left hand at the same position on the steering wheel (approximating to '10-o'clock' on an analogue clock face) and were asked to press the button presented on the screen as quickly and as accurately as possible following the presentation of a new stimulus. However, they had been reminded prior to the drive that the primary task was the driving task and that they should drive as safely as possible. After pressing the button, it disappeared from the screen, and participants were instructed to return their hand back to the steering wheel (to the same ’10-o’clock’ position) so they could start each task from the same point on the steering wheel. Participants heard two different audio tones for when a button appeared on the screen and when they successfully pressed the button and it disappeared off the screen. Participants completed 48 button presses during each drive. After each drive they were asked to complete a NASA TLX questionnaire (Hart and Staveland, 1988) on subjective workload (Appendix 11.1).

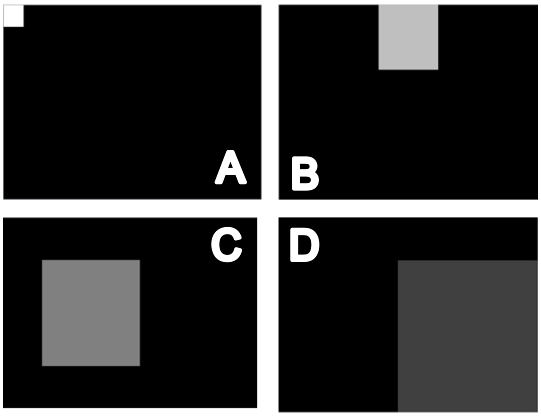


Figure 23. (A) Small button, contrast level 1, corner; (B) medium button, contrast level 2, edge; (C) large button, contrast level 3, middle; (D) extra-large button, contrast level 4, corner (Note: letter did not appear during study)

4.2.3 Apparatus and Stimuli

The driving scenario consisted of a UK motorway with trees and fields to both sides. The road itself was a straight road with no bends. Participants were required to follow a yellow car on the left lane of the motorway (Brookhuis, Waard and Mulder, 1994) and were asked to stick to the speed limit and keep a safe headway distance. The speed of the lead car varied from 60mph to

70mph. There were no lane changes involved in the scenario. The car used for the simulator was a right-hand drive car and the touch screen was located to the left side of the steering wheel in the centre console.

A single button appeared on the screen at a time and the order of the buttons was randomised for each participant. The order of presentation of the four contrast levels was also counterbalanced between participants. Participants were asked to press the button with one finger and they used their left hand to interact with the screen. Participants were also asked to wear the SMI eye tracking glasses to collect glance behaviour data (Chapter 3) which was calibrated at the beginning of the study for each participant.

4.2.4 Procedure

Before they started the study, participants were given an information sheet to read and a consent form to sign (Appendix 11.3). They also filled out a data capture form to collect basic information such as age, number of years with a UK driving licence, annual mileage and experience of using touch screen devices (Appendix 11.2). Participants were then given 5-10 minutes to test drive the simulator and familiarise themselves with the controls and the driving scenario. They were also shown an example of the interface to know what to expect when they were interacting with the touch screen.

After the test drive, each participant completed four drives – representing each of the four contrast levels – which lasted approximately 10 minutes each. For each drive participants were instructed to press the button that appeared on the screen. The buttons were presented with a 3 to 5 seconds’ gap in between to give the participants enough time to place their hand back on the steering wheel. Participants were also asked to drive as they naturally would in a real driving environment and to remember that their primary task was the driving task. A semi-structured interview was also conducted at the end of the study on what the participants thought about the touch screen/button designs in general. The whole study took approximately 45 minutes to complete.

4.3 RESULTS

4.3.1 Glance Frequency

A three-way repeated measures ANOVA was conducted to determine the effects of button size, button location and contrast levels on glance frequency. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the three-way interaction, $\chi^2(170) = 294.564$, p = .0001 and for the main effect of button size, $\chi^2(5) = 35.094$, p = .0001. Epsilon (ε) was 0.405 for the three-way interaction and 0.543 for button size, as calculated according to Greenhouse-Geisser, and was used to correct the three-way repeated measures ANOVA. The three-way interaction was not statistically significant F (7.284, 167.535) = .802, p = .592. However, there was a significant main effect of button size F (1.625, 37.369) = 17.802, p = .0001 and button location F (2,46) = 3.982, p = .025 on glance frequency.

Table 4. Significant differences on glance frequency between all button sizes

(I) Size		Mean Difference (I-J)	Std. Error
Small	**Medium**	.152*	.048
	Large	.270*	.066
	Extra-Large	.365*	.072
Medium	**Small**	-.152*	.048
	Large	.118*	.042
	Extra-Large	.214*	.051
Large	**Small**	-.270*	.066

	Medium	-.118*	.042
	Extra-Large	.095*	.023
Extra-Large	**Small**	-.365*	.072
	Medium	-.214*	.051
	Large	-.095*	.023

Pairwise comparisons showed that there was a significant difference between all button sizes (Table 4). Small buttons resulted in a significantly higher glance frequency and extra-large buttons resulted in a significantly lower glance frequency. Also, the buttons located on the edge of the touch screen resulted in considerably lower glance frequencies than those located on the corners of the screen.

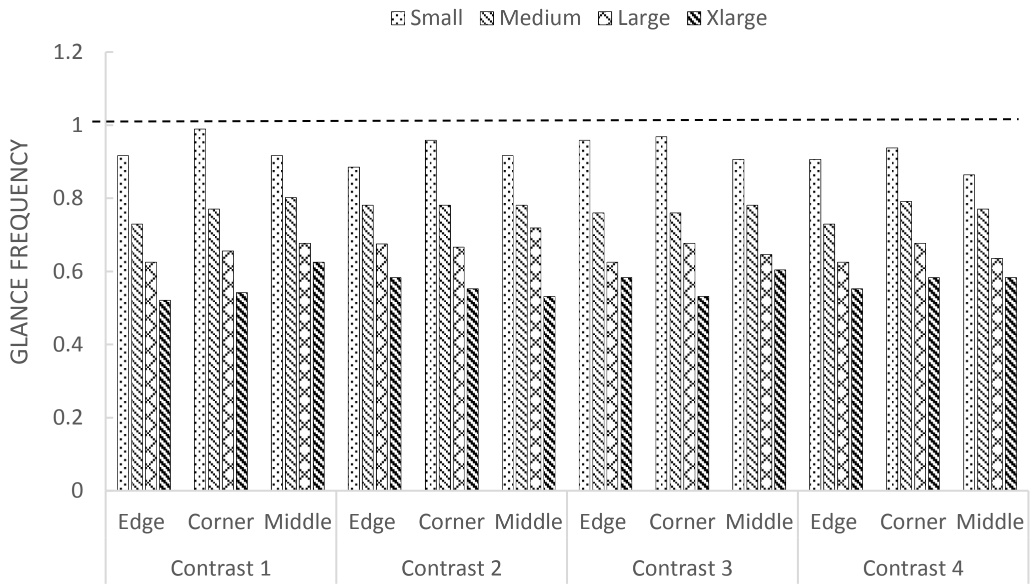


Figure 24. Mean glance frequency across all conditions of the study

As seen in Figure 24 the average glance frequency for all combinations of button size, location and contrast level were below one glance made away from the road ahead. These results show that for some of the interactions participants were able to complete the button selection task without taking their eyes off the road. Consequently, Table 5 shows the percentage of zero glances for the four different button sizes and three different locations. This shows the percentage of presentations of each button type in which drivers did not glance towards the screen when completing the button selection task. The data is not split by contrast level, as this variable was found to be non-significant in terms of visual behaviour.

Table 5. Percentage of zero glances for the different buttons

	Edge	Corner	Middle
Small	10.42%	8.59%	11.20%
Medium	25.00%	22.66%	22.66%
Large	36.46%	33.85%	34.38%
Extra-Large	44.53%	45.31%	44.53%

Extra-large corner buttons were found to produce the highest percentage of zero glances; specifically, the button with the highest percentage of zero glances was top right corner extra-large button with 48.96 per cent zero glances. 12.5 per cent of participants did not take their eyes off the road at all at any instance when interacting with the extra-large buttons. On the other hand, 16 per cent of participants on average made at least one glance or more towards the touch screen whilst interacting with every single button displayed on the screen for every button size, location and contrast level. There were also some instances where some participants made two or more glances away from the road with the highest number of off-road glances being five. Across all button sizes, locations and contrast levels 3.5 per cent of button presses resulted in two or more off-road glances. 56 per cent of the 3.5 per cent of button presses that resulted in two or more off-road glances were for small buttons.

4.3.2 NASA TLX

The overall results below show the perceived workload experienced by the participants for different contrast levels (Figure 25). A Friedman test was run to determine if there were differences in NASA TLX results between different contrast levels. The median values for the different levels were C1 = 41.50, C2 = 39, C3 = 36 and C4 = 41 but no statistically significant effect of contrast level on the overall NASA TLX scores was found $X^2(3) = 5.296$, p = .151.

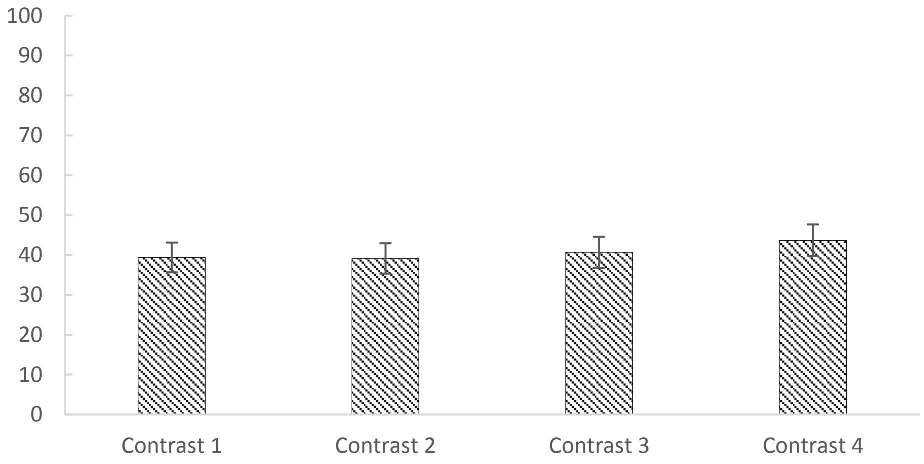


Figure 25. Overall NASA TLX results across all contrast levels (error bars: Standard Error)

4.4 DISCUSSION

This study investigated drivers' interactions with different button sizes, locations and contrast ratios presented on an in-vehicle touch screen and observed the effects of these different elements on glance frequency and subjective workload whilst driving. The aim of the study was to identify the characteristics for in-vehicle touch screen buttons that influenced glance frequency. The characteristics chosen in the study were based on existing research and principles on in-vehicle display design and touch screen design in domains other than driving (Parhi, Karlson and Bederson, 2006; Sun, Plocher and Qu, 2007; Kane, Wobbrock and Ladner, 2011; Kirkpatrick *et al.*, 2018).

The results of the study showed that smaller buttons required significantly more glances made towards the touch screen than the largest size of buttons presented. The results also highlighted that the highest mean glance frequency for small buttons across all conditions was 0.92 which is still less than 1 glance. The button size and location that required the greatest number of glances away from the road was the small button located at the bottom right of the display which on average required more than one glance compared to all the other buttons. A possible explanation for this may have been the fact that the location of this button was obscured by the driver's left hand in some cases as the study took place in a right-hand drive car with the touch screen positioned to the left of the steering wheel. Another reason may have been that the buttons that were displayed at the bottom of the display were not as within the line of sight of the driver as those that were presented nearer the top of the display (Horrey and Wickens, 2004a; Dukic, Hanson and Falkmer, 2006; Wittmann *et al.*, 2006). On the other hand, the extra-large button size required the least number of glances to complete the button selection task out of all the button sizes presented. The study has shown that it is possible to activate the largest buttons with no glances away from the road ahead as these buttons provide a larger responsive area on the display.

Out of all the extra-large buttons the one in the top right corner of the screen required the fewest glances made away from the road. This may have been a result of this specific button's proximity to the driver on the touch screen. Top right corner of the screen is also more in line with the driver's sight– within their peripheral vision - when looking at the forward road scene which may have resulted in fewer glances as drivers were able to see this button in their peripheral vision. Items displayed on in-vehicle displays that are further away from the driver's line of sight are likely to result in higher visual distraction (Horrey and Wickens, 2004a; Dukic, Hanson and Falkmer, 2006; Wittmann *et al.*, 2006).

Figure 26. Glance behaviour during interaction with the touch screen a) gaze on forward scene during primary task; b) gaze during secondary task; c) gaze after completing the task

Throughout the study and using the videos collected during the study it was observed that participants adopted different strategies and glance behaviours when interacting with the interface. As discussed, 12.5 per cent of the participants were able to find and select a majority of the buttons without having to take their eyes off the road. On the other hand, 16 per cent of participants made at least one glance towards the touch screen. Based on observations made from the video data collected it was apparent that some participants looked at the touch screen when they had already located the button and were in the process of selecting it (i.e. aiming movement). They were observed to be making glances towards the screen at this point to confirm that their finger was on the button before selecting it. Other participants glanced towards the display as soon as the button appeared to try and find the button with their gaze (i.e. target detection) (Figure 26).

The highlight of the results from this study was that there was a group of participants who were able to achieve blind interaction. Hence it is important to understand how these participants were able to achieve an interaction of this nature. By understanding the behaviour of these participants, it may be possible to identify ways for the 16 per cent of the participants who looked at the screen at least once during each interaction to also achieve blind interaction. It is known from literature that a sufficient practice of certain tasks could result in establishing muscle memory which may allow the user to perform the interaction without relying on vision (Proteau *et al.*, 1987; van Dam, 1997; Ecker *et al.*, 2009). It is also important to consider that in-vehicle displays in general – and in this study – are placed in the periphery of the driver. Similar to muscle memory, literature also shows the utilisation of peripheral vision during highly visual foveal tasks can allow the user to keep their attention on the foveal task but still be able to detect information in the periphery (Nikolic and Sarter, 2001; Somervell *et al.*, 2002).

Another finding worth highlighting from the study is that the size of the button as well as button location had a significant effect on glance frequency. Hence there are certain design elements that could have an impact on achieving blind interaction with the in-vehicle display if combined appropriately.

4.5 SUMMARY OF CHAPTER

In summary this study has shown that contrast ratios do not have a significant effect on glance frequency. However, it has shown that increased button sizes significantly decrease glance frequency. Most importantly this study has demonstrated that some participants are able to successfully complete the target selection task without requiring any glances away from the road for extra-large buttons. This highlights the possibility of achieving “blind interaction” with in-vehicle touch screens with the appropriate design characteristics. However, it also highlights the importance of understanding the reasons behind those who were able to achieve non-visual interaction. A further consideration is the number of buttons displayed on the screen which may influence the glances made away from the road as the target detection phase of the selection task would be more complex for a display of more than one target. The number of targets could also have an impact on the off-road glances during the aiming phase of the selection task.

The study discussed in the next chapter investigates the effect of the number of items displayed on an in-vehicle touch screen on glance frequency and task performance. This is achieved by a similar driving simulator study during which participants are presented with a different number of items on an in-vehicle display whilst driving.

5 CHAPTER 5: EFFECT OF NUMBER OF BUTTONS PRESENTED ON AN IN-VEHICLE DISPLAY ON GLANCE BEHAVIOUR

5.1 INTRODUCTION

Having established the importance of the effect of location and size of buttons displayed on in-vehicle touch screens on off-road glances in the previous chapter, the next area of investigation is understanding the effect of the number of buttons presented on the screen on glance behaviour. The study discussed in the previous chapter investigated the presence of a single button in order to explore other independent variables. However as real-life displays have more than a single button presented on them at a time to represent a variety of functions, a key goal in this study was to understand the threshold of the number of buttons present at which blind interaction with a touchscreen is possible, i.e. no off-road glances.

In-vehicle touch screens typically have a number of buttons presented on them at a time allowing the driver to have access to a variety of functions. The location of these buttons could change on each screen to represent a different function. In order to complete a single task, the driver may be required to go through a number of menu levels. For example, in order to select a song from their favourites list, the driver may be required to perform the following actions; 1) select ‘music’ from the main menu, 2) select ‘favourites’ within the music menu, 3) scroll down a list of songs within the favourites list, 4) make a selection when they have found the song they were searching for. It is a challenging task for designers of these displays to choose the ideal number of buttons presented on a screen as fewer buttons may result in more sub-levels for the driver to go through to reach their end goal. On the other hand, the presence of a higher number of buttons to counteract having various levels for each task could also result in high visual demand imposed by the display causing the driver to take their eyes off the road for longer periods of time. This represents a trade-off between menu depth (i.e. number of menu screens) and breadth (i.e. number of buttons on any single screen).

Although there have been attempts at identifying an acceptable number of items presented on in-vehicle touch screens that will decrease levels of visual demand, there is still a gap in existing research focusing on the number of buttons displayed on in-vehicle touch screens. Also, the little existing work in this area focuses on identifying a number for the items displayed in order to decrease off-road glance duration rather than trying to achieve non-visual interaction. A study conducted by Kujala and Saariluoma (2011) investigated the effect of menu structure and the number of items (n = 2, 4, 6, 9) displayed on a screen on glance behaviour. Their results showed that the number of items displayed on the screen had a significant effect on maximum glance durations. Another study conducted by Lasch and Kujala (2012) investigated the use of three types of scrolling methods (buttons, swipe, kinetic) in combination with three sets of items displayed on the screen (n = 3, 5, 7). The results were in line with their hypothesis showing that seven items were significantly more distracting than three and five items displayed on the screen. Similarly another driving simulator study conducted by Kujala and Salvucci (2015) investigated the number of items displayed (n = 6, 9, 12) on an in-vehicle display in grid or list form. Their results showed that there was a significant increase in the number of glances made towards the inside of the vehicle when the number of buttons displayed on the screen increased. Feng et al., (2017b) also conducted a driving simulator study to assess the effects of the number (n = 4, 8, 15) and size of buttons (14 mm, 24 mm, 33 mm) displayed on an in-vehicle touch screen whilst driving. Their results highlighted that although the difference in button sizes did not have a significant effect on the total eyes off road time (TEORT), the number of buttons displayed resulted in significantly higher TEORT for higher number of buttons displayed.

The aim of this driving simulator study was to investigate the effect of the number of buttons displayed on a touch screen on the number of glances. The following main research question was aimed to be answered as a result of this study:

> ***RQ1. What are the design characteristics of in-vehicle touch screens that can help in achieving non-visual interaction?***

More specifically the following research question was answered as a result of this study.

RQ 1.4. How does the number of items displayed on the in-vehicle touch screen affect the number of off-road glances?

5.2 METHOD

5.2.1 Participants

Sixteen participants (3 Females, 13 Males) recruited from the University of Nottingham took part in the study (mean age = 32.75; s.d = 13.8 years). All participants held a UK driving license and had experience driving on UK roads for at least 1 year (mean time with license = 13 years; average annual mileage = 8075 miles). All participants also had experience using touchscreen devices such as smartphones and tablets. They owned at least one touch screen device that they interacted with on a daily basis.

5.2.2 Design

A within-subjects study with one independent variable; the number of buttons presented on the touchscreen which had four levels; 1, 2, 4 and 6 buttons. The dependent variables were the number of glances, driving performance, and subjective workload. All participants completed four conditions in a medium-fidelity driving simulator. In each condition, they were presented with a different number of buttons on the touch screen located in the centre console of the simulator and were asked to locate and press a single button at a time (for the purposes of this study a button is identified as a white square presented on the touchscreen). The conditions were counterbalanced. During each condition the buttons were presented in the same layout (Figure 27) but the location of the target button varied on each screen. Before each button screen appeared, participants were informed verbally of the target button (e.g. “bottom right”, “top left”, “middle right”). Two distinctive audible tones were played for when the buttons appeared on the screen and when they disappeared off the screen as the correct button was pressed. Participants performed twenty-four button presses consecutively with a between each button appearance for each condition which varied from 5 to 10 seconds. The size (6x6cm) of the button selected was chosen based on studies discussed in literature focusing on target sizes (Jin, Plocher and Kiff, 2007; Kim *et al.*, 2011; Sesto *et al.*, 2012) , the size of the display used in the study and the findings from the previous study. As the aim of this study was to investigate the number of buttons presented on the display it was important that the size of the buttons allowed for a number of buttons to be displayed on the screen at a time. Hence the size of the extra-large buttons from the study discussed in the previous chapter was not used even though it was established that they resulted in the lowest off-road glances.

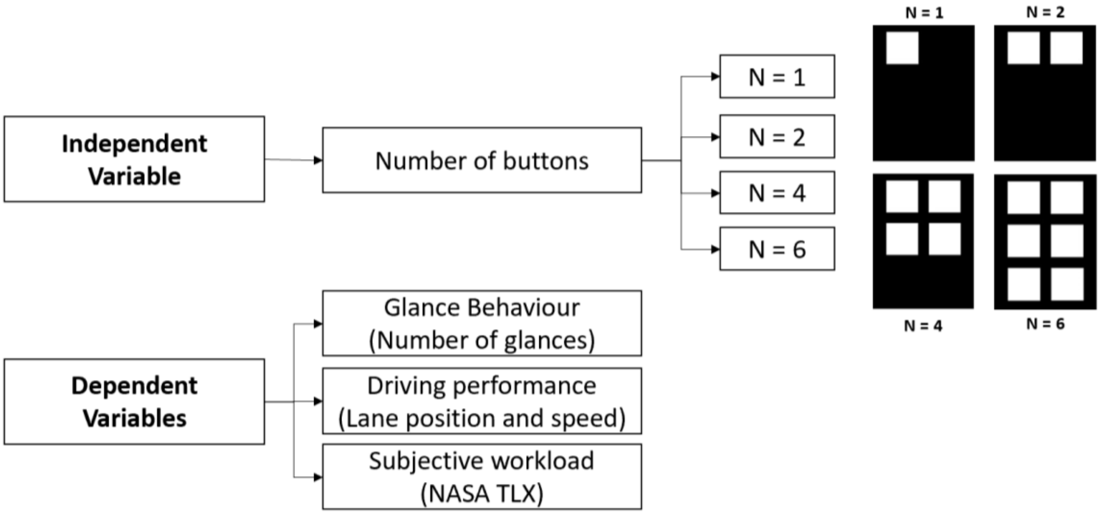


Figure 27. An overview of the independent and dependant variables

Participants were asked to fill out a NASA TLX questionnaire (Hart and Staveland, 1988) (Appendix 11.1) at the end of each condition to measure subjective workload.

5.2.3 Apparatus and Stimuli

The scenario employed for this study consisted of a simple motorway driving task. Participants were asked to drive on a UK motorway with trees and fields to both sides on a straight road with no bends. Participants were asked to follow a lead vehicle (Brookhuis, Waard and Mulder, 1994) whose speed varied between 60-70mph at what they perceived to be a safe distance. There were no safety critical events instigated by the lead vehicle. Participants were not required to interact with other vehicles and there were no lane changes involved in the scenario.

The buttons were presented on a touch screen that was located within the centre console of the right-hand drive car (i.e. to the left side of the steering wheel). The order of the presentation of target buttons and conditions was randomised for each participant to counteract any learning effects.

5.2.4 Procedure

At the beginning of the study participants were given a consent form and a data capture questionnaire to fill out to collect basic demographic information. Before each condition participants were shown the touchscreen interface they were required to interact with. Each participant completed a test drive for 5-10 minutes before starting the study to familiarise themselves with the driving scenario and the driving simulator controls.

During each condition participants were asked to drive for 1 minute before starting the touchscreen task. The whole study took approximately 45 minutes to complete. All participants provided written consent before taking part and were given shopping vouchers as compensation for their time at the end of the study.

5.3 RESULTS

5.3.1 Glance Frequency

A one-way repeated measures ANOVA was used to identify the statistical effect of the number of buttons presented on the in-vehicle displays on the number of off-road glances. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated, $\chi^2(5) = 20.876$, $p = .001$. Epsilon (ε) was 0.803, as calculated according to Huynh-Feldt, and was used to correct the one-way repeated measures ANOVA. There was no statistically significant difference between the number of glances made away from the road for the different number of buttons displayed on the touch screen F (2.409, 36.134) = 2.799, $p = .065$. As seen in Figure 28 the average number of glances away from the road for all four conditions was below 1. This highlighted that some participants were able to interact with the display without taking their eyes off the road for any of the button presses (seen in Table 6), hence achieving a zero-glance interaction. 56 per cent of the participants looked at the screen at least once for every single button press across all conditions. Although no statistically significant differences were found, a general trend was observed where the average number of glances made towards the touchscreen for one single button press increased as the button size increased for the current dataset as predicted. Also, as observed in Figure 28 the average number of off-road glances were all under one glance for all of the number of buttons.

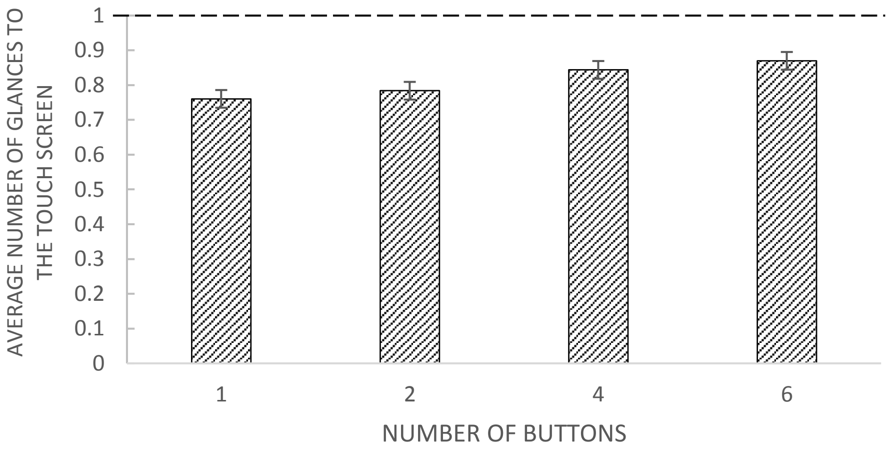


Figure 28. Average number of glances for a single button press for each condition (error bars: Standard Error)

Table 6. Percentage of participants who achieved non-foveal interaction for more than half of the button presses

	Percentage of participants
One-button	25%
Two-button	19%
Four-button	19%
Six-button	12%

Figure 29 shows the percentage of zero glance interactions for each condition. A one-way ANOVA was conducted to identify whether the differences between the percentage zero glances for different number of buttons was significant. No statistically significant differences were found, F (3, 60) = .395, p = .757. The graph also shows that zero glance interactions occurred less than 30% of the time for each button number. Although the difference between conditions was not statistically significant, as seen in the graph the percentage of zero glance interactions decreased as the number of buttons presented on the touchscreen increased.

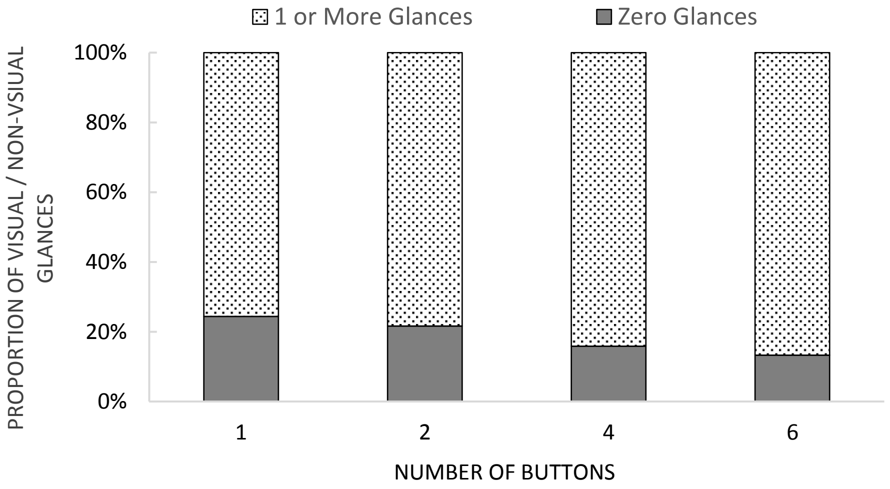


Figure 29. Proportion of zero glance interaction for each button number

5.3.2 NASA TLX

A one-way repeated measures ANOVA was conducted to determine the effect of the number of buttons displayed on the in-vehicle display on the overall NASA TLX measures (Figure 30). No statistically significant effect of the number of buttons was observed F (3,60) = 2.677, p = .055.

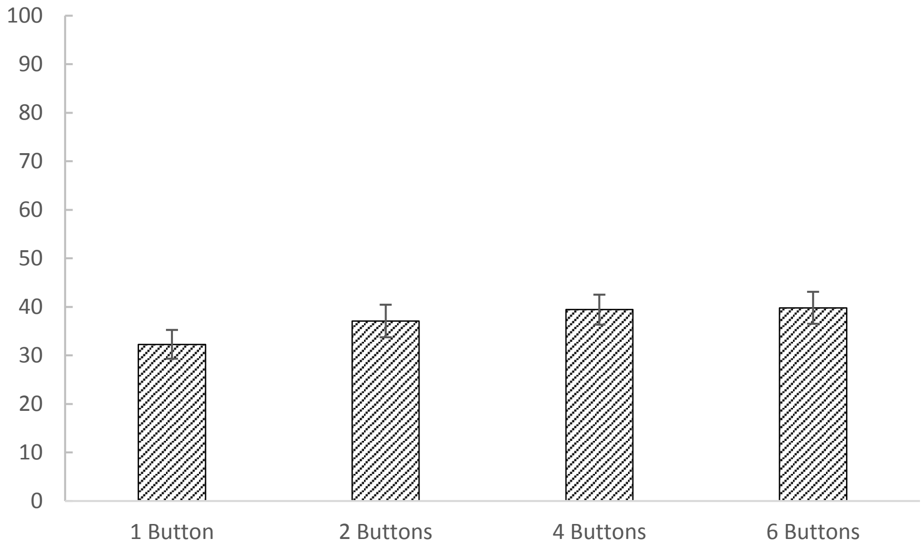


Figure 30. Overall NASA TLX results for all conditions (error bars: Standard Error)

5.3.3 Driving Performance

The standard deviation of lane position values for all number of buttons are seen in Figure 31. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, χ2(5) = 3.833, p = .574. The number of buttons displayed on the screen did not lead to any statistically significant changes in lane position, F (3, 72) = .184, p = .907.

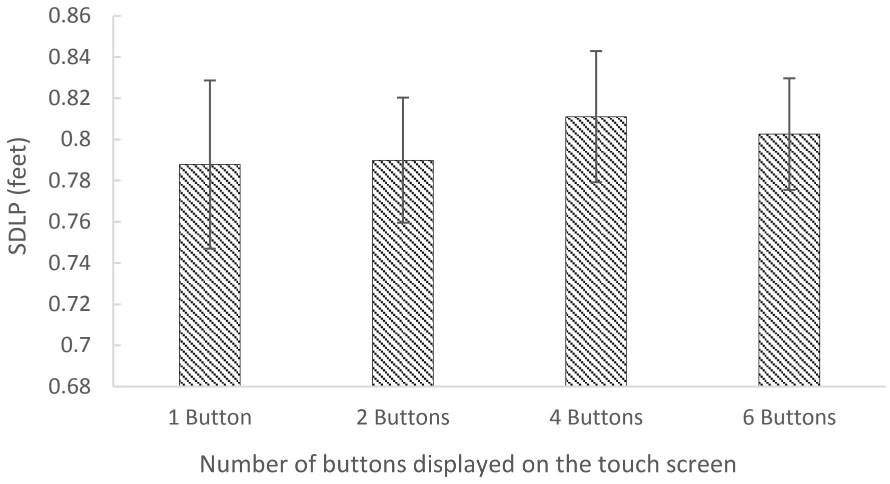


Figure 31. Standard deviation of lane position (error bars: Standard Error)

The standard deviation of speed for all number of buttons are seen in Figure 32. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated, χ2(5) = 23.322, p = .0001. Epsilon (ε) was 0.588, as calculated according to Greenhouse & Geisser, and was used to correct the one-way repeated measures ANOVA. The number of buttons displayed on the touch screen did not lead to any statistically significant changes in speed, F (1.764, 42.334) = 0.286, p = .725.

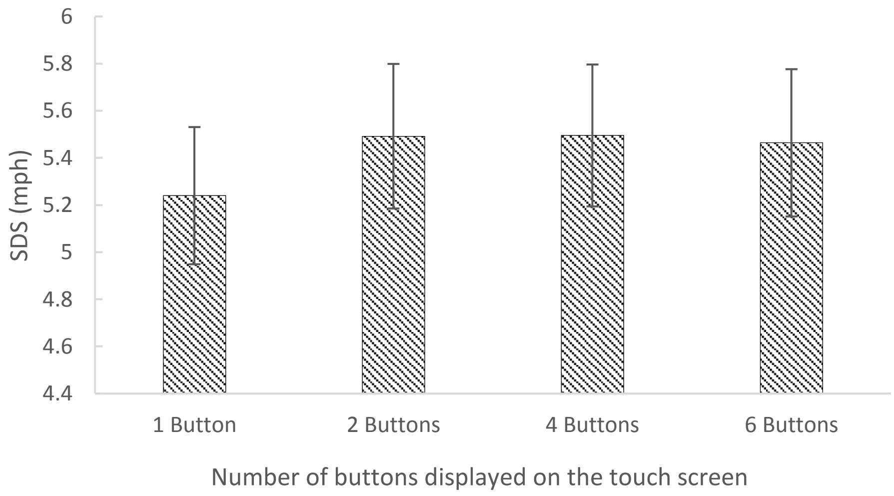


Figure 32. Standard deviation of speed (error bars: Standard Error)

5.4 DISCUSSION

The aim of this study was to investigate the effect of the number of buttons presented on a touch screen display on glance frequency and driving behaviour and consequently whether a maximum threshold exists for the number of buttons presented on the in-vehicle touch screen which would still allow drivers to interact with the screen with zero visual demand.

Although there was no statistically significant effect of the number of buttons presented on the in-vehicle display on the number of off-road glances, a general trend was observed showing an increase in off-road glances proportional to the number of buttons. The results of the glance frequency highlighted that the average number of off-road glances was below 1 for all numbers of buttons. This emphasised the fact that some participants were able to complete the button selection task with no off-road glances (blind interaction). Although a different design element was investigated in this study compared to the study discussed in the previous chapter, the results showed similar patterns in terms of the ability of a certain group of participants being able to achieve blind interaction.

The proportion of zero glance interactions was between 12 and 24 per cent, varying based on the number of buttons displayed. This meant that participants took their eyes off the road to look at the touchscreen for most interactions, but vision was not needed for all successful target selections. Although there was no significant difference between conditions, a decreasing trend was observed as the number of buttons increased. Based on the feedback received from participants and observations made during the study it was identified that participants were able to make non-visual interactions on some occasions by using peripheral vision to locate on-screen targets and/or muscle memory, by which the repeated movement of the arm/hand/fingers to the screen is memorised sufficiently to allow 'blind' operation. It is also assumed that based on the knowledge from literature, participants may have also utilised proprioception to determine where they hand was in space to locate the buttons (Desmurget *et al.*, 2000; Wolpert and Flanagan, 2001). However, it is also worth considering that proprioception degrades in the long term if it is not supported by vision. It was also apparent that for all conditions the average number of glances for a single button press was smaller than one, implying that in all conditions, some button presses were achieved with zero visual demand.

5.5 SUMMARY OF CHAPTER

This chapter discussed the second driving simulator study that was conducted as part of this research which aimed to identify whether or not a threshold exists for the number of buttons displayed on an in-vehicle touch screen to achieve non-visual interaction. The results of the study showed that although a threshold does not exist drivers are sometimes able to interact with in-vehicle displays without taking their eyes off the road ahead. The fact that participants in this study were able to make some non-visual interactions with the touch screen is encouraging for the design of future in-vehicle interfaces. It is therefore not possible to define from this data a threshold (for the number of buttons displayed on screen simultaneously) under which non-visual interactions would be possible, and therefore suggest a recommendation for an appropriate number of buttons to encourage non-visual interaction.

However, it is clear that participants were able to perform some interactions without taking their eyes of the road. Although the study did not find a threshold for the number of buttons it highlighted the need to understand the way drivers interact with the display and their strategies when achieving non-visual interaction.

The next chapter details the results of the driving simulator study which aimed to gain a better understanding into the strategies adopted by drivers when interacting with in-vehicle displays who are able to achieve successful blind interactions. This study compared the use of two interaction mechanisms (peripheral vision and muscle memory) and their effects on secondary task performance.

6 CHAPTER 6: EFFECTS OF INTERACTION MECHANISM AND BUTTON SIZE ON SECONDARY TASK PERFORMANCE

6.1 INTRODUCTION

The study discussed in chapter five which investigated the impact of the number of items displayed on an in-vehicle touch screen on achieving non-visual interaction and showed that on average across all conditions 18.75 per cent of participants were naturally able to perform the target selection task successfully with no off-road glances. An important consideration for enabling non-visual interaction with a touchscreen therefore is understanding the way in which this was achieved by these participants. Based on existing literature (van Dam, 1997; Nikolic and Sarter, 2001; Somervell *et al.*, 2002; Ecker *et al.*, 2009; Rümelin and Butz, 2013) (section 2.6) and the observations made during the previous driving simulator studies (Chapter 4 and 5), two interaction mechanisms were identified that would make non-visual interaction possible; peripheral vision and muscle memory. The role of both interaction mechanisms have been investigated in previous literature in a driving context, however these have focused on the role of these interaction mechanisms as a part of the primary task of driving (Summala, Nieminen and Punto, 1996) rather than their potential contribution to interaction with secondary tasks performed whilst driving. Both peripheral vision and muscle memory have shown to be useful in other areas where the user may be presented with a visually demanding secondary task whilst engaged in a highly visual primary task (similar to the driving task), such as aviation (Brown, Holmqvist and Woodhotjse, 1961) and as an interaction method for people with disabilities (Ebrahimi and Kunov, 1991). Peripheral vision is also particularly relevant in interaction with in-vehicle displays as these displays are likely to be located in the driver's periphery.

This study therefore aimed to assess the identified interaction mechanism (peripheral vision and muscle memory) that contributed to achieving non-visual interaction when performing a single button press task on the in-vehicle touch screen. The three research questions listed below were addressed with the aim to address the one of the overall research questions of this thesis (RQ2).

> ***RQ2. What are the interaction mechanisms adopted by drivers to achieve non-visual interaction when interacting with in-vehicle displays?***

RQ2.1. How does muscle memory interaction impact the button selection task performance?

RQ2.2. How does peripheral vision interaction impact the button selection task performance?

RQ2.3. How does the size of the item displayed on the screen impact the button selection task when using peripheral vision and muscle memory as interaction mechanisms?

In order to gain a better understanding of the role of these two interaction mechanisms when interacting with in-vehicle touch screens, an experiment was designed that enforced behaviour; utilising peripheral vision and muscle memory when interacting with the display.

6.2 METHOD

6.2.1 Participants

Twenty-five (12 Female, 13 Male) participants took part in the study from Virginia Polytechnic Institute and State University (mean age = 25.5; s.d. 5.3 years). These participants were recruited using posters placed around the Industrial and Systems Engineering (ISE) department. All participants held a US driving licence and had experience driving on US roads for at least 1 year (mean time with license = 7 years; mean annual mileage = 7594 miles). All participants also had experience using touch screen devices such as smartphones and tablets. They owned at least one touch screen device that they interacted with on a daily basis.

6.2.2 Design

The study followed a within-subjects design. There were two independent variables; interaction mechanism (muscle memory vs peripheral vision) and button size (small 6x6cm, medium, 10x10cm and large, 14x14cm), resulting in six conditions (Figure 33). The button sizes were chosen based on the previous driving simulator studies conducted as a part of this thesis and other similar studies identified in literature that focus on button sizes (Jin, Plocher and Kiff, 2007; Sun, Plocher and Qu, 2007; Sesto *et al.*, 2012; Feng, Liu and Chen, 2017b) . There were two dependant variables; secondary task performance, which was measured using task time and subjective workload which was obtained from NASA TLX scores. All participants had to complete six conditions in total, which took approximately 40 minutes. The order of the conditions presented was counterbalanced for each participant to avoid any order effects.

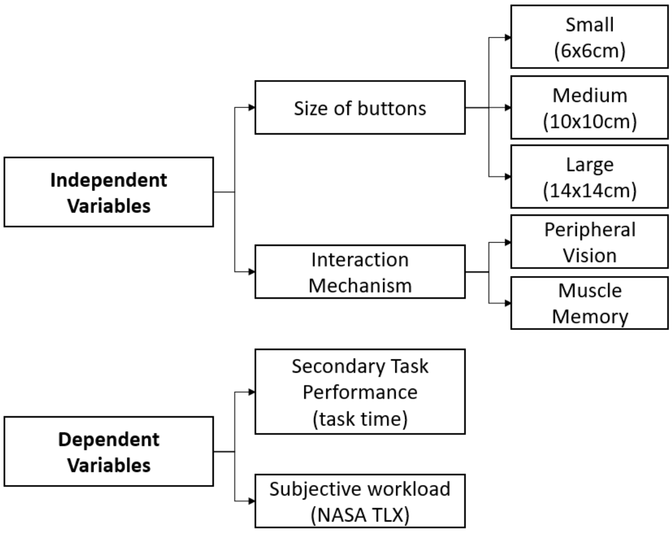


Figure 33. Overall independent and dependant variables

Throughout the study participants were asked to sit in a stationary driving simulator (this study did not involve any driving) and interact with the touch screen that was placed on the right-hand side of the steering wheel in the centre console. Participants were asked not to drive in this study as the investigation was on whether or not they were able to interact with the touch screen using the selected interaction mechanisms in the first place. The touch screen task consisted of a single, white, square button appearing on the touch screen at a time and participants were asked to press the button as quickly and accurately as possible. Within each condition participants were presented with the same sized button in the same location 24 times, requiring 24 button presses, to make sure they built up some muscle memory. However, in between six different conditions the size and the location of the button changed. The buttons were either presented on the edges or corners of the screen as having been established as being better locations that would allow for non-visual interaction in the previous study. Participants also heard two different audio tones during their interaction with the screen; firstly, to indicate the button had appeared on the screen, and secondly, to confirm that their selection was successful. Once a successful selection was made, the presentation moved onto a blank screen before moving onto the next screen displaying the next target.

To isolate the two mechanisms, the following approaches were used. During the muscle memory conditions participants were given a pair of glasses to wear which blocked their peripheral vision (Figure 34), and asked to maintain a forward-facing posture, as if driving. This ensured that they could not see the touch screen. However, to aid their initial selection, participants were shown where the button would appear on the touch screen before each condition, so they were familiar with the location of the button displayed on the touch screen. During the peripheral vision conditions, a forced-peripheral technique was used (Summala, Nieminen and Punto, 1996), whereby participants were instructed to focus on the vehicle which was parked in front of them (which had flashing back lights) and to keep their head still when detecting and selecting the button displayed on the screen.

Figure 34. The glasses participants were asked to wear during the muscle memory conditions

Participants were asked to fill out a NASA TLX questionnaire (Hart and Staveland, 1988) at the end of each condition which was taken as a measurement of their subjective workload (Appendix 11.1). Cameras were placed in the simulator facing the participants. The researcher permanently observed the participants throughout the study using these cameras to ensure that they were following the instructions when interacting with the touch screen display. There was no evidence to suggest that participants did not follow the instructions exactly as directed.

6.2.3 Apparatus and Stimuli

6.2.4 Procedure

At the beginning of the study, participants were asked to read the information sheet and sign the consent form (Appendix 11.3). They were also asked to fill out a data capture questionnaire, which consisted of basic information such as age, gender, driving experience, annual mileage and experience with touch screens (Appendix 11.2). The researcher went through the information sheet and explained the study in detail at the beginning and participants were given the opportunity to ask any questions they might have before they started.

During the study, participants were asked to sit in the driver's seat and to ensure to keep their focus on the car displayed in front of them in the simulated driving scene as well as keeping their head still during both muscle memory and peripheral vision conditions. They were not allowed to move the driver's seat, but they could adjust the headrest, so they could rest their head against it comfortably to ensure they kept their head still. They were also instructed to: 1) keep their hands on the steering wheel specifically at the 10 o'clock and 2 o'clock position (unless they were actively interacting with the touchscreen) and 2) only use their right hand to interact with the touch screen. This was important in order to ensure that every participant started reaching for the touch screen from the exact same point on the steering wheel and the positioning of their hands was not impacting task time.

6.3 RESULTS

6.3.1 Task Time

Task times were used to compare performance in the completely non-visual condition (muscle memory) and the peripheral vision condition. Twenty-four repetitions of the button selection task were completed during each condition. A two-way repeated measures ANOVA was run to determine the effect of button size and interaction mechanism on task time (Figure 35). There was a statistically significant interaction between button size and interaction mechanism on task time, $F(2, 46) = 12.052$, $p < .0005$, partial $\eta 2 = 0.344$, $d = 1.448$. Task time was higher for the muscle memory conditions 2638±60 ms compared to peripheral vision conditions 1798±18 ms. The difference of 840±49 ms was statistically significant, $p < 0.0005$, $\eta 2 = 0.927$, $d = 7.127$. Task time also significantly increased as button size decreased from large 1983±32 ms to medium 2173±41 ms to small 2497±55 ms. The statistically significant differences in task time between the different button sizes are as seen in Table 7, $p < 0.0005$, η2 = 0.771, d = 3.669.

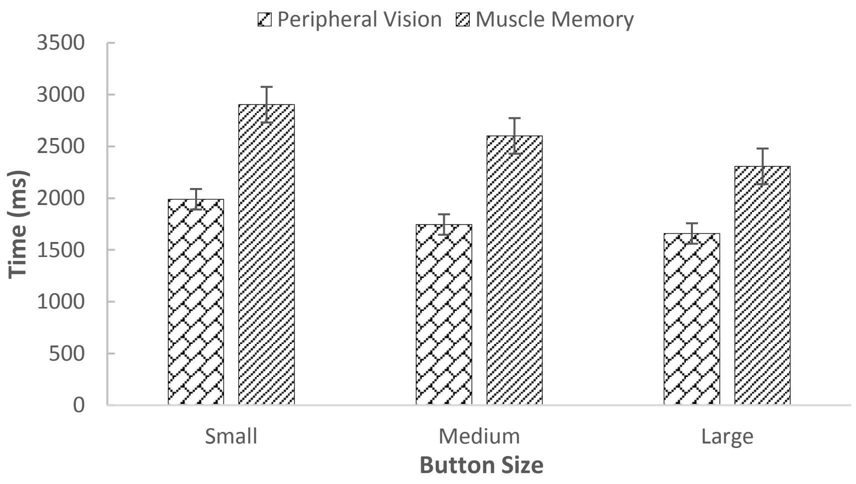
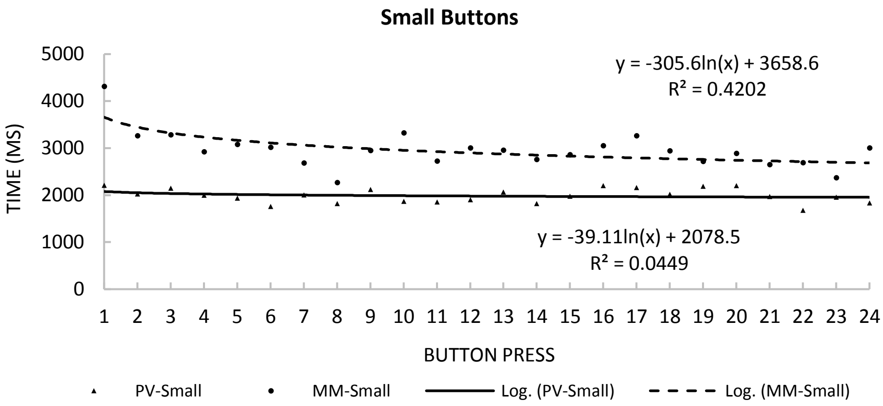


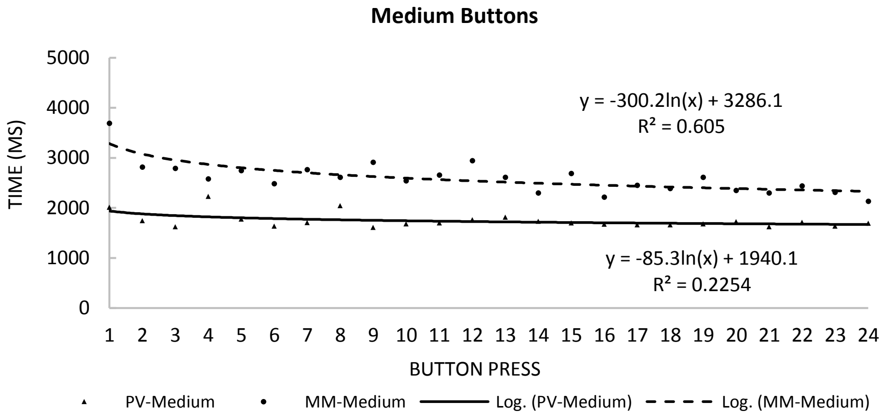
Figure 35. Average task time for all conditions (error bars: Standard Error)

Table 7. Significant differences in task time between the three button sizes

(I) Button Size	(J) Button Size	Mean Difference (I-J) (ms)	Std. Error (ms)
Small	Medium	324.046	45.363
	Large	514.295	42.912
Medium	Small	-324.046	45.363
	Large	190.249	36.523
Large	Small	-514.295	42.912
	Medium	-190.249	36.523

Another point of interest was the change in performance over time for all conditions but particularly for muscle memory conditions. A change in performance would be expected over time when muscle memory is utilised as muscle memory is time and repetition dependant and an improvement would be expected in the performance of the task.





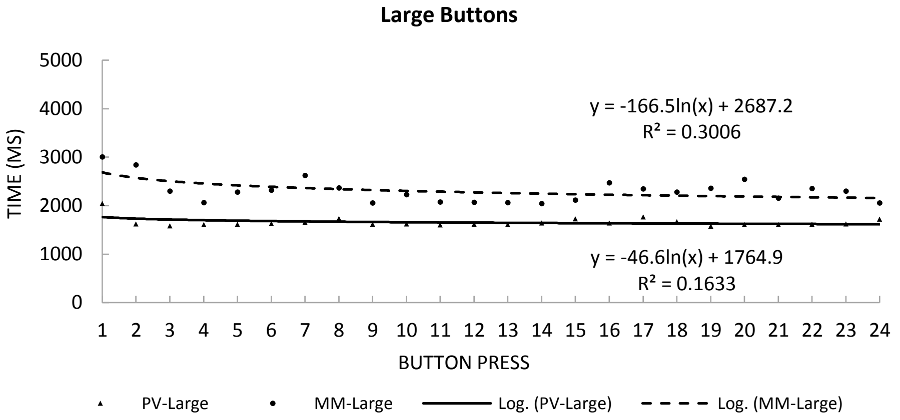


Figure 36. Mean task times for successive button presses

The graphs (Figure 36) show the trend-line for task times of the two interaction mechanisms for the three different button sizes. There is a steeper decrease in muscle memory task time for small and medium buttons compared with the larger buttons. In addition, in comparison to muscle memory task time, peripheral vision task time stayed more constant within each condition. For both interaction mechanisms, small button presses took longer to execute than medium and large buttons. Observations suggested that, the number of button press attempts for small buttons was higher, as participants had difficulties in pressing the small buttons on their first attempt more so during the muscle memory conditions than the peripheral vision conditions.

6.3.2 NASA TLX

A two way-repeated measures ANOVA was performed to determine the effect of button size and interaction mechanism on NASA TLX measures. Both the interaction mechanism and button size had a largely significant effect on subjective workload, $F(1, 24) = 59.703$, $p < 0.0005$, $\eta2= 0.713$ and $F(1.574, 37.767)$, $p < 0.0005$, $\eta2=0.422$, $d = 1.709$. Overall NASA TLX scores were higher for muscle memory conditions, 42±3 than peripheral vision conditions, 25±2. The difference of 17±2 was statistically significant, $p < 0.0005$, $\eta2 = 0.713$, $d = 3.152$. Overall NASA TLX scores were also higher for smaller buttons, 40±3 than medium, 30±2 and large buttons, 30±3. The differences of 9±2 between small and medium buttons and 10±2 between small and large buttons were statistically significant, $p < 0.0005$ and $p = 0.001$, $\eta2 = 0.553$, $d = 2.225$. These results show that muscle memory conditions with smaller buttons were perceived to be considerably more demanding by participants (Figure 37).

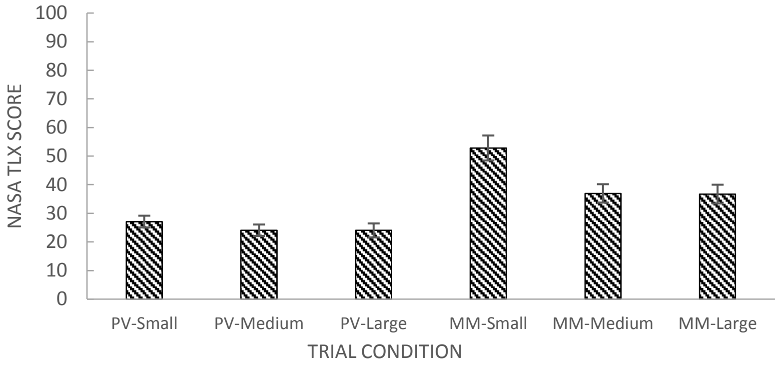


Figure 37. Overall NASA TLX scores for all conditions (error bars: Standard Error)

6.4 DISCUSSION

The aim of this study was to assess the two identified interaction mechanisms – peripheral vision and muscle memory – and better understand their contribution to non-visual interaction in combination with the displayed button size which had been established as a design characteristic that contribute to non-visual interaction in the previous chapters (Chapter 4).

Muscle memory (motor learning) is a key component of selection tasks and is developed or ‘learned’ over a series of repetitions. The results of this study showed that for completely ‘non-visual’ operation of in-vehicle touch screen controls, a muscle memory effect is evident. When utilising muscle memory participants did not have any visual indication of the target selection task, they were completing but were still successful in performing the task non-visually after a number of repetitions (Proteau *et al.*, 1987). It is expected with muscle memory that over time behaviour is learnt and performance improves due to repetition of the same task (Shusterman, 2011). The results highlighted that task time reduced over repeated exposures across all conditions. However, the small button muscle memory condition had the highest task-time compared to all other conditions. In addition, the benefits of muscle memory resulted in a maximum effect over time, i.e. task-time plateaued. This is likely to represent the theoretical number of repetitions after which the benefit from repeated exposure no longer exists, and the motor operation reduces to a constant duration. This duration represents the inherent physical demand of the task (i.e. if the task was being performed independent of the driving task). Also, drivers would not be expected to perform so many repeated button presses in close succession for the same button location and as a result muscle memory would be developed over a much longer period of time.

The extrapolated results for button selection times for the two independent variables (muscle memory and peripheral vision interaction) had a difference in the number of repetitions required for muscle memory task time to reach to similar levels of peripheral vision task times depending on button size. The number of repetitions required for the smaller buttons represent a theoretical ‘maximum’ limit to performance as they represented the most difficult tasks. It would be expected that for larger buttons the number of repeats required to reach a constant operation time would be lower. Nevertheless, the results for the large button size condition did not support this hypothesis. This may have been due to the large button press task being too easy from the outset for the user to develop any learning effects. As a result of this, task time was also relatively constant for large buttons compared to small and medium buttons. Another explanation for this unexpected result might be that large buttons covered a greater surface area on the touch screen, which meant that participants were not necessarily pressing the same spot on the button repeatedly but still making successful selections.

As participants were asked to focus on the vehicle ahead, which was presented as a still image, to enforce the use of peripheral vision rather than foveal vision; there was no change in their main field of view during the peripheral vision condition. As a result, task time for peripheral vision conditions stayed relatively constant during each condition unlike muscle memory conditions where changes in task performance were observed over time. There was an increase in task time as the button size decreased. This was likely to be a result of larger buttons being more ‘visible’ in the periphery (Van Kleunen *et al.*, 2017). As expected, for interfaces that utilise peripheral visual processing (i.e. located in a position that enables the driver to view them in their peripheral vision) there were no learning effects evident and operation times remained fairly constant over time (in contrast, learning effects were evident during the muscle memory conditions). This suggests that peripheral vision in comparison to muscle memory as an interaction mechanism would require less time adaptation time to achieve a reasonable level of secondary task performance which may be a more suitable interaction mechanism in a driving environment during which drivers may not have the opportunity to practice their interaction with the display prior to their interaction whilst driving.

Data was also extrapolated to investigate whether an intersection point between the muscle memory and peripheral vision task time was present to understand whether after a certain number of repetitions muscle memory resulted in similar task times as peripheral vision. The extrapolated data showed that the number of repetitions it would take for muscle memory to plateau and offer the same benefits as peripheral vision is very high. This suggests that realistically the use of muscle memory alone to achieve non-visual interaction with in-vehicle touchscreens would not be an efficient strategy. It is also assumed that people have a natural tendency to look at the interface they are interacting with (Brumitt and Cadiz, 2000) so it may take time for people to get used to muscle memory interaction where there is no visible element to the interaction. For muscle memory to be achieved it is also assumed that the driver would be pressing the same button repeatedly for the given number of times. However, in a realistic driving environment the driver would not be required to press the same button uninterruptedly so regularly. Nevertheless, ‘relative’ effects revealed by the data are still of value. It is also worth considering that people have a natural tendency to look at a screen when they are interacting with it. It is also worth noting that a shorter task time may be possible if participants were provided with full, foveal vision, but this will be at the expense of vision directed towards the primary driving task and the aim of the current work is to encourage drivers to use their foveal vision to attend to the road ahead.

Overall, results suggest that in situations where peripheral vision interaction is not possible (e.g. due to the in-vehicle display being located outside of a driver’s peripheral vision or if peripheral vision is not available due to high demands in primary driving tasks (Horberry *et al.*, 2006), drivers may still be able to select buttons non-visually via motor memory. However, this will be dependent on repeated exposure and may therefore take considerable time to acquire. Consequently, such benefits are limited.

Moreover, the results of this study are limited to single button selection operations. It is likely that more repetitions would be required to realise the full benefits of muscle memory (i.e. reduce task time to a constant level) when more buttons are present on a single screen. This is because participants would need to 'memorise' which button was in which location. This limits the usefulness of these results for designers of in-vehicle touch screens, but it is believed that this study has shown that those who were able to achieve zero glance interactions with the touch screen in the study discussed in chapter five may have used peripheral vision or muscle memory as an interaction mechanism.

6.5 SUMMARY OF CHAPTER

In summary, this study has shown that there are two interaction mechanisms that make it possible for those who are able to achieve zero glance interactions with the in-vehicle touch screen; peripheral vision and muscle memory. It has also highlighted some of the differences between the two interaction mechanisms with the main difference being their effect over time. The results showed that the effect of peripheral vision on non-visual interaction is more constant compared to muscle memory during which fluctuations in secondary task performance are observed. This study has also highlighted a limitation regarding the utilisation of the muscle memory interaction mechanism for non-visual interaction which is the fact that it would require enough number of repetitions to achieve successful non-visual interaction which is not very likely in a real driving environment. In terms of the design characteristic of button size that was assessed in this study, the results highlighted that independent of the interaction mechanism, the increase in button size resulted in decreased secondary task performance.

The next chapter investigates the performance of the secondary and driving task when utilising muscle memory or peripheral vision under different driving complexities. This is to understand whether the possibility of using these two interaction mechanisms would still be viable in more complex driving environments and also whether the complexity of the driving environment impact the interaction with the in-vehicle display at all.

7 CHAPTER 7: THE RELATIONSHIP BETWEEN DRIVING COMPLEXITY AND INTERACTION MECHANISM

7.1 INTRODUCTION

The study in chapter six identified two potential interaction mechanisms to enable non-visual interaction. However, it remains unclear how efficient and successful these mechanisms are, and what if any is the impact of variability in primary task demand (i.e. driving complexity). The next study therefore aims to explore the relationship between driving complexity and the different types of interaction mechanisms. Apart from the two interaction mechanisms that have been identified in the previous study it also aims to compare them against foveal vision interaction as this is the most effective interaction mechanism in a non-driving scenario.

Having identified two potential interaction mechanisms to achieve non-visual interaction the aim is to assess the efficiency and success of these two mechanisms. Based on existing research in literature it is known that driving complexity can influence when and how drivers choose to interact with in-vehicle displays – the more demanding a driving environment is (e.g. harsh weather conditions, constant need to change speed, traffic, presence of other cars on the road, etc) the less spare capacity the driver will have to allocate to the secondary task (Strayer, Drews and Johnston, 2003; Jahn *et al.*, 2005; Patten *et al.*, 2006; Young and Regan, 2007). By providing various driving conditions it was is to identify the impact of changes in primary task demand.

The simple driving condition is based on NHTSA guidelines (NHTSA, 2013) and the complex driving condition was created by modifying the simple one.

However is was modified to make it more realistic (Large *et al.*, 2015). For example, the NHTSA guidelines suggest that the lead vehicle appears in the driver's lane after 360 metres of travel. However, it is assumed that this would not provide a realistic experience for the participants. For that reason, participants were asked to start in the hard shoulder, join the motorway and follow the lead car.

The aim of the study is to investigate the effects of three interaction mechanisms (muscle memory, peripheral vision, and foveal vision) and three levels of driving complexity (stationary, simple, and complex) on in-vehicle display secondary task visual performance. There are four main research questions that are addressed in the study:

> ***RQ2. What are the interaction mechanisms adopted by drivers to achieve non-visual interaction when interacting with in-vehicle displays?***

RQ2.4. How does driving complexity impact task time?

RQ2.5. How does interaction mechanism impact task time?

RQ2.6. What is the relationship between driving complexity and interaction mechanism?

7.2 METHOD

7.2.1 Participants

Twenty participants (11 males, 9 Females) from the University of Nottingham took part in the study (mean age = 40 years; s.d = 10). Participants were recruited via email. All participants held a UK driving licence for at least 1 year (average time with licence = 20 years; average annual mileage = 7788 miles). All participants were also experienced in using touch screen devices such as smartphones and tablets.

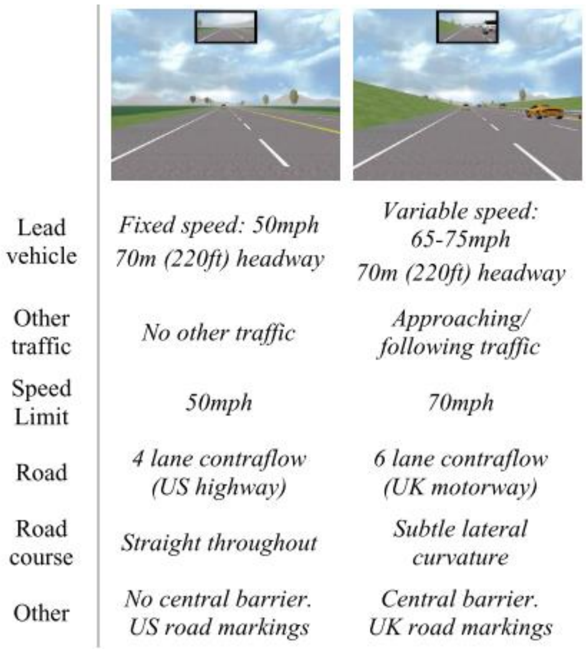
7.2.2 Design

The study followed a within-subjects design. There were two independent variables; driving condition (stationary, simple and complex) and interaction mechanism (muscle memory, peripheral vision and foveal vision), resulting in 9 drives (Figure 39).

During the ‘stationary’ driving condition, participants were sat in the driving simulator, but the vehicle remained stationary in the hard shoulder of a UK-style motorway scenario. During this condition, participants were not required to drive.

The ‘simple’ driving condition involved participants driving in the slow lane on a straight UK-style motorway following a lead car (Brookhuis, Waard and Mulder, 1994) which travelled at a constant speed of 60 mph with no other traffic on the road, in line with the NHTSA testing protocol.

The ‘complex’ driving condition similarly took place on a UK-style motorway but there were some bends on the road, the lead car’s speed varied between 65-75 mph and there was other traffic present on the road (Figure 38).



Lead vehicle	*Fixed speed: 50mph* *70m (220ft) headway*	*Variable speed: 65-75mph* *70m (220ft) headway*
Other traffic	*No other traffic*	*Approaching/ following traffic*
Speed Limit	*50mph*	*70mph*
Road	*4 lane contraflow (US highway)*	*6 lane contraflow (UK motorway)*
Road course	*Straight throughout*	*Subtle lateral curvature*
Other	*No central barrier.* *US road markings*	*Central barrier.* *UK road markings*

Figure 38. Properties of the simple (left) and complex (right) driving conditions (Large *et al.*, 2015, p. 119)

For all driving conditions during which participants were in control of the vehicle (i.e. simple and complex), participants were asked to keep what they deemed to be a safe and appropriate distance between themselves and the lead car and to always stay in the left-hand lane of the motorway. No lane changes were performed during any of the drives.

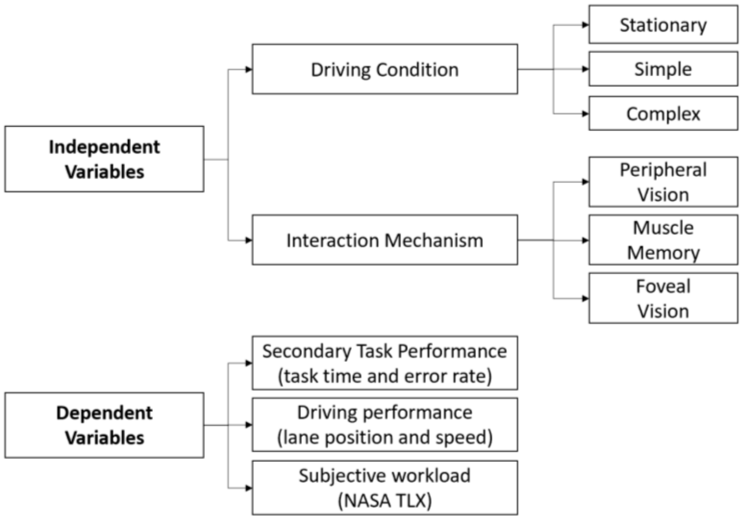


Figure 39. Independent and dependant variables

Participants were also instructed to interact with the touch screen that was located within the centre console of the simulator (Figure 40) whilst driving or stationary. They were provided a single, white square button (12 x 12 cm) at a time on the touch screen. They were reminded to drive as they would in a real driving environment and that the primary task was the driving task. They heard an audible tone every time the button appeared on the screen and a different tone once they had successfully touched the button. If they failed to locate the button on their first attempt, participants were instructed to keep trying until they heard the confirmation sound. The button was displayed on the same location on the screen within each condition. However, the location of the button differed in between conditions. So overall, the buttons appeared in 9 different locations.

Figure 40. Location of the in-vehicle touch screen

There were three different interaction mechanisms participants used when pressing the button on the touch screen: muscle memory, peripheral vision, and foveal vision.

During the muscle memory condition, participants were asked to wear a pair of glasses which blocked their peripheral vision, so they could not see the touch screen when interacting with it (Figure 41). Before each muscle memory condition participants were shown where the button would appear on the screen, so they had an idea of where to place their finger on the touch screen.

During the peripheral vision condition, participants were instructed to keep their eyes on the lead car at all times and only use their peripheral vision to detect the button appearing on the screen.

Finally, during the foveal vision condition, participants were asked to keep their eyes on the lead car in between button presses but to look directly at the touch screen when pressing the button. During peripheral and foveal vision conditions participants were asked to complete 24 button presses and during muscle memory conditions the number of repetitions was 50. The increase in the number of repetitions for the muscle memory conditions was to ensure that participants were performing enough button presses to build up muscle memory.

Figure 41. A participant wearing the glasses used for the muscle memory condition

Consequently, there were 9 conditions in total and each condition was a different combination of driving condition and interaction mechanism. However, participants only experienced one interaction mechanism per condition. The order of the conditions was counterbalanced between participants. Each condition lasted for approximately 10 minutes. At the end of each condition participants were asked to complete a NASA TLX workload questionnaire (Hart & Staveland, 1988).

Other dependent variables were task time and error rate (Figure 39). Task time was recorded from the moment the button appeared on the screen until the moment the participant pressed the button, and error rate was determined based on the number of times the participant touched the screen but did not press the button during this time. Both the task time and error rate were recorded using a code which was running in the background whilst the participants were interacting with the interface.

7.2.3 Apparatus and Stimuli

A touch screen was placed to the left-hand side of the steering wheel on which participants were presented with the buttons they were asked to interact with. Participants were also video recorded using the three video cameras in the simulator; two facing the participants (visible in Figure 40) and one facing the tablet on the centre console. Video cameras were present in the simulator to ensure participants were following the instructions given to them successfully.

7.2.4 Procedure

At the beginning of the study participants were asked to complete a pre-trial consent form, data capture questionnaire and a simulator sickness checklist. They were asked to complete a post-trial consent form and another simulator sickness checklist at the end of the study to make sure that they were not experiencing any negative symptoms. The data capture questionnaire asked participants about their age, gender, driving license, annual mileage, and touch screen device use. Each participant was given a number on arrival to ensure their anonymity.

Once the forms were completed participants were given the opportunity to drive the simulator in the complex driving condition for 10 minutes to get used to the controls and the driving scenario. As the test drive was to allow the participants to familiarise themselves with the simulator and it’s controls it was assumed that getting them to do the test drive in the complex driving environment would achieve this. At the end of each drive, participants were given the opportunity to rest and were also asked to complete a NASA TLX form. At the end of the study participants were given vouchers for their time and were advised to wait 30 minutes before driving their own car.

7.3 RESULTS

7.3.1 Task Time

A two-way repeated measure ANOVA was carried out to determine the effect of interaction mechanism and driving condition on task time (Figure 42). Outliers were removed from the data set which were caused by a number of reasons during the experiment such as the participant missing the audio instructions and the touchscreen not registering the participants’ selection correctly. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the main effect of driving condition $\chi^2(2) = 41.379$, p = .0001 and the two-way interaction $\chi^2(9) = 61.884$, $p = .0001$. Epsilon (ε) was 0.547 for driving condition and 0.491 for the two-way interaction, as calculated according to Greenhouse-Geisser, and was used to correct the two-way repeated measures ANOVA. There was a statistically significant two-way interaction between driving condition and interaction mechanism, F (1.818,41.823) = 23.194, p = 0.0001 (**Error! Reference source ot found.**).

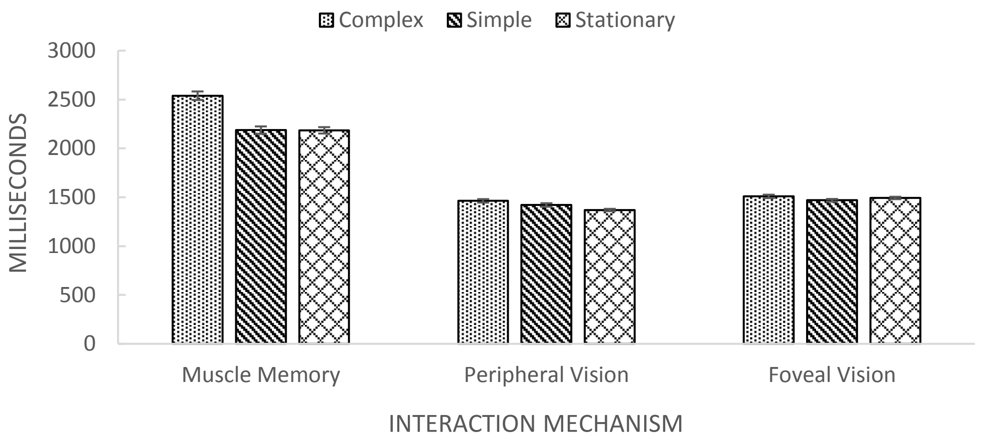
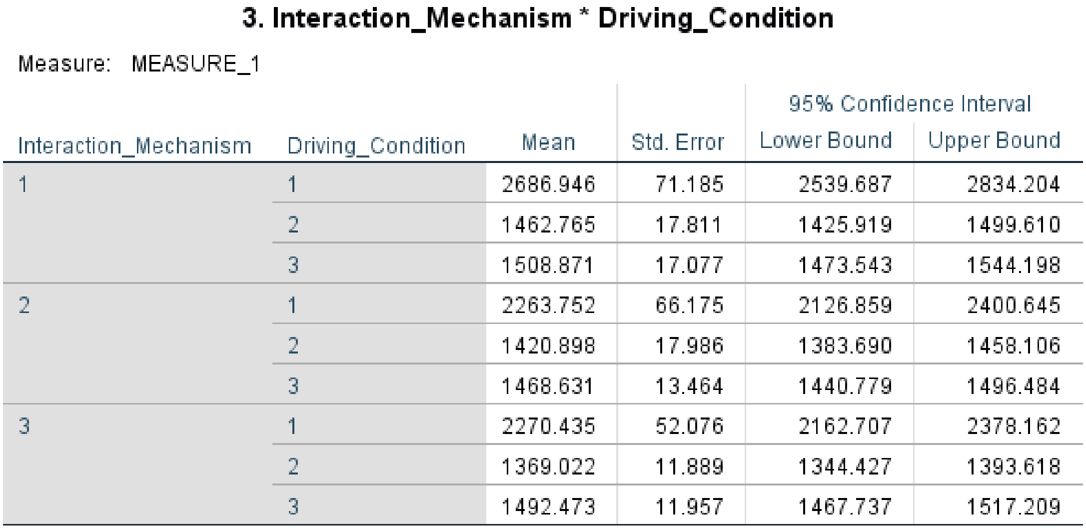


Figure 42. Mean task time for all conditions across all participants (error bars: Standard Error)

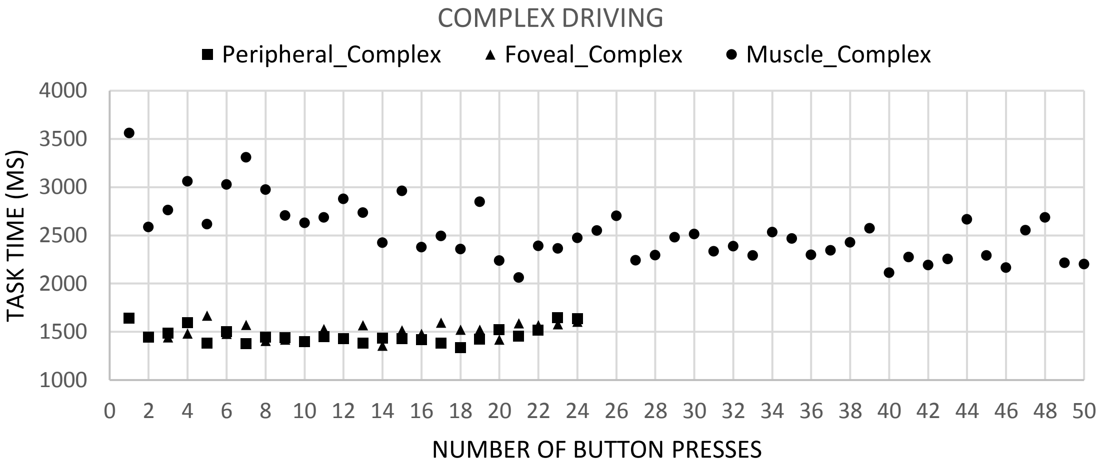
Table 8. Two-Way ANOVA for Task Time (Driving condition: (1) Complex, (2) Simple, (3) Stationary; Interaction Mechanism: (1) Muscle Memory, (2) Peripheral Vision, (3) Foveal Vision)

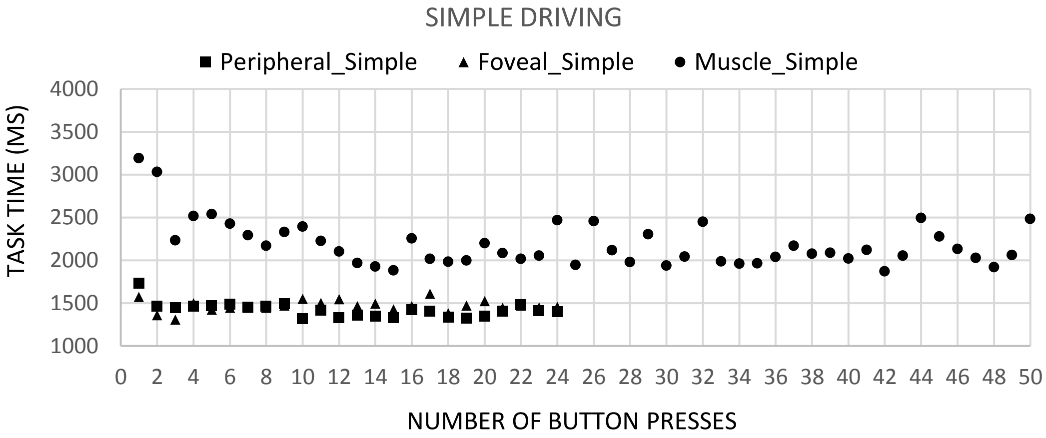


3. Interaction_Mechanism * Driving_Condition

Measure: MEASURE_1

				95% Confidence Interval	
Interaction_Mechanism	Driving_Condition	Mean	Std. Error	Lower Bound	Upper Bound
1	1	2686.946	71.185	2539.687	2834.204
	2	1462.765	17.811	1425.919	1499.610
	3	1508.871	17.077	1473.543	1544.198
2	1	2263.752	66.175	2126.859	2400.645
	2	1420.898	17.986	1383.690	1458.106
	3	1468.631	13.464	1440.779	1496.484
3	1	2270.435	52.076	2162.707	2378.162
	2	1369.022	11.889	1344.427	1393.618
	3	1492.473	11.957	1467.737	1517.209


COMPLEX DRIVING
■ Peripheral_Complex
▲ Foveal_Complex
● Muscle_Complex
TASK TIME (MS)
4000
3500
3000
2500
2000
1500
1000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
NUMBER OF BUTTON PRESSES


SIMPLE DRIVING
■ Peripheral_Simple
▲ Foveal_Simple
● Muscle_Simple
TASK TIME (MS)
4000
3500
3000
2500
2000
1500
1000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
NUMBER OF BUTTON PRESSES

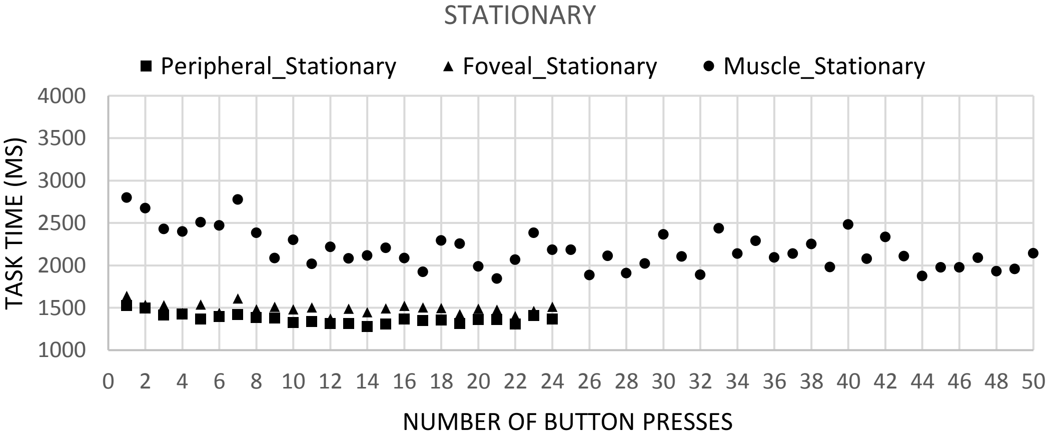

STATIONARY
■ Peripheral_Stationary
▲ Foveal_Stationary
● Muscle_Stationary
TASK TIME (MS)
4000
3500
3000
2500
2000
1500
1000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
NUMBER OF BUTTON PRESSES

Figure 43. Task times for all interaction mechanisms across all drives

Fluctuations were observed in task time during muscle memory conditions as seen in Figure 44. This was interpreted as during periods of muscle memory being developed, secondary task performance gradually increased as represented by the gradual decrease in task time at certain periods during the overall drive. After a number of button presses, a sudden increase in task time would indicate that the previously developed muscle memory would have deteriorated resulting in a decrease in task performance.

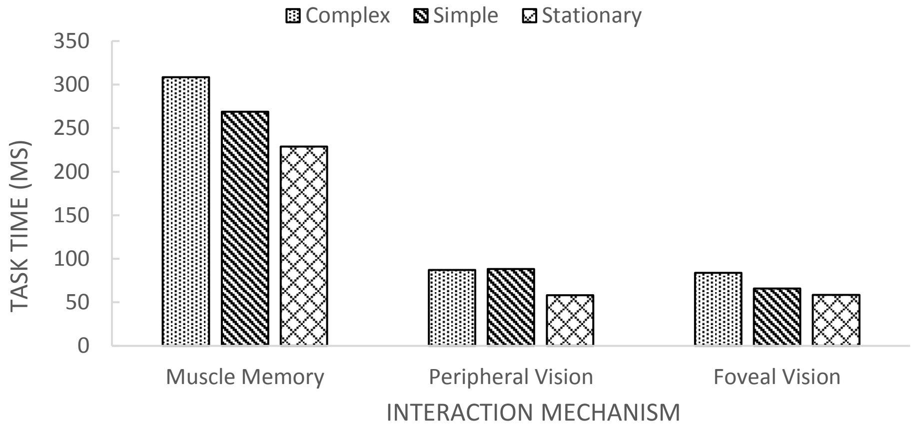


Figure 44. Standard deviation of task time

As there were fluctuations observed in the task time data during muscle memory conditions standard deviation of task time was considered as well as mean task time to understand whether these fluctuations were significant. As seen in Figure 44 standard deviation of task time was considerably higher during all muscle memory conditions across all driving complexities. This shows that there were greater variations in task time during muscle memory conditions compared to peripheral and foveal vision conditions.

7.3.2 Error Rates

The number of attempts it took for participants to press the button correctly was recorded during the study. A two-way repeated measure ANOVA was carried out to determine the effect of interaction mechanism and driving condition on error rate. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the main effect of interaction mechanism $\chi^2(2) = 61.547$, p = .0001 and the two-way interaction $\chi^2(9) = 139.378$, $p = .0001$. Epsilon (ε) was 0.518 for interaction mechanism and 0.456 for the two-way interaction, as calculated according to Greenhouse-Geisser, and was used to correct the two-way repeated measures ANOVA. There was a statically significant two-way interaction between driving condition and interaction mechanism, F (1.701, 39.117) = 18.644, p = 0.0001 (Table 9). Data show that participants made more errors – did not press the button correctly the first time – during muscle memory conditions compared to peripheral and foveal vision conditions and they also made considerably more errors during complex driving conditions compared to simple driving and stationary conditions (Figure 45).

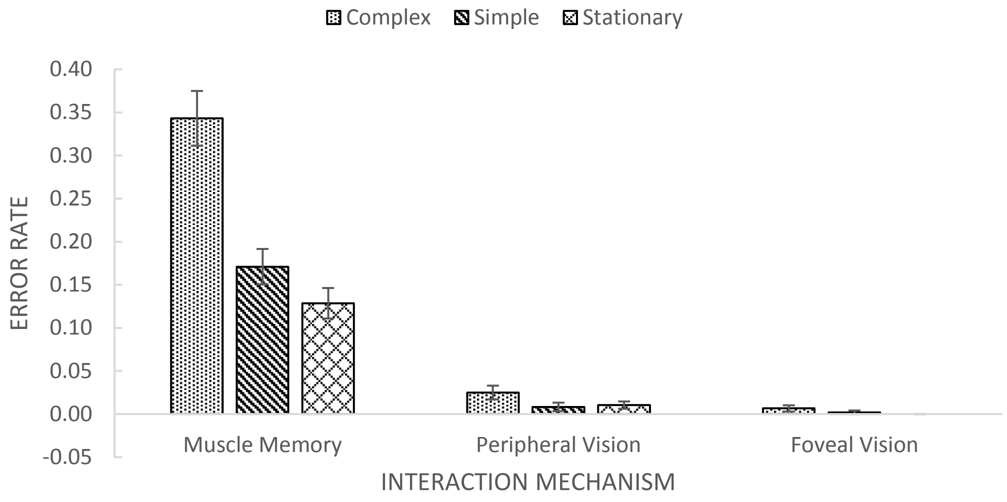
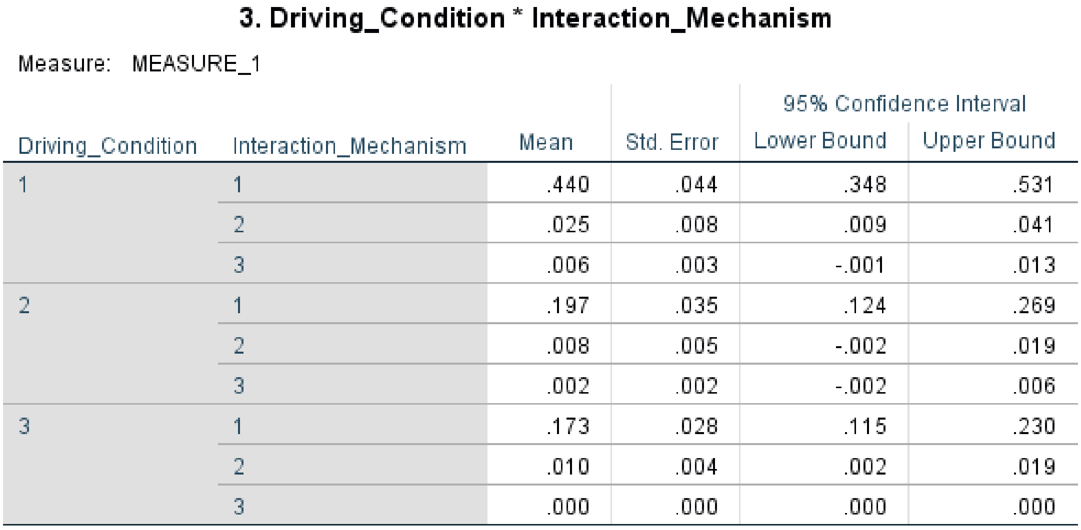


Figure 45. Mean error rate for all conditions across all participants (error bars: Standard Error)

Table 9. Two-way ANOVA for Error Rate (Driving condition: (1) Complex, (2) Simple, (3) Stationary; Interaction Mechanism: (1) Muscle Memory, (2) Peripheral Vision, (3) Foveal Vision)



3. Driving_Condition * Interaction_Mechanism

Measure: MEASURE_1

Driving_Condition	Interaction_Mechanism	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	.440	.044	.348	.531
	2	.025	.008	.009	.041
	3	.006	.003	-.001	.013
2	1	.197	.035	.124	.269
	2	.008	.005	-.002	.019
	3	.002	.002	-.002	.006
3	1	.173	.028	.115	.230
	2	.010	.004	.002	.019
	3	.000	.000	.000	.000

7.3.3 NASA-TLX

A two-way repeated measures ANOVA was run to determine the effect of interaction mechanism and driving condition on the sum of the NASA TLX scores (Figure 46). Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the two-way interaction, χ2(9) = 22.426, p =

.008 and interaction mechanism, χ2(2) = 14.322, p = .001. There was no statistically significant two-way interaction between interaction mechanism and driving condition F (2.729, 51.854) = 1.713, p = .180. However, there was a statistically main effect of interaction mechanism, F (2, 38) = 30.504, p = .0005 and driving condition, F (1.291, 24.536) = 59.623, p = .0005 independent of each other.

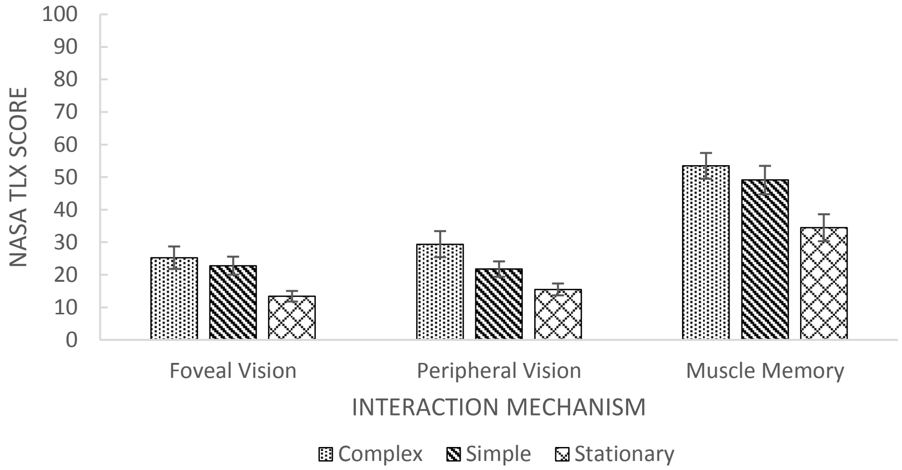


Figure 46. Overall NASA TLX results (error bars: Standard Error)

7.3.4 Driving Data

A two-way repeated measures ANOVA was run to determine the effect of interaction mechanism and driving condition on the standard deviation of lane position (Figure 47) and standard deviation of speed (Figure 48) (Green *et al.*, 2003). Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, χ2(2) = .712, p = .700. There was no statistically significant two-way interaction between interaction mechanism and driving complexity, F (2, 34) = .885, p = .422.

The main effect of interaction mechanism on lane position F (2, 34) = 40.922, p = .0001. Muscle memory as an interaction mechanism had significantly considerably less effect on lane position than peripheral vision and foveal vision. Standard deviation of lane position increased by 0.835 ft (p = 0.0001) and 0.733 ft (p = 0.0001) during foveal vision and peripheral vision conditions respectively.

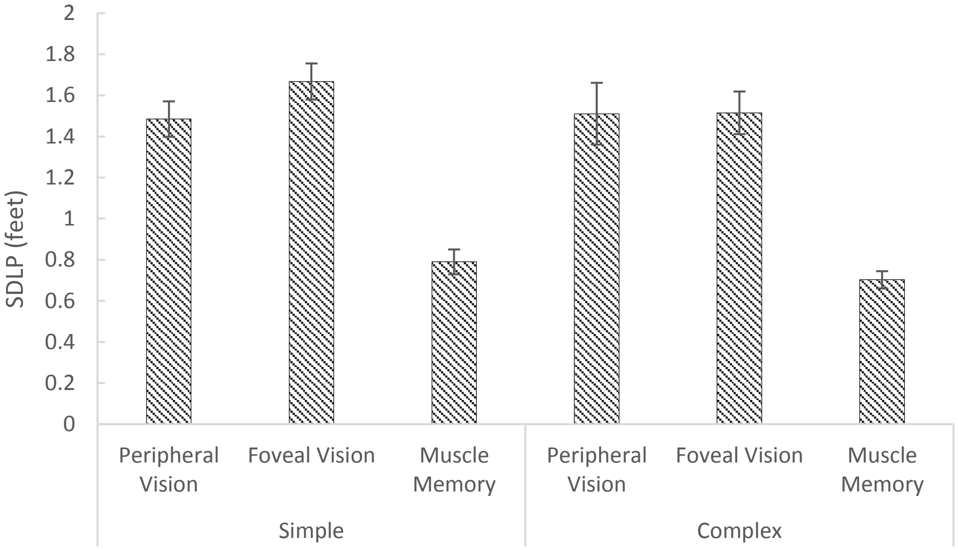


Figure 47. Standard deviation of lane position (error bars: Standard Error)

Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, χ2(2) =5.717, p = .057. There was no statistically significant two-way interaction between interaction mechanism and driving complexity, F (2, 34) = .486, p = .619. The main effect of interaction mechanism showed a statistically significant difference in change in speed F (2, 34) = 12.963, p = .0001. Muscle memory as an interaction mechanism had significantly less effect on speed than peripheral vision and foveal vision. Standard deviation of speed increased by 2.854 mph (p = 0.0001) and 2.022 mph (p = 0.020) during foveal vision and peripheral vision conditions respectively.

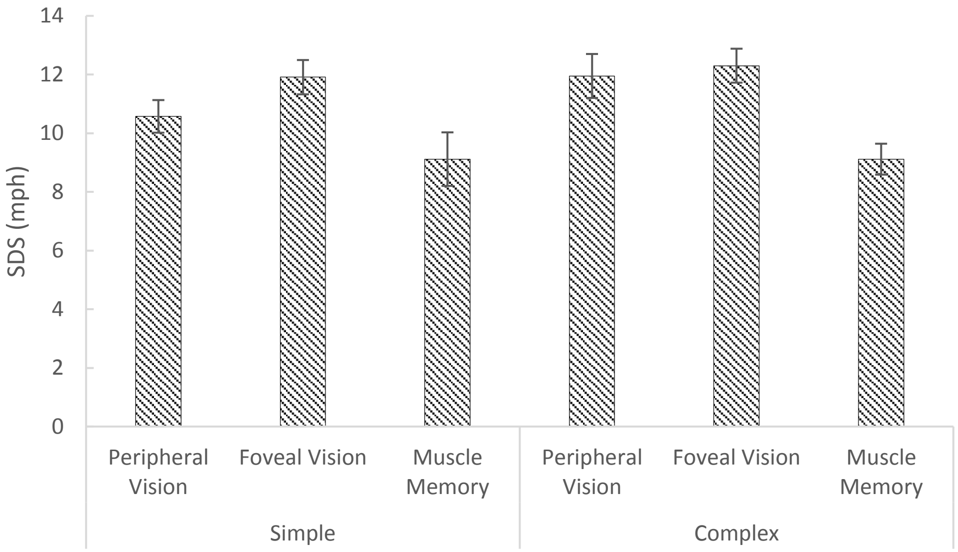


Figure 48. Standard deviation of speed (error bars: Standard Error)

7.4 DISCUSSION

This study aimed to investigate the effects of three interaction mechanisms with in-vehicle touch screens, combined with three different levels of driving complexity, on secondary task performance. The independent variables were driving condition (stationary, simple and complex) and interaction mechanism (muscle memory, peripheral vision and foveal vision). Subjective workload data was collected using NASA TLX forms. Objective data was based on task time and error rates of the secondary in-vehicle touch screen task and driving performance measures.

NASA TLX results show that participant's subjective ratings of their performance were considerably worse for muscle memory conditions, which is supported by the task time data. Task time for muscle memory conditions is higher compared to peripheral and foveal vision conditions which show that the objective task performance was worse. The driving condition also had a significant effect on task time, where complex driving condition task times were higher than the stationary and simple driving condition. This was expected as participants were not driving during the stationary conditions resulting in the touch screen task being the primary (and indeed, only) task. This implied that the touch screen task would require less effort, would be less demanding and would cause less frustration as shown in the NASA TLX results during stationary conditions. Similar to the task time data, the error rates showed that muscle memory conditions resulted in participants making more errors when completing the button press task. Consequently, the more errors made the higher task time was.

The objective and subjective measures show that peripheral and foveal vision conditions were similar to one another. As seen in previous graphs, there was a minimal difference in subjective workload for all NASA TLX measures between foveal and peripheral vision conditions. This may show that drivers can successfully complete touch screen tasks without taking their eyes off the road when driving by solely using their peripheral vision.

Muscle memory conditions were more likely to have higher task times. The results show that peripheral vision could be as efficient as using foveal vision when interacting with the touch screen with regard to task time. This may explain the fluctuations in task time in the muscle memory graphs. These fluctuations may have occurred for a number of reasons. This may have been due to fatigue or a result of enforced repetition of the same task in rapid succession. Data also showed that variance in task time for muscle memory conditions between different button presses were significant compared to peripheral and foveal vision. This also highlighted the fact that during muscle memory conditions participants were building up muscle memory over time which was reflected in the decrease of secondary task time, however, would lose this muscle memory after a number of repetitions which was reflected in the increase of secondary task time.

A limitation with this particular study is that participants were not given the option to practice the secondary task prior to the start of the study to develop any muscle memory. This was due to the fact that in a real driving scenario a driver would not ‘practice’ their interaction with the in-vehicle display to the point where they develop muscle memory for a certain interaction before using the system whilst driving. However, they are likely to develop muscle memory over time as they use the interface whilst driving. Therefore, participants were not given the opportunity to practice the interaction before the drive.

7.5 SUMMARY OF CHAPTER

In summary, the study discussed in this chapter has shown that muscle memory as an interaction mechanism result in poorer secondary task performance compared to peripheral and foveal vision. It highlights that in order to build enough muscle memory for the successful completion of the touch screen task drivers would need to have sufficient number of repetitions of the button press. It also has shown that although muscle memory could be beneficial for shorter periods for zero glance interaction, this benefit declines over time and drivers would need to build that muscle memory back up again. Considering the use of muscle memory in a real driving context, drivers would not be expected to repeat the same button selection consecutively enough number of times to be able to achieve non-visual interaction solely relying on muscle memory as an interaction mechanism. Although for commonly performed button selection tasks they may be able to use muscle memory for non-visual interaction, however this would develop in a longer amount of time compared to using peripheral vision for non-visual interaction. This study has also shown that there was a significant effect of the different driving complexities on task performance during muscle memory conditions.

The next chapter discusses the final study – validation study – that was conducted as a part of research which aimed to observe the difference between two interfaces (peripheral vision friendly and non-peripheral vision friendly) interacted with using two interaction mechanisms (peripheral vision interaction and natural interaction) and their effect on secondary task and driving performance and glance behaviour.

8 CHAPTER 8: VALIDATION STUDY

8.1 INTRODUCTION

The previous four driving simulator studies focused on various design elements of in-vehicle touch screens and investigated the interaction mechanisms that make non-visual interaction possible.

- Chapter four focused on three design elements; button location, size and contrast level and showed that button size and location had a significant impact on the number of off-road glances. The number of off-road glances significantly increased as the size of the buttons displayed on the touch screen increased. Additionally, buttons that were displayed on the edges of the screen also resulted in significantly fewer off-road glances compared to buttons located on the corners and centre of the display. The main findings from the study discussed in chapter four were 1) the average glance frequency for all button sizes, locations and contrast levels was 0.92 which was still less than 1 glance; 2) the proportion of zero glance interactions was a maximum of 45 per cent showing that participants at times were able to perform the button selection task without taking their eyes off the road.
- Chapter five investigated the number of buttons displayed on the touch screen. The results showed that the number of off-road glances significantly increased as the number of buttons displayed on the screen increased. This study also highlighted that the maximum proportion of zero glance interaction were 24 per cent across all number of buttons highlighting that vision was not needed for all successful button selections.

- Chapter six investigated the two interaction mechanisms – peripheral vision and muscle memory – that contributed to the successful non-visual interactions observed in chapters four and five. It highlighted the differences between peripheral vision and muscle memory showing that muscle memory required more repetitions than peripheral vision in order to achieve the same level of secondary performance.
- Chapter seven highlighted that the increase in driving complexity and the use of muscle memory as an interaction mechanism resulted in poorer secondary task performance compared to peripheral and foveal vision and simple driving and stationary conditions. The study also highlighted that although it is possible to achieve zero glance interaction with muscle memory, it takes time to build up sufficient muscle memory and that muscle memory fluctuates over time resulting in varied secondary task performance over time. Conversely, peripheral vision and foveal vision resulted in similar secondary task and driving performance and performed better than muscle memory. Secondary task performance was also more constant during peripheral vision conditions compared to muscle memory.

The results of these studies showed that with the appropriate elements of display design incorporated for peripheral vision interaction it is possible for drivers to rely on their peripheral vision to achieve blind interaction with the in-vehicle touch screen.

This final driving simulator study is conducted as a validation study to combine the findings from the previous four studies and to validate the relationship between peripheral vision interaction and peripheral vision-friendly displays. Muscle memory is not taken forward as a part of the validation study based on some of the findings from the previous studies. First of all, to be able to achieve zero glance interactions utilising muscle memory, drivers would potentially need to 'practice' their interactions with the in-vehicle display to develop a sufficient level of muscle memory in the first place. During interactions with the in-vehicle display, drivers would not be required to perform the same target selection task in close succession during driving to be able to develop a sufficient level of muscle memory. In the previous studies conducted participants were asked to press the same button in succession with less than 20 seconds in between each button press and at least 24 times. This type of repetition would not happen in a real driving environment. Although the effects of muscle memory may be observed over time as drivers become more familiar with the in-vehicle displays in their own vehicles. Consequently, this still would not provide the same performance as with the use of peripheral vision within the same time frame. Also, previous studies show that when using muscle memory, there were fluctuations observed in task performance where the effect of muscle memory would deteriorate over time and would require the driver to develop the sufficient level of muscle memory again to achieve successful zero glance interactions.

The approach is to test peripheral vision interaction with both a peripheral vision friendly interface (high contrast, lower number of buttons) and a non-peripheral vision friendly interface (low contrast, higher number of buttons). It is also to compare the performance of peripheral vision interaction with natural interaction where participants were asked to interact with the touch screen as they would with a display in their vehicle. Two sets of buttons are used (four and six) as the touchscreen stimuli to create a realistic interface.

The study aims to investigate the differences between foveal vision interaction (the interaction mechanism adopted by most participants in previous studies when interacting with the display) and the newly suggested peripheral vision interaction to validate the viability of this interaction mechanism. The following main research questions are investigated in this study which are also broken down into more specific research questions for this study:

> ***RQ1. What are the design characteristics of in-vehicle touch screens that can help in achieving non-visual interaction?***
>
> ***RQ2. What are the interaction mechanisms adopted by drivers to achieve non-visual interaction when interacting with in-vehicle displays?***

RQ1.4. How does a peripheral vision-friendly designed interface impact task performance?

RQ1.5. How does the number of buttons on a peripheral vision-friendly display impact task performance?

RQ2.7. How does interaction mechanism impact task performance?

RQ2.8. What is the relationship between peripheral vision and natural interaction?

8.2 METHOD

8.2.1 Participants

Twenty participants (13 males, 7 Females) from the University of Nottingham took part in the study (mean age = 39 years; s.d = 11). Participants were recruited via email and posters placed around campus. All participants held a UK driving licence for at least 1 year (average time with licence = 19.7 years; average annual mileage = 9140 miles). All participants were also experienced in using touch screen devices such as smartphones and tablets on a daily basis.

8.2.2 Design

The study followed a within-subjects design. There were three independent variables; number of buttons displayed on the screen (n = 4 and 6), contrast level (low and high) of the screen and interaction mechanism (Figure 49). The low contrast level conditions represented the “non-peripheral vision friendly” interface making it difficult for the participants to detect the buttons displayed on the touch screen using their peripheral vision. It was also intended that the conditions with the low contrast level and higher number of buttons displayed on the screen would be the least peripheral vision friendly conditions. Although in the study discussed in chapter five, it was shown that in comparison with displaying 4 or 6 buttons on the screen, displaying 1 button on the screen resulted in fewer off-road glances; for the purpose of the validation study it was believed that displaying a single button on the touch screen would not have been a realistic representation of a touch screen a driver would likely to interact with in a real vehicle. The combination of the two sets of buttons and contrast levels meant that all participants completed 4 drives in total. The contrast levels used in this study were the same as the lowest and highest contrast levels used in the study discussed in chapter four.

During the first two drives, participants were asked to interact with the touch screen naturally, as they would if the system was in their own car. They were not given any specific instructions as to whether they should be looking at the touch screen or not when interacting with it. This was not to influence their preferred interaction mechanism. They were asked to wear eye tracking glasses for these drives. This was to observe the effect of the peripheral vision-friendly interface on glance behaviour during natural interaction. The aim was to see whether this type of interface also made interaction easier for natural interaction.

During the last two drives, participants were specifically instructed to only use their peripheral vision when interacting with the display. The cameras placed within the simulator allowed the researcher to observe the participants to ensure that they were following these instructions. The reason participants were asked to complete the natural interaction drives prior to the peripheral interaction drives was to ensure that their natural interaction strategies were not influenced by the fact that they had experienced peripheral vision interaction. All participants experienced one low contrast and one high contrast drive for each interaction mechanism. During each drive, they were presented with a set of 4 and 6 buttons. The order of the different set of buttons was randomised to counteract the learning effect. Participants were asked to touch each button in the set of 4 and 6 buttons four times resulting in sixteen button presses for the set of 4 buttons and twenty-four button presses for the set of 6 buttons.

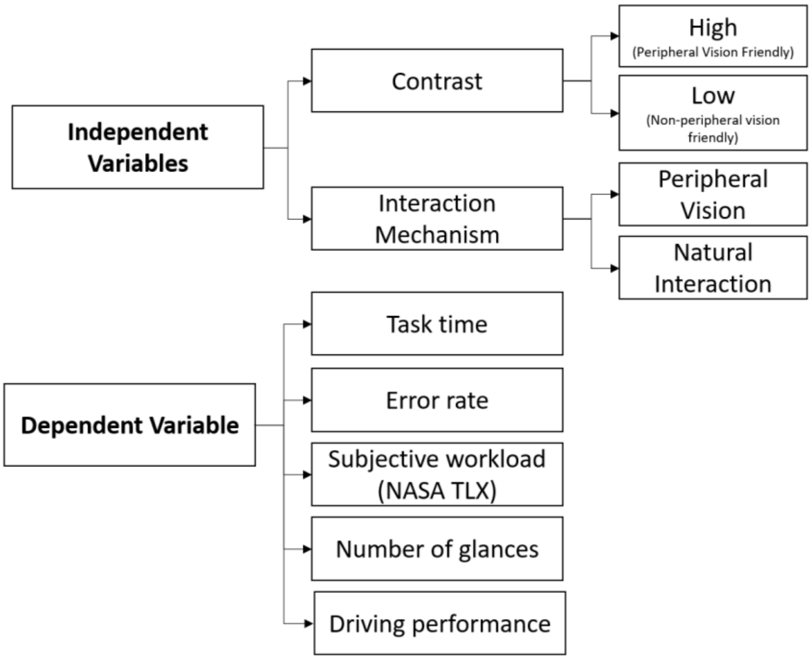


Figure 49. Dependant and independent variables

Each drive lasted approximately 10 minutes. The drive took place on a UK motorway and participants were instructed to follow a lead car (Brookhuis, Waard and Mulder, 1994) as if they are travelling to a shared destination at all times and comply with the rules of the motorway. There were no lane changes involved in any of the drives. However, there were curves on the road and the lead car varied its speed between 60mph to 70mph. Participants were asked to drive for 1 minute before starting the task for each condition.

Participants were instructed to interact with the touch screen that was located within the centre console of the simulator whilst driving. They were shown 4 or 6 white square buttons (6 x 6 cm) on the touch screen at a time and were asked to press the button as quickly and as accurately as possible. They were reminded to drive as they would in the real world and that the primary task was the driving task. They were informed of which button they needed to press for each selection. They heard an audible instruction (such as “top left” or “bottom right" to minimise additional visual and cognitive workload locating the target) before the buttons appeared on the screen, followed by a tone as the buttons appeared. They then heard a different tone once they had successfully pressed the correct button to inform them that the button had now disappeared. Participants were instructed to keep trying until they heard the confirmation sound in case they could not press the button on their initial try. At the end of each drive participants were asked to complete a NASA TLX workload questionnaire (Hart & Staveland, 1988) (Appendix 11.1).

Dependent variables were task time, error rate, glance frequency, driving performance and NASA TLX results. Task time was recorded using a MATLAB code running in the background from the moment the button appeared on the screen until the moment the participant successfully pressed the correct button, and error rate was calculated based on the number of times the participant touched the screen but did not press the correct button during this time. Glance frequency data was derived from the eye movement data collected using the eye tracking glasses.

8.2.3 Apparatus and Stimuli

The buttons presented on the touch screen all had symbols on them that are relevant in a driving environment. However, for the purpose of this study these buttons did not have any functions assigned to them (Figure 50).

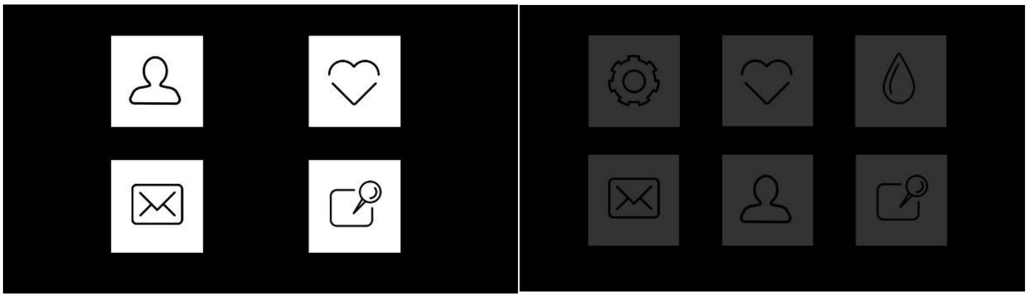


Figure 50. On the left is a high contrast display with 4 buttons; on the right is a low contrast display with 6 buttons

Participants were also video recorded. There were three video cameras in the simulator; two facing the participants and one facing the tablet on the centre console to allow the observation of the participants during the trial to ensure that they were adhering to the instructions, especially during the peripheral vision conditions.

8.2.4 Procedure

At the beginning of the study participants were asked to complete a pre-trial consent form, data capture questionnaire and a simulator sickness checklist. They were asked to complete a post-trial consent form and another simulator sickness checklist at the end of the study to make sure that they were not experiencing any negative symptoms. The data capture questionnaire asked participants about their age, gender, driving license, annual mileage, and touch screen device use (Appendix 11.2). Each participant was given a number on arrival to ensure their anonymity. Once the forms were completed participants were given the opportunity to drive the simulator for 10 minutes to familiarise themselves with the controls and the driving scenario. At the end of each drive they were given the opportunity to rest and were also asked to complete a NASA TLX form. At the end of the study participants were compensated for their time in shopping vouchers and were advised to wait 30 minutes before driving their own car.

8.3 RESULTS

8.3.1 Secondary Task Performance

8.3.1.1 Task Time

A two-way repeated measures ANOVA was run to determine the effect of number of buttons, contrast level and interaction mechanism on task time. There was no statistically significant three-way interaction between number of buttons, contrast level and interaction mechanism, F (1,278) = .515, p = .474, no two-way interaction between contrast level and interaction F (1,278) = 0.463, p = .497 and no two-way interaction between interaction mechanism and number of buttons F (1,278) = 1.741, p = .188. However, there was a statistically significant interaction between contrast level and number of buttons F (1,278) = 6.958, p = .009. In low contrast conditions task time for 6 buttons was considerably higher than 4 buttons regardless of the interaction mechanism. The different interaction mechanisms did not have a significant impact on task time (Figure 51).

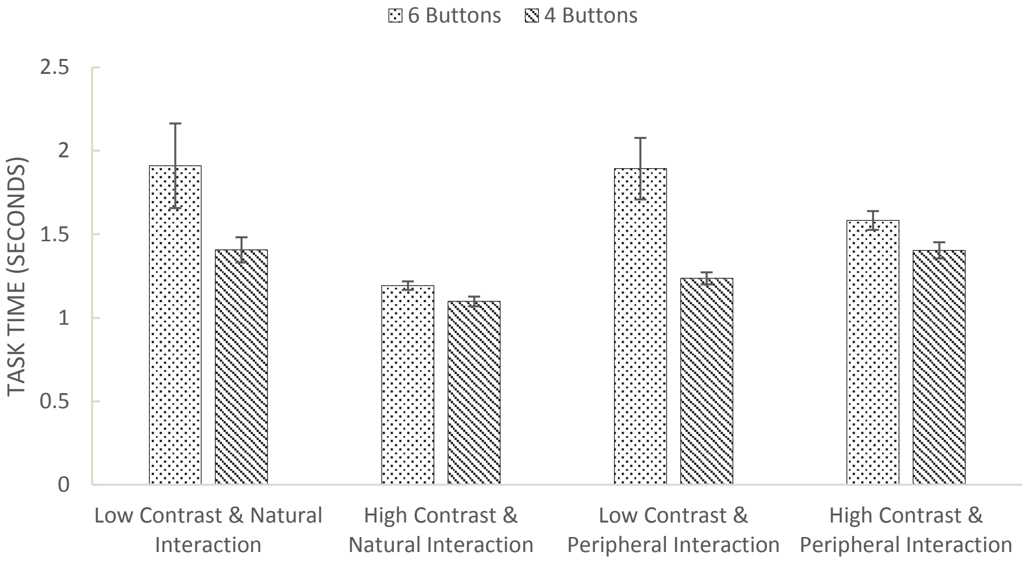


Figure 51. Mean task time across all conditions (error bars: Standard Error)

8.3.1.2 Error Rate

A two-way repeated measures ANOVA was run to determine the effect of number of buttons, contrast level and interaction mechanism on error rates. There was no statistically significant three-way interaction between number of buttons, contrast level and interaction mechanism, F (1,302) = .907, p = .342, and no two-way interaction between contrast level and number of buttons F (1,302) = 2.534, p = .112 and no two-way interaction between contrast level and interaction mechanism, F (1,302) = .489, p = .485. However, there was a statistically significant interaction between interaction mechanism and number of buttons F (1,302) = 8.121, p = .005.

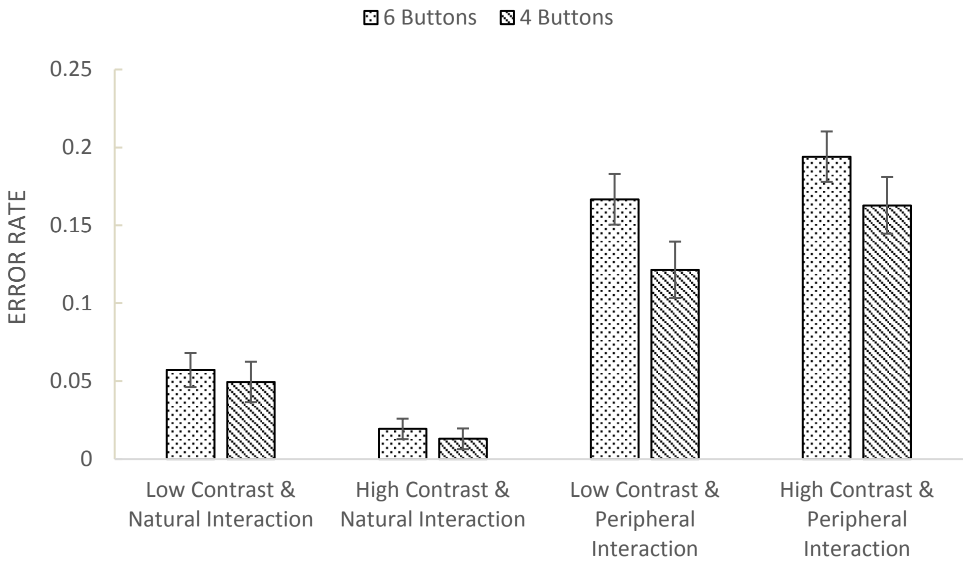


Figure 52. Mean error rate across all conditions (error bars: Standard Error)

Overall, peripheral vision conditions had considerably higher error rates compared to natural interaction conditions (Figure 52). Within peripheral vision conditions, error rates were considerably higher for 6 button conditions compared to 4 button conditions. However, contrast levels did not have an effect on error rates.

8.3.2 NASA TLX

A two-way repeated measures ANOVA was run to determine the effect of interaction mechanism and contrast on overall NASA TLX scores. There was no statistically significant two-way interaction between interaction mechanism and contrast F (1, 18) = .022, p = .884. However, there was a statistically main effect of contrast, F (1, 18) = 6.150, p = .023. Overall NASA TLX scores for the high contrast conditions were statistically significantly lower compared to low contrast conditions (Figure 53).

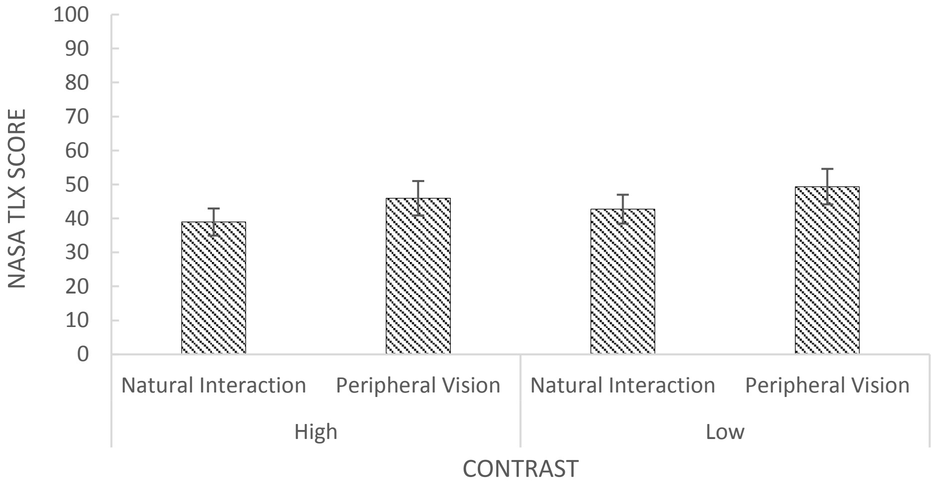


Figure 53. NASA TLX overall scores (error bars: Standard Error)

8.3.3 Number of Glances

The number of glances only apply to the drive during which participants were asked to adopt a natural interaction as during the peripheral vision drive participants were asked to use their peripheral vision to interact with the display hence there were no off-road glances to analyse. A two-way repeated measures ANOVA was run to determine the effect of number of buttons and contrast level on number of glances away from the road (Figure 54). Three participants' eye tracking data was taken out for analysis due to poor trackability.

The number of buttons did not have a statistically significant effect on the number of glances F (1,191) = 1.789, p = .183. However, contrast level did have a statistically significant effect on number of glances F (1,191) = 6.316, p = .013. Low contrast level conditions had statistically 0.068 ± 0.037 more number of glances made away from the road for both 4 and 6 buttons displayed on the screen compared to high contrast level conditions. There was no statistically significant interaction effect of contrast level and number of buttons

F (1,191) = 2.110, p = .148. As seen in Figure 54, the mean glance frequency is greater than one in all conditions, suggesting that on average, every participant took their eyes of the road at least once when interacting with the in-vehicle display naturally.

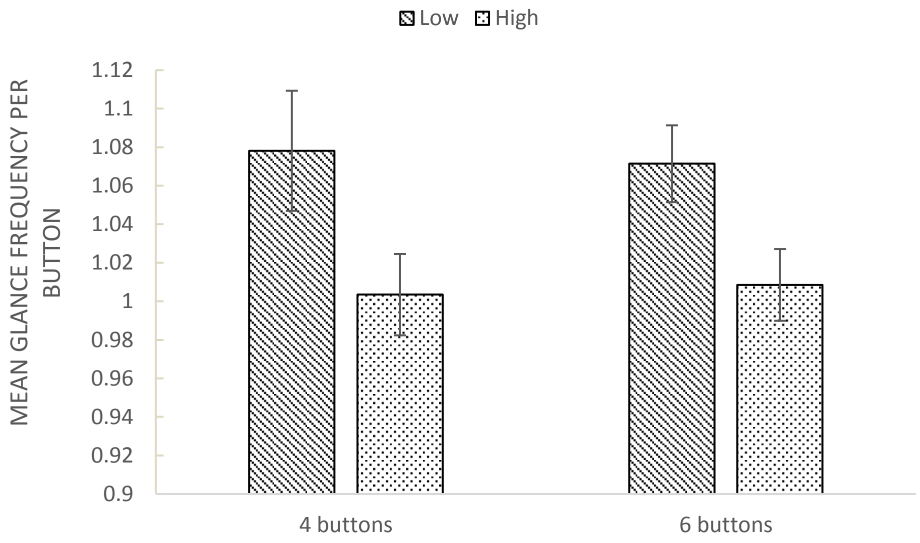


Figure 54. Mean glance frequency per button press for natural interaction conditions (error bars: Standard Error)

8.3.4 Driving Data

A two-way repeated measures ANOVA was run to determine the effect of interaction mechanism and contrast level on driving performance measures; standard deviation of lane position (SDLP) and standard deviation of speed (SDS). The results of the statistical analysis showed no statistically significant two-way interaction between contrast level and interaction mechanism, F (1, 19) = .404, p = .533 for SDLP. There was also no significant main effect of contrast level F (1, 19) = .001, p = .975 or interaction mechanism F (1, 19) = 2.091, p = .164 (Figure 55).

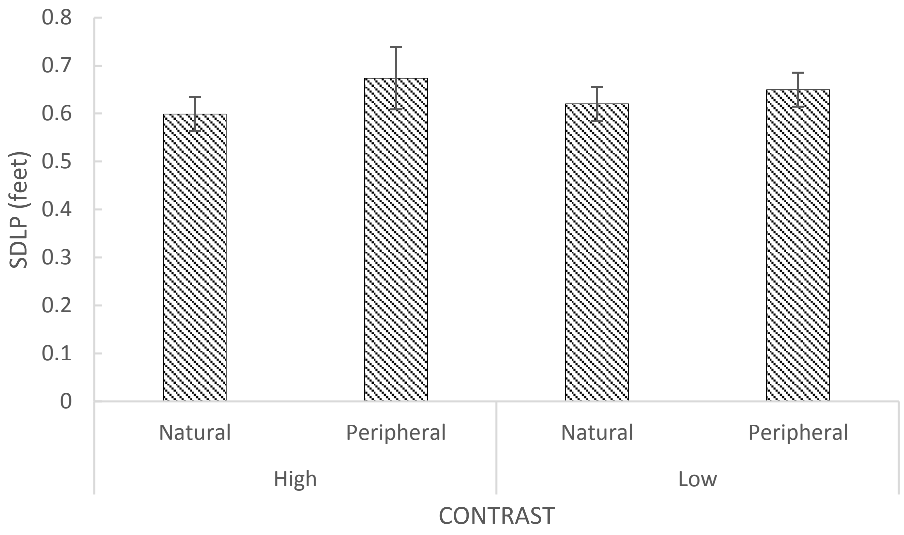


Figure 55. Standard deviation of lane position (SDLP) (error bars: Standard Error)

There was also no statistically significant two-way interaction between contrast level and interaction mechanism, F (1, 19) = .353, p = .560 for SDS and no statistically significant main effect of contrast level F (1, 19) = 1.139, p = .299 or interaction mechanism F (1, 19) = 1.519, p = .233 (Figure 56).

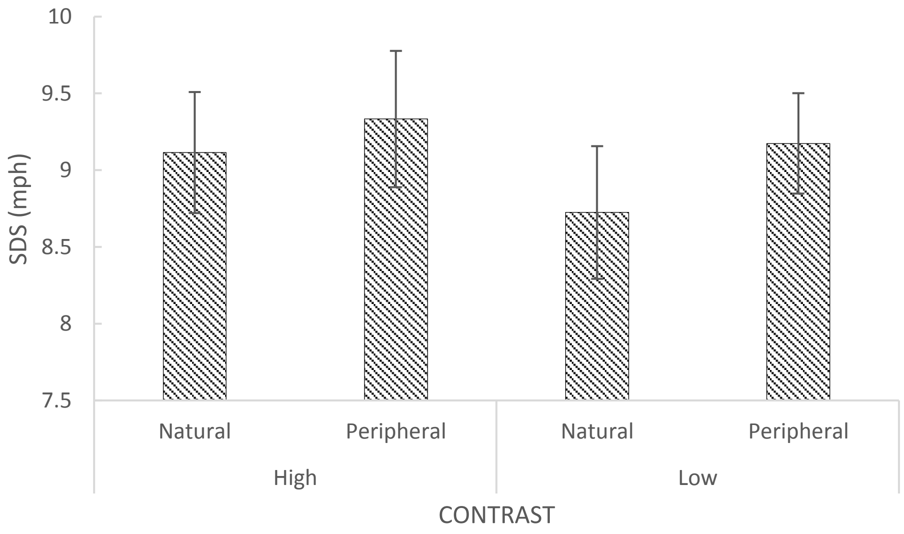


Figure 56. Standard deviation of speed (SDS) (error bars: Standard Error)

The lack of statistically significant differences in both the SDLP and SDS driving performance measures indicate that the differences in contrast levels and interaction mechanisms did not result in variations in speed and lane position. It shows that participants were successful in controlling the vehicle laterally and longitudinally without their driving performance being impacted by the secondary task. As discussed in Chapter 3, previous literature shows that demanding secondary tasks can result in variations in speed and lane position (Burns *et al.*, 2002; Siebert *et al.*, 2002; Liang and Lee, 2010).

8.4 DISCUSSION

The aim of this study was to assess the impact of peripheral vision friendly interface on secondary task performance when being interacted with using two different interaction mechanisms; peripheral vision interaction and natural interaction. It also set out to understand the relationship between natural interaction and peripheral vision by combining the knowledge gained from the previous four studies (Chapters 4-7).

The main difference between the peripheral vision and natural interaction mechanisms in this study was that similar to the studies discussed in chapters six and seven, the peripheral vision interaction was enforced on participants hence all of the interactions during these conditions were non-visual compared to natural interaction. As a result, one of the aims of the study was also to understand how an enforced non-visual interaction compared against natural interaction – the way drivers would normally interact with the display – in terms of secondary task performance and driving performance.

Natural interaction and peripheral vision interaction resulted in similar secondary task times as there were no considerable differences between these two interaction mechanisms. Although the number of buttons displayed on the screen did not influence task time for natural interaction, six buttons displayed on the screen resulted in considerably higher task times for peripheral vision interaction in low contrast conditions. So, when participants were interacting with a non-peripheral vision friendly interface using their peripheral vision, the number of buttons displayed on the screen had an effect on their secondary task performance. Out of the four versions of the interface participants were presented with (low contrast & n = 4, low contrast & n = 6, high contrast & n = 4, high contrast & n = 6) the version that had low contrast and 6 buttons displayed on the screen was accepted to be the worst combination for peripheral interaction based on the previous results regarding contrast levels and number of items displayed on the screen. Therefore, it was expected that secondary task performance would be considerably negatively impacted when participants were interacting with this particular interface using peripheral vision. Similar to the results of the study from chapter five, the results of this study showed that even with higher contrast levels higher number of buttons resulted in higher secondary task time. Although task time did not considerably vary between natural and peripheral vision interaction.

The results highlight that larger number of buttons are not ideal for peripheral vision interaction and smaller number of buttons presented are more likely to benefit from the utilisation of peripheral vision in terms of secondary task performance. In terms of subjective workload, the results showed that there were no significant differences between the two interaction mechanisms and the only significant difference was between the two contrast levels (high and low). This showed that participants did not find their subjective workload to be different when using either of the interaction mechanisms but for both interaction mechanisms they found their workload was higher when interacting with the low contrast displays.

Due to the design of the study glance behaviour was only measured during the natural interaction mechanism as during peripheral vision interaction participants kept their eyes on the road ahead. The number of off-road glances were considerably higher during low contrast conditions compared to high contrast conditions. However, the difference in the number of buttons presented on the display did not have a significant considerable impact on the off-road glances. During natural interaction conditions more than 50% of the participants took their eyes off the road to look at the touch screen at least once. This once again highlights the natural tendency people have to look at things as they interact with them (Desmurget *et al.*, 1998; Gribble *et al.*, 2002; Crawford, Medendorp and Marotta, 2004). During natural interaction conditions the average glance frequency per button was above 1 glance for all versions of the interface.

The results of this study show that with the appropriate design elements, peripheral vision as an interaction mechanism could be utilised for non-visual interaction without having a major detrimental effect on driving performance or secondary task performance in comparison to using natural interaction methods.

8.5 SUMMARY OF CHAPTER

The validation study discussed in this chapter aimed to understand the impact of peripheral-vision friendly interfaces on secondary task performance and the differences in the impact when peripheral vision or natural interaction was utilised to interact with the in-vehicle display. It also investigated the relationship between peripheral vision interaction and natural interaction to understand the differences and similarities between them.

The results of this study showed that even when participants were interacting with the ‘peripheral vision-friendly’ displays using natural interaction, they took their eyes off the road for more than half of their interaction showing that natural interaction is likely to lead to higher off-road glances. It highlighted the possibility of utilising peripheral vision interaction with the suitable design characteristics as an alternative to natural interaction in order to achieve non-visual interaction. The details of the impact of these findings on design implications for future displays are discussed in the next chapter.

The final chapter restates the overall aim and research questions of this thesis that were introduced in chapter one and provides an overall discussion. It assesses the extent to which the results of the studies discussed in chapters four to eight addressed the overall research questions and relates the findings of these studies back to the literature discussed in chapter two. The final chapter also outlines the design implications of these findings on in-vehicle touch screens and identifies some of the future work that could follow the current research.

9 CHAPTER 9: OVERALL DISCUSSION AND CONCLUSIONS

9.1 INTRODUCTION

This chapter provides an overall discussion on the findings of the research presented in this thesis. It revisits the research questions introduced in chapter one and addresses each of them and assesses the extent to which the research has answered these questions and achieved the overall aim. This chapter also addresses some of the limitations of the work outlined in the thesis and outlines further investigation that can build on the current work.

9.2 OVERALL AIM OF RESEARCH AND RESEARCH QUESTIONS

The overall aim of this thesis is:

> *"To understand the underlying mechanisms that will facilitate non-visual interaction with in-vehicle touchscreens"*

The overall aim was divided into three main research questions introduced in chapter one which were addressed throughout the thesis:

RQ1. What are the design characteristics of in-vehicle touch screens that can help in achieving non-visual interaction?

RQ2. What are the interaction mechanisms adopted by drivers to achieve non-visual interaction when interacting with in-vehicle displays?

RQ3. What is the relationship between the design characteristics and interaction mechanisms?

9.3 CONTRIBUTION

This thesis demonstrates that drivers at times drivers are able to interact with in-vehicle touch screens without having to take their eyes off the road by using either peripheral vision or muscle memory as an interaction mechanism. This allows them to be able to visually attend the driving task even when they are performing a secondary in-vehicle task. It also highlights that there are design elements that contribute to zero glance interactions that can specifically work with these two interaction mechanisms. It shows the importance of better understanding the behaviour of those drivers who are able to achieve successful zero glance interactions with in-vehicle displays so designers can use that information to design their systems in a way that enables peripheral vision or muscle memory interaction.

The findings are therefore novel and significant, as previous research has not considered the role of peripheral vision and muscle memory in the driving context in relation to interactions with a secondary task, and rather focused on the role of these interaction mechanisms as a part of the overall driving task. Hence these findings are an important consideration when designing visual interfaces for in-vehicle touch screens.

9.3.1 RQ1. What are the design characteristics of in-vehicle touch screens that can help in achieving non-visual interaction?

There are design characteristics identified in literature not just in driving but also in other contexts that allow easier and less visually demanding interactions with touch screens. For instance, research has previously investigated the following design characteristics; target size and location, number of targets and contrast levels (Parhi, Karlson and Bederson, 2006; Sun, Plocher and Qu, 2007; Kane, Wobbrock and Ladner, 2011; Kirkpatrick *et al.*, 2018) which have been identified as having the potential to contribute to visual demand. The driving simulator study (Chapter 4) which studied button size, location and contrast level revealed that smaller buttons resulted in more off-road glances confirming previous research findings that highlight that smaller buttons are more visually demanding compared to larger buttons (Parhi, Karlson and Bederson, 2006; Sun, Plocher and Qu, 2007; Kim *et al.*, 2011). Smaller buttons can lead to more visual clutter on the display as more information can be presented on the display at a time. It has been shown in the study discussed in chapter five that larger number of buttons displayed on the screen result in a higher number of off-road glances.

The study discussed in chapter four also showed that button location is an important consideration when aiming to achieve non-visual interaction. The results showed that buttons that are located on the edges of the in-vehicle display are less likely to result in more off-road glances compared to buttons located at the middle of the display which do no provide a reference point for the driver during the target selection task. Other research in literature also show that poorly chosen locations for button placement can result in more off-road glances (Wilfinger, D. Meschtscherjakov, A. Perterer and Tscheligi, 2012). It has especially been shown in previous research that buttons that are placed outside of the normal line of sight of the driver whilst driving result in longer off-road glances (Dukic *et al.*, 2005).

The two studies focusing on the design characteristics (Chapter 4 and 5) were imperative in highlighting the considerable proportion of zero glance interactions which lead into the next two research questions addressed. These studies showed that across all of the conditions in both studies, the proportion of zero glance interactions was between 10 to 45 per cent. These findings made it clear that there was a considerable amount of zero glance interactions upon further investigation could provide a better insight how some drivers could achieve successful non-visual interactions.

9.3.2 RQ2. What are the interaction mechanisms adopted by drivers to achieve non-visual interaction when interacting with in-vehicle displays?

The two interaction mechanisms identified in the work conducted as a part of this research that play a role in achieving non-visual interaction were peripheral vision and muscle memory. It has been shown in literature that peripheral vision plays a useful role in driving; helping drivers with lane keeping, detection of headway and monitoring vehicles and road signs (Mourant and Rockwell, 1970; Summala, Nieminen and Punto, 1996; Lamble *et al.*, 1999). The previous work that focus on the role of peripheral vision also assume that the driver’s foveal vision would be engaged otherwise when interacting with a secondary task, hence researchers have focused on understanding how peripheral vision aids the driving task. Although this has been proven to be useful in a driving context, ultimately it is important to ensure in-vehicle systems are designed in such a way that drivers can keep their eyes on the road for a majority of the time as required by the driving task.

Muscle memory also plays a role within driving similar to other tasks that are learnt over time and with repetition where certain movements or parts of the task become automated (Zaharis *et al.*, 2010). Specifically, in driving muscle memory is observed in certain actions required for the driving task to become automatic such as changing gears or lane keeping (Charlton and Starkey, 2011). Similarly to peripheral vision, even though muscle memory can be considered as a part of the driving task it should also be taken into consideration when investigating drivers' interaction with in-vehicle displays.

The studies conducted as a part of this thesis have shown that the behaviour of the driver when using peripheral vision or muscle memory as an interaction mechanism differs significantly. One of the main differences is that muscle memory fundamentally relies on change and increase in performance over time (Hassanpoor, Fallah and Raza, 2012). With the use of muscle memory people build up expertise, and, as a result after some time they do not have to rely on vision to complete certain tasks. Hence during muscle memory conditions, the secondary task of target selection performance improves as the target selection behaviour is learnt. The issue with muscle memory is that in a real driving context, drivers generally do not complete the same sequence of actions frequently enough to accumulate the required muscle memory for non-visual interaction. Even in the studies discussed in chapters six and seven where participants were performing the same button press repeatedly unlike they would do in a real driving context, fluctuations were observed in secondary task performance. Consequently, the positive effect of muscle memory on secondary task performance did not last throughout the whole drive during these conditions. Also, performance in muscle memory is likely to be better if one gets to practice the target selection task, which again is not relevant in a driving context as drivers tend not to practice their interaction with the system before driving their vehicle. However, it would be expected for drivers to gradually learn the location of the items on the touch screen over time to be able to perform certain regularly performed sequence of item selections without the need for vision. There are also ways to design the system in a way that it allows the driver to learn the location of certain buttons by placing the buttons that offer the same functionality across all screens (e.g. exit, back or home) in the same location every time (Shneiderman, 2010). This will be discussed in detail in the next section (section 9.4) of this chapter.

In contrast to muscle memory, peripheral vision does not require the driver to learn the task that is going to be performed in order to perform it without taking their eyes off the road. There also is little change in performance over time with the use of peripheral vision, as it is expected that the field of vision generally stays uniform throughout. However, there may be some instances during which this may not be the case. For instance, when the driving scenario is particularly complex (Gugerty, Rakauskas and Brooks, 2004), the task demand within foveal vision may not leave the driver with enough bandwidth to attend to information in their peripheral vision (Williams, 1985, 1995; Miura, 1986) otherwise known as tunnel vision. It is argued that this is due to the cognitive demand caused by a high complexity situation and the "*narrowing field of view is attentional rather than perceptual"* (Dirkin and Hancock, 1985;

Olsson and Burns, 2000, p. 2). Effectively, the cognitive demand caused by the complex driving task ultimately has an impact on the driver's peripheral visual capability in as it has a narrowing effect on the peripheral field. With such situations, even with peripheral vision friendly displays, the performance in the interaction with the in-vehicle touch screen is likely to suffer. However, it is expected that if the driving condition is too complex and requires the attention of the driver to the road ahead, then the safe option would be to not interact with the touch screen during these instances.

9.3.3 RQ3. What is the relationship between the design characteristics and interaction mechanisms?

Out of the three possible interaction mechanisms drivers can use to interact with an in-vehicle touch screen, it is expected that foveal vision would have the most detrimental effect on driving performance as the driver would be taking their eyes off the road ahead to attend the in-vehicle task. Although from the performance of a secondary task point of view foveal vision would result in higher secondary task performance, in a driving context the primary concern of drivers should be the driving task and they should be aiming to keep their eyes on the road ahead. The reality though is that drivers will interact with the in-vehicle display even in the expense of degradation in the driving performance, although they may or may not realise the negative impact of their actions on their driving performance (Oviedo-Trespalacios *et al.*, 2017). It is stated that drivers report that they believe if IVIS functions are provided in the vehicle, then they are safe to use whilst driving (Silber, 2018). In such cases, drivers compensate for the change in overall demand (as this would increase when they are performing the driving task and the secondary task simultaneously) by showing compensatory behaviours in their driving, to increase safety margins (e.g. increasing the distance between themselves and the car in front when interacting with the display and quickly speeding up to catch up with the car in front when they are finished interacting with the display). There is clearly a need to find the right balance between the two tasks to make sure that the in-vehicle systems are designed in a way to encourage drivers to keep their eyes on the road ahead.

At this point, one could argue that car manufacturers should not provide these systems to be used in the vehicle whilst the vehicle is in motion. However, as discussed in the introduction chapter (Chapter 1), the reality of it is that the advancements in the in-vehicle technologies accessible within vehicles is becoming a selling point for car manufacturers and allow them to compete with each other by offering more features to their customers.

The results show that secondary task performance when using muscle memory suffers considerably more than peripheral and foveal vision under different driving complexities. This finding may have arisen due to the complete non-visual nature of muscle memory. Muscle memory interaction relies wholly on the number of repetitions and eventually building a mental model of the task and where the items are located on the touch screen. It may also be due to the fact that people generally struggle to perform a visual task completely non-visually with no indicators of how they’re interacting with the task.

The driving simulator study that compared the three interaction mechanisms under three different driving conditions showed that muscle memory as an interaction mechanism had the least impact on driving performance. This finding arose presumably because the foveal vision conditions required the drivers to take their eyes off the road, consequently leading to the most detrimental effect on driving performance out of the three interaction mechanisms. Peripheral vision followed foveal vision in terms of its detrimental effect on driving performance. This may have been due to the fact that it is established in the literature that drivers use their peripheral vision to help with lane keeping when driving. Thus, it is not surprising that whilst drivers were asked to use their peripheral vision for the successful completion of the secondary task, their driving was affected. Nevertheless, it is important to highlight that this effect was less detrimental in the peripheral vision conditions compared to foveal vision.

9.4 DESIGN IMPLICATIONS

The target selection task model that was introduced in chapter one is revisited at this point. This diagram has been updated based on the findings from the empirical studies conducted in chapters four to eight (Figure 57). The results of the user trials conducted as a part of this research have shown that there is potential to use peripheral vision for secondary in-vehicle tasks in a driving context to achieve successful non-visual interactions. These results highlight the importance of understanding what design elements of displays make them appropriate for interaction with peripheral vision and how we can incorporate that knowledge into the design of new in-vehicle interfaces. Peripheral vision friendly displays are particularly useful for environments where users are expecting to multitask, such as a driver performing a secondary task by interacting with an in-vehicle display whilst driving. Such displays would require less attention from the driver allowing them to keep their attention on the road ahead (Weiser and Brown, 1996).

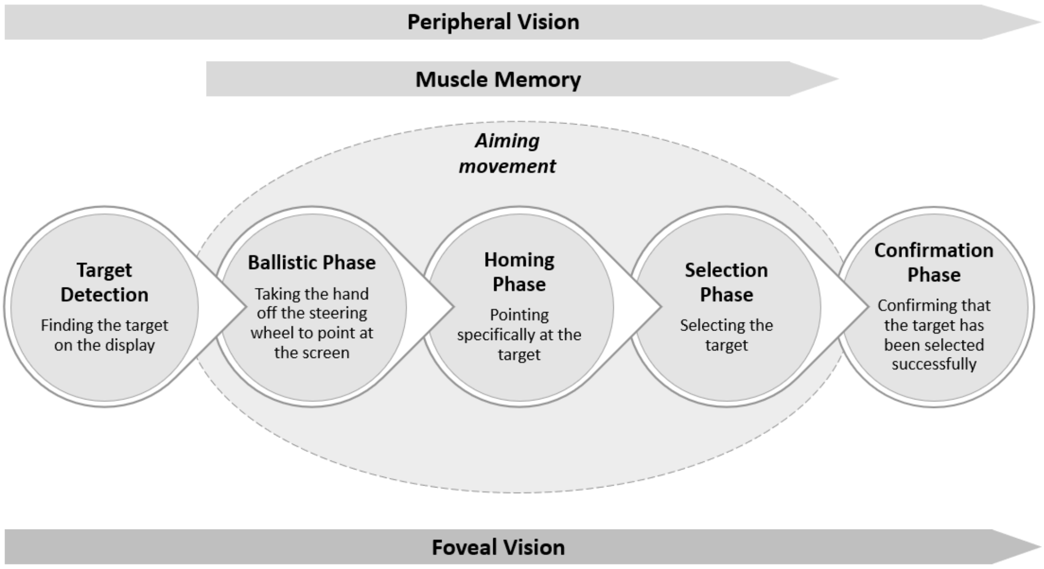


Figure 57. Updated version of the target selection task model from chapter one

It has been established based on the drivers' interaction with the in-vehicle display in the driving simulator studies that the aiming movement for touch screen interaction can be extended to the selection phase as the homing and selection phases can merge when interacting with touch screens (Figure 57). Under ideal circumstances foveal vision can be used for all stages of the model. However, in a driving environment as the driver is required to keep their eyes on the road ahead this is not possible. Consequently, this research has highlighted the stages in a target selection task where peripheral vision could be adopted to achieve blind interaction resulting in drivers being able to keep their foveal vision assigned to the road ahead. Muscle memory also could be used in the aiming movement phase of the target selection task to achieve non-visual interactions. However, for the reasons discussed earlier in this chapter muscle memory may not as be as viable as peripheral vision.

The possibility of using peripheral vision in some of the stages of the target selection task depends on the characteristics of the display. The focus of this thesis has been mainly on the stages covered by the aiming movement. However, there may be ways to incorporate peripheral vision into other stages of the selection task too. A screen with more targets to choose from may not make it possible for the driver to use their peripheral vision, especially if the targets are similar to each other. There are various design guidelines and theories outlining ways to help designers of displays that present numerous functions to make it easier for the users of these displays to interact with them. For example, there are guidelines around reconfigurable systems specifically within aviation outlining that frequently used buttons/switches should be assigned the same task for each sub-level (Calhoun, 1978). Another guideline provided by Little and Hannen (1993) suggest that there should be buttons providing a high-level access to smaller subsets. There are guidelines suggesting that buttons with similar functions should be grouped together (McDonald, Dayton and McDonald, 1988; Seidler and Wickens, 1992; Large *et al.*, 2016).

It is important to remember that for either peripheral vision or muscle memory to be used by drivers to interact with the in-vehicle touch screen, the interface would need to be designed in a way to accommodate these interaction mechanisms. Design goals such as a smaller number of targets (Wolfe, 1997), targets that are visibly different from each other (Yoon, Lim and Ji, 2015) – colour, shape or size (Monterey Technologies Inc., 1996; Greenstein, 1997; Dandekar, Raju and Srinivasan, 2003) – or the location of the target could have an influence on achieving ‘blind interaction’ during certain stages of the target selection process. Studies have been conducted investigating the effects of various design characteristics such as display cluster (e.g. number of items, size of items and colour) specifically for in-vehicle displays (Yoon, Lim and Ji, 2015; Lee, Hwangbo and Ji, 2016).

As muscle memory does not rely on vision and in-vehicle touch screens generally lack tactile feedback, it is more difficult for a driver to find the target on a display solely using muscle memory. However, there is research investigating how to incorporate tactile feedback into in-vehicle touch screens (Pitts *et al.*, 2012) or even into mid-air using ultrasound (Harrington, Burnett and Georgiou, 2018). These advancements in technology may still allow the driver to build up some muscle memory and mental model of where the buttons are located on a screen and experience the tactile feedback they would if they were using traditional buttons. Peripheral vision may be more appropriate for the target detection stage of the target selection task compared to muscle memory. Another observation during the driving simulator studies is that some participants were finding the target on the display using their finger, so at times the target detection stage became absorbed within the aiming movement. During target detection a pop-out effect can be incorporated as it has been established that a pop-out effect also helps direct the attention of the user to the target item (Baldassi and Burr, 2004) and this could be achieved by making the target item visually distinctive compared to its surrounding items by using colour, brightness and movement (Beck, 1982; Julesz, 1984; Treisman, 1998) but not size (Baldassi and Burr, 2004).

The aiming movement stage of the target selection task can incorporate both peripheral vision and muscle memory at its different substages. The ballistic phase could highly benefit from muscle memory and, as an extension, proprioception as discussed in the literature review (section 2.6). The driver does not necessarily need to be looking at their hand when they are in the ballistic stage.

Another design element to consider in relation to achieving blind interaction is the type of confirmation feedback and the way it is presented during the ‘confirmation phase’ which can potentially eliminate the need for the driver to glance at the screen for confirmation of target selection. Some of this feedback from the system when the target is selected may be obvious due to the nature of the selection such as the change in the volume of the audio or the change in fan speed on the HVAC. However, in other cases the feedback may not be as obvious, and the display may need to provide audio or tactile feedback to confirm that the selection task has been completed. On a similar note, feedback should be given not only when a selection is successful but also when it is unsuccessful. The presence of tactile feedback may help during the selection phase for the driver to know that they are selecting a target on the display. During the confirmation phase of the button selection task non-visual feedback can help drivers keep their eyes on the road. It has been shown that non-visual feedback is especially useful in scenarios during which there is low visibility of the screen the user is interacting with or scenarios during which they are expected to multitask; such as interacting with an in-vehicle display whilst driving (Richter *et al.*, 2010). Tactile feedback provided by the touch screen is particularly useful as not having it results in difficulty in exploring the items presented on the display. As the aim is to decrease visual demand from the in-vehicle displays, tactile feedback can be an alternative solution to provide feedback to the user as a result of their action.

As discussed in the literature review (section 2.6.1, p. 40), humans are capable of processing a significant amount of useful information using their peripheral vision. Peripheral/ambient displays aim to exploit this natural capability and attempt to divide the information presented to the user by presenting appropriate information in the periphery (Mankoff *et al.*, 2003). There are certain characteristics that ambient display design focus on such as the use of image over text (Plaue, Miller and Stasko, 2004; Plaue and Stasko, 2007). Another concept that has been researched previously is glanceable displays (Stasko *et al.*, 2005; Matthews *et al.*, 2006; Matthews, 2007; Rogers, Payne and Todd, 2010) which aim to help people manage information in environments in which they may be overloaded with information. Specifically, the intention of these displays is to decrease the amount of time that the user needs to look at the display to extract the information they need, rather than avoiding looking at the display completely. Although the focus of the current work was zero glance interactions, learnings can still be taken from glanceable displays that may encourage zero glance interactions. For example glanceable displays help during task switching by highlighting the new information that may cause the user to switch between the primary and secondary task (Matthews, 2007). Another approach is to chunk similar information together to make it easier for the user to learn where the information is presented hence make it more glanceable (Miller, 1956). Similarly to the results obtained in the study discussed in chapter five, glanceable displays also benefit from a lower number of stimuli presented on the display as reaction time increases as the number of stimuli increase (Teichner and Krebs, 1974).

There are various other considerations for HMI design other than safety when using in-vehicle displays that has not been the focus of this research such as customer expectations, increase in complexity of functions, requirements management, commercial differentiation and user experience (Nymark and Zhang, 2010). There has been a shift in the design approach for in-vehicle HMI design over the last decade due to the limited spare capacity the driver has when driving and the potential road safety implications. The shift has been from technology-centred design to human-centred design (Francois *et al.*, 2016). Ultimately designing an interface that requires less visual demand from the driver also has an impact on the other HMI design considerations. If the system is designed in a way in which the driver does not need to choose between whether to keep their eyes on the road or to take their eyes off the road to interact with the in-vehicle display, overall not having to make the decision of where to allocate their visual attention whilst ensuring that they are driving safely will positively impact their experience of using the in-vehicle HMI.

According to a Connected Car survey conducted by Bird (2016) in the US with 1003 new car intenders showed that those who already own a vehicle with an infotainment system - which was 70% of the participants – stated that they want their next car to have the ability to have over the air updates to allow to fix or enhance the HMI user experience in the vehicle. The results also showed that a touch screen in the most preferred method for system settings (41%), navigation (40%) smart phone apps (39%) radio (29%) and climate control settings (27%) (Bird, 2016). This data shows that drivers are becoming more open to having more technology available to them in their vehicles. Although these are expectations from people who are looking to purchase new vehicles, ultimately drivers want their driving experience to be safe. Until drivers are not required to drive anymore and can engage in other tasks in the vehicle without having to consider monitoring the driving task, driver distraction will remain an issue. The balance between creating interfaces that customers desire that allow customers to perform numerous tasks and simultaneously safely driving their vehicle will be a challenge for car manufacturers.

Overall, the findings of this work certainly do not suggest that drivers can use an in-vehicle touch screen solely based on peripheral vision and muscle memory or that car manufacturers should design interfaces that are solely based on the use of these two interaction mechanisms. There are various aspects to the design of in-vehicle displays that need to be balanced in order to provide an aesthetically pleasing interface – mainly for commercial differentiation and competitiveness – a positive user experience (e.g. ease of interaction) and safety. Hence designing an interface that could purely use peripheral vision and muscle memory as an interaction mechanism although potentially may allow for a safer interaction in terms of encouraging drivers to keep their eyes on the road, but it may also present limitations related to other aspects of in-vehicle HMI design. Consequently, the aim of the work is to highlight the stages of a target selection task on an in-vehicle touch screen that these interaction mechanisms can be used so designers could incorporate the approach and learnings for specific aspects of their design. As an example, a single button that covers the whole screen can be presented to the driver which would allow for peripheral vision interaction. However, this would not be aesthetically pleasing or potentially would not provide a positive customer experience due to the number of functions an in-vehicle displays needs to incorporate and accommodate resulting in too many menu levels the driver would need to navigate through.

9.5 LIMITATIONS

There were a number of limitations with the studies conducted as a part of this research. First of all, due to the nature of the studies conducted, as discussed in chapter three, a driving simulator environment was chosen over real life driving. From an ethical point of view, as participants were actively told to look away from the road or were given a secondary task that was likely to impair driving performance, it would not have been possible to conduct these studies on a real road. As a result, although there was relative validity in the use of the simulator, there may not have been absolute validity. However, the driving simulator studies still were able to highlight the differences between different interaction mechanisms and the impact of the various design elements on glance behaviour.

A further limitation may have been the simplicity of the touch screen design used in the studies. In order to make sure there was tight control of independent variables, a real life in-vehicle system was not chosen for these studies. As a compromise in the validation study (Chapter 8), participants were presented with icons on the display that drivers would be likely to see on an in-vehicle touch screen to try to imitate a real-life display. Similarly, the nature of the secondary task the participants were asked to perform in the studies conducted was a visual detection task. This consisted of participants correctly detecting and selecting the required button appearing on the in-vehicle touch screen. The reason why a visual detection task was chosen over a visual search task was the potential complexity a visual search task would have introduced to the experiments. The studies conducted already consider a number of variables related to the interaction with in-vehicle displays such as design characteristics and interaction mechanisms. Introducing a visual search task could have added more complexity to the trials potentially not allowing for the role of the two interaction mechanisms to be explored sufficiently. Research also shows that the increased complexity on a display are more likely to require the drivers' taking their eyes off the road to complete the visual search task (Feng, Liu and Chen, 2017b). It was assumed that the nature of the visual search task would not allow for a zero-glance interaction. However, it was believed that the target detection task would be more likely to accommodate this type of interaction and is still a valid and relevant part of interacting with in-vehicle displays. Contrarily, the simplicity of the target detection task may have led to floor effects not showing any significant differences between foveal and peripheral vision in terms of driving performance. Adversely, the results of the studies still showed that participants were able to successfully complete the target detection task using peripheral vision without having to take their eyes off the road ahead.

9.6 FUTURE WORK

This thesis raises a new set of requirements for designers of in-vehicle infotainment systems to help them design interfaces, so they are not visually distracting and interfere with the driving task.

Future work should investigate the balances between in-vehicle touchscreen designs which are aesthetically pleasing, provide utility but also minimise visual demand. Technically it is possible to design in-vehicle touchscreen interfaces that do not require any off-road glances. However, these most likely will not be desirable interfaces or may not be able to capture all the possible functions drivers can interact with within these systems. The research of this thesis has shown that a small number of buttons that are large in size, positioned on the edges of the display and have high contrast levels result in fewer glances (or potentially zero glances) away from the road. Although the findings from the current research outline the ideal design of an interface for a less visually demanding interaction, it is not always possible to design interfaces in such a way. For instance, a button presented on the touch screen that is the size of the entire screen may not require any visual demand. However, this is not a realistic design, and thus is challenging to find a balance between interfaces that are sellable by car manufacturers which are also safe for drivers to use whilst driving.

Another point to further investigate is the individual differences amongst drivers. Based on existing literature (Brouwer *et al.*, 1991; Maltz, Shinar and -Gurion, 1999), it is apparent that there are differences in visual patterns amongst, younger vs older, and novice vs experienced drivers. It would be useful to consider how designing for peripheral vision impacts these different groups of drivers.

This thesis also chose to focus on four design variables; button location, size, contrast level and the number of buttons. This work should extend to considering more design variables such as colour, grouping, menu levels, etc. it should also consider the impact of design variables such as the number of buttons on menu levels and the amount of information that can be displayed on the screen at a time.

9.7 CLOSING REMARKS

In closing, this work highlights the importance of designing in-vehicle touch screens for peripheral vision use in order to encourage drivers to keep their eyes on the road whilst they are performing an IVIS task whilst driving. It is essential that more research is done considering the developments in in-vehicle technologies as it has been established that the guidelines and recommendations that currently exist are not enough to provide guidance when designing safer newer in-vehicle technologies. Although designing for peripheral vision may not completely eliminate the need for drivers to take their eyes off the road whilst performing secondary tasks, it certainly helps in decreasing the visual demand imposed on drivers by in-vehicle displays. The use of a peripheral vision interaction has proven to be a successful way of interacting with displays and allowing more successful multitasking in other domains such as aviation (Brown, Holmqvist and Woodhotjse, 1961; Ebrahimi and Kunov, 1991; Somervell *et al.*, 2002). There is considerable scope in the automotive domain for this knowledge to be exploited to design safer systems for drivers.

10 REFERENCES

Absar, R. and Guastavino, C. (2008) 'USABILITY OF NON-SPEECH SOUNDS IN USER INTERFACES', in *Proceedings of the 14th International Conference on Auditory Display*. Paris, France. Available at: https://smartech.gatech.edu/bitstream/handle/1853/49965/AbsarGuastavino2008.pdf?sequence=1&isAllowed=y (Accessed: 16 December 2018).

Adell, E., Várhelyi, A. and Hjälmdahl, M. (2008) 'Auditory and haptic systems for in-car speed management – A comparative real life study', *Transportation Research Part*, F(11), pp. 445–458. doi: 10.1016/j.trf.2008.04.003.

Ahmad, B. I. *et al.* (2016) 'You Do Not Have to Touch to Select: A Study on Predictive In-car Touchscreen with Mid-air Selection', *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - Automotive'UI 16*, (October), pp. 113–120. doi: 10.1145/3003715.3005461.

Akamatsu, M., MacKenzie, I. S. and Hasbroucq, T. (1995) 'A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device', *Ergonomics*, 38(4), pp. 816–827.

Alliance of Automobile Manufacturers (2006) *Statement of Principles, Criteria and Verification Procedures on Driver Interactions with Advanced In-Vehicle Information and Communication Systems*. Washington, DC. Available at: https://autoalliance.org/wp-content/uploads/2018/08/Alliance-DF-T-

Guidelines-Inc-2006-Updates.pdf (Accessed: 12 December 2018).

Angell, L. S. *et al.* (2006) *Driver workload metrics task 2 final report (No. HS-810 635)*.

Anstis, S. M. (1974) ‘A chart demonstrating variations in acuity with retinal position’, *Vision Research*, 14(7). Available at: https://pdfs.semanticscholar.org/166a/c8048aa7b9e3b99943c27bd68da3a5d9b6d4.pdf (Accessed: 9 September 2018).

Antin, J. F. *et al.* (1990) ‘An evaluation of the effectiveness and efficiency of an automobile moving-map navigational display’, *International Journal of Man-Machine Studies*, 33(5), pp. 581–594.

Avsar, H., Fischer, J. E. and Rodden, T. (2016) ‘Designing Touch Screen User Interfaces for Future Flight Deck Operations’, *Digital Avionics Systems Conference (DASC)*, pp. 1–9. Available at: http://eprints.nottingham.ac.uk/37401/1/Designing Touch Screen User Interfaces for Future Flight Deck Operations.pdf (Accessed: 24 November 2018).

Bach, K. M. *et al.* (2008) ‘You can touch, but you can’t look: Interacting with In-Vehicle Systems’, *Proceeding of the twenty-sixth annual CHI conference on Human factors in computing systems - CHI ’08*, pp. 1139–1148. doi: 10.1145/1357054.1357233.

Baldassi, S. and Burr, D. C. (2004) ‘“‘Pop-out’” of targets modulated in luminance or colour: the effect of intrinsic and extrinsic uncertainty’, *Vision Research*, 44, pp. 1227–1233. doi: 10.1016/j.visres.2003.12.018.

Banter, B. (2010) ‘Touch screens and touch surfaces are enriched by haptic force-feedback’, *Information Display*, 26(3), pp. 26–30. doi: 10.1016/j.physc.2007.03.109.

Bao, S. *et al.* (2015) ‘Distracted Driving Performance Measures’, *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies , 2518, pp. 68–72. doi: 10.3141/2518-09.

Beck, J. (1982) ‘Textural segmentation’, in Beck, J. (ed.) *Organization and Representation in Perception*. Hillsdale, NJ, pp. 285–317.

Becker, S., Hanna, P. and Wagner, V. (2014) ‘Human Machine Interface Design in Modern Vehicles’, *Encyclopedia of Automotive Engineering*.

Bella, F. (2008) ‘Driving simulator for speed research on two-lane rural roads’, *Accident Analysis and Prevention*, 40, pp. 1078–1087. Available at: https://s3.amazonaws.com/academia.edu.documents/45249687/F._Bella_Driving_Simulator_for_Speed_Res20160501-27900-59dlux.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1539097861&Signature=ydkXpfE4VmTwb23Vp7xN16B%2FNZA%3D&response-content-disposition=inlin (Accessed: 9 October 2018).

Bellotti, F. *et al.* (2005) ‘COMUNICAR: designing a multimedia, context-aware human-machine interface for cars’, *Cognition, Technology & Work*. Springer-Verlag, 7(1), pp. 36–45. doi: 10.1007/s10111-004-0168-9.

Bhalla, M. R. and Bhalla, A. V. (2010) ‘Comparative Study of Various Touchscreen Technologies’, *International Journal of Computer Applications*, 6(8), pp. 12–18. doi: 10.5120/1097-1433.

Bhise, V., Dowd, J. and Smid, E. (2003) *A Comprehensive HMI Evaluation Process for Automotive Cockpit Design*. doi: 10.4271/2003-01-0126.

Bhise, V. and Rockwell, T. H. (1971) 'Role of peripheral vision and time-sharing in driving', in *Proceedings: American Association for Automotive Medicine Annual Conference*, pp. 320–341.

Bird, C. (2016) *Consumer Survey - Connected Car US*. Available at: https://cdn.ihs.com/www/pdf/TEST.pdf (Accessed: 12 May 2019).

Birnholtz, J. *et al.* (2010) 'Awareness Beyond the Desktop: Exploring Attention and Distraction with a Projected Peripheral-Vision Display', in *Proceedings of Graphics Interface*. Canadian Information Processing Society. Available at: https://pdfs.semanticscholar.org/01de/fceadd2f29cc86d96991724ffff5d12bd809.pdf (Accessed: 22 September 2018).

Biswas, P. and Langdon, P. (2012) 'Developing Multimodal Adaptation Algorithm for Mobility Impaired Users by Evaluating Their Hand Strength', *International Journal of Human-Computer Interaction*, 28(9), pp. 576–596. doi: 10.1080/10447318.2011.636294.

Blaauw, G. J. (1982) 'Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study', *Human Factors*, 24(4), pp. 473–486. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.925.6181&rep=rep1&type=pdf (Accessed: 9 October 2018).

Blana, E. (1996) 'Driving simulator validation studies: A literature review'. Leeds: Institute of Transport Studies, University of Leeds. doi: 10.1016/S1366-5545(02)00012-1.

Bouma, H. (1970) ‘Interaction Effects in Parafoveal Letter Recognition’, *Nature*. Nature Publishing Group, 226(5241), pp. 177–178. doi: 10.1038/226177a0.

Boyle, L. N. *et al.* (2013) ‘Text Reading and Text Input Assessment in Support of the NHTSA Visual-Manual Driver’, (August), pp. 1–73. doi: DOT HS 811 820.

Brewster, S. S. A. and Brown, L. M. L. M. (2004) ‘Tactons: structured tactile messages for non-visual information display’, *Australasian User Interface Conference*, 28(January), pp. 15–23. Available at: www.dcs.gla.ac.uk/~stephen.

Brookhuis, K. A., Waard, D. D. D. . and Mulder, B. (1994) ‘Measuring driving performance by car-following in traffic’, *Ergonomics*, 37(3), pp. 427–434. doi: https://doi.org/10.1080/00140139408963661.

Broström, R. (2015) *Design implications for visual- manual interfaces in cars Design Implications for Visual- Manual Interfaces in Cars*.

Brouwer, W. H. *et al.* (1991) ‘Divided Attention in Experienced Young and Older Drivers: Lane Tracking and Visual Analysis in a Dynamic Driving Simulator’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 33(5), pp. 573–582. doi: 10.1177/001872089103300508.

Brown, I. D., Holmqvist, S. D. and Woodhotjse, M. C. (1961) ‘A Laboratory Comparison of Tracking With Four Flight-Director Displays’, *Ergonomics*, 4(3), pp. 229–251. doi: 10.1080/00140136108930523.

Brown, I. D., Tickner, A. H. and Simmonds, D. C. (1969) ‘Interference between concurrent tasks of driving and telephoning.’, *Journal of Applied Psychology*, 53(5), pp. 419–424. doi: 10.1037/h0028103.

Brumitt, B. and Cadiz, J. J. (2000) *Let There Be Light!: Comparing Interfaces for Homes of the Future*. Redmond, WA. Available at: https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/tr-2000-92.pdf (Accessed: 12 December 2018).

Burnett, G. *et al.* (2011) ‘Designing touchpad user-interfaces for vehicles: which tasks are most suitable?’, *Behaviour & Information Technology*. Taylor & Francis , 30(3), pp. 403–414. doi: 10.1080/0144929X.2011.553743.

Burnett, G. and Joyner, S. M. (1997) ‘An assessment of moving map and symbol-based route guidance systems’, *Ergonomics and safety of intelligent driver interfaces*, pp. 115–137.

Burnett, G. and Porter, J. M. (2001) ‘Ubiquitous computing within cars: Designing controls for non-visual use’, *International Journal of Human Computer Studies*, 55(4), pp. 521–531. doi: 10.1006/ijhc.2001.0482.

Burnett, G., Summerskill, S. and Porter, J. M. (2004) ‘On-the-move destination entry for vehicle navigation systems: Unsafe by any means?’, *Behaviour & Information Technology*, 23(4), pp. 265–272. doi: 10.1080/01449290410001669950.

Burns, P. C. *et al.* (2002) ‘How Dangerous is Driving with a Mobile Phone? Benchmarking the Impairment to Alcohol’, *Transport Research Laboratory*.

Calhoun, G. L. (1978) ‘Control logic design criteria for multifunction switching devices', *Proceedings of the Human Factors Society Annual Meeting*, 22(1), pp. 383–387.

Campbell, F. W. and Maffei, L. (1974) 'Contrast and Spatial Frequency', *Scientific American*. Scientific American, a division of Nature America, Inc., 231(5), pp. 106–115. doi: 10.2307/24950220.

Campbell, J. L. *et al.* (2004) *In-Vehicle Display Icons and Other Information Elements. Volume 1: Guidelines*. Available at: https://trid.trb.org/view/754994 (Accessed: 23 September 2018).

Cantin, V. *et al.* (2009) 'Mental workload when driving in a simulator: Effects of age and driving complexity', *Accident Analysis and Prevention*, 41(4), pp. 763–771. doi: 10.1016/j.aap.2009.03.019.

Cao, Y. *et al.* (2010) 'Evaluating Informative Auditory and Tactile Cues for In-Vehicle Information Systems', in *Proceedings of the Second International Conference on Automotive User Interfaces and Interactive Vehicular Applications* . Pittsburgh, Pennsylvania, USA: ACM, pp. 102–109. Available at: http://apple2.org.za/gswv/a2zine/GS.WorldView/ (Accessed: 10 December 2018).

Caprani, N., O'Connor, N. E. and Gurrin, C. (2012) 'Touch Screens for the Older User', *Assistive Technologies*.

Carney, C., Campbell, J. L. and Mitchell, E. A. (1998) 'In-Vehicle Display Icons and Other Information Elements: Literature Review'. Turner-Fairbank Highway Research Center. Available at: https://rosap.ntl.bts.gov/view/dot/14094 (Accessed: 19 July 2018).

Carter, T. *et al.* (2013) ‘UltraHaptics : Multi-Point Mid-Air Haptic Feedback for Touch Surfaces’, *Proc. UIST 2013*, pp. 505–514. doi: 10.1145/2501988.2502018.

CarWow (no date) *New Land Rover Range Rover Review*. Available at: https://www.carwow.co.uk/land-rover/range-rover (Accessed: 13 October 2018).

Chapman, P. R. and Underwood, G. (1998) ‘Visual search of driving situations: Danger and experience’, *Perception*, 27(8), pp. 951–964.

Charlton, S. G. and Starkey, N. J. (2011) ‘Driving without awareness: The effects of practice and automaticity on attention and driving’. Pergamon, 14(6), pp. 456–471. Available at: https://www.sciencedirect.com/science/article/pii/S1369847811000490 (Accessed: 9 September 2018).

Chiang, D. P., Brooks, A. M. and Weir, D. H. (2004) ‘On the highway measures of driver glance behavior with an example automobile navigation system’, *Applied Ergonomics*, 35(3), pp. 215–223. doi: 10.1016/j.apergo.2004.01.005.

Chisholm, S. L., Caird, J. K. and Lockhart, J. (2008) ‘The effects of practice with MP3 players on driving performance’, *Accident Analysis and Prevention*, 40, pp. 704–713. doi: 10.1016/j.aap.2007.09.014.

Christ, R. E. (1975) ‘Review and Analysis of Color Coding Research for Visual Displays’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 17(6), pp. 542–570. doi: 10.1177/001872087501700602.

Christ, R. E. (1984) ‘Research for evaluating visual display codes: An emphasis on colour coding’, in *Information design: The design and evaluation of signs and printed materials*. John Wiley & Sons, pp. 209–228.

Christiansen, L. H. *et al.* (2011) ‘LNCS 6947 - Don’t Look at Me, I’m Talking to You: Investigating Input and Output Modalities for In-Vehicle Systems’, in *IFIP Conference on Human-Computer Interaction*. Berlin: Springer, pp. 675–691. Available at: https://link.springer.com/content/pdf/10.1007/978-3-642-23771-3_49.pdf (Accessed: 16 December 2018).

Chung, M. K. *et al.* (2010) ‘Usability evaluation of numeric entry tasks on keypad type and age’, *International Journal of Industrial Ergonomics*, 40, pp. 97–105. Available at: https://ac.els-cdn.com/S0169814109001012/1-s2.0-S0169814109001012-main.pdf?_tid=2c8f3550-5141-4750-aa0c-5f158b752bb8&acdnat=1536495458_a05949483b7de6597b24d8448a305b4c (Accessed: 9 September 2018).

Chung, S. C. *et al.* (2006) ‘Differences in psychophysiological responses due to simulator sickness sensitivity’, in *World Congress on Medical Physics and Biomedical Engineering*, pp. 1218–1221.

Classen, S., Bewernitz, M. and Shechtman, O. (2011) ‘Driving simulator sickness: An evidence-based review of the literature’, *American Journal of Occupational Therapy*, 65(2), pp. 179–188. doi: 10.5014/ajot.2011.000802.

Commission of the European Communities (2008) *Recommendation on safe and efficient in-vehicle information and communication systems: update of the European Statement of Principles on human-machine interface*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008H0653&from=EN (Accessed: 12 December 2018).

Cooper, G. E. and Harper, Robert P, J. (1969) ‘THE USE OF PILOT RATING IN THE EVALUATION OF AIRCRAFT HANDLING QUALITIES’. Available at: https://apps.dtic.mil/docs/citations/AD0689722 (Accessed: 24 November 2018).

Costanza, E. *et al.* (2006) ‘eye-q: Eyeglass Peripheral Display for Subtle Intimate Notifications’, in *Proceedings of the 8th conference on Human-computer interaction with mobile devices and services* . ACM, pp. 211–218. Available at: https://eprints.soton.ac.uk/270955/1/glasses-mobileHCI.pdf (Accessed: 22 September 2018).

Crawford, J. D., Medendorp, W. P. and Marotta, J. J. (2004) ‘Spatial Transformations for Eye-Hand Coordination’, *Journal of Neurophysiology*, 92, pp. 10–19. doi: 10.1152/jn.00117.2004.

Crossman, E. R. F. W. and Goodeve, P. J. (1983) ‘Feedback control of hand-movement and Fitts’ Law’, *Quarterly Journal of Experimental Psychology*, 35, pp. 251–278. Available at: https://journals.sagepub.com/doi/pdf/10.1080/14640748308402133 (Accessed: 12 December 2018).

Curry, G. A., Hieatt, D. J. and Wilde, G. (1975) *Task load in the motor vehicle operator: A comparative study of assessment procedures*. Ottowa, Canada.

van Dam, A. (1997) ‘Post-WIMP: User Intefaces’, *Communications of the ACM*, 40(2), pp. 63–67. Available at: http://www.sensable.com (Accessed: 9 September 2018).

Dandekar, K., Raju, B. I. and Srinivasan, M. A. (2003) ‘3-D Finite-Element Models of Human and Monkey Fingertips to Investigate the Mechanics of Tactile Sense’, *Journal of Biomechanical Engineering*, 125(5), p. 682. doi: 10.1115/1.1613673.

Department for Transport (2016) *Reported road casualties in Great Britain: main results 2015*. Available at: www.gov.uk/government/ (Accessed: 23 September 2018).

Department for Transport (2017) *Advanced driver assistance systems and automated vehicle technologies: supporting their use in the UK*.

Desmurget, M. *et al.* (1998) ‘From Eye to Hand: Planning Goal-directed Movements’, *Neuroscience and Biobehavioral Reviews*, 22(6), pp. 761–788. Available at: http://chronos.isir.upmc.fr/~gas/pam/img_auth.php/f/f5/Desmurget1998.pdf (Accessed: 13 December 2018).

Desmurget, M. *et al.* (2000) ‘Proprioception does not quickly drift during visual occlusion’, *Experimental Brain Research*, 134(3), pp. 363–377. doi: 10.1007/s002210000473.

Dirkin, G. R. and Hancock, P. (1985) ‘An attentional view of narrowing: The effect of noise and signal bias on discrimination in the peripheral visual field’, in *Ergonomics International 85: Proceedings of the Ninth Congress of the International Ergonomics Association*. Bournemouth, England, pp. 751–753.

Donges, E. (1978) ‘A Two-Level Model of Driver Steering Behavior’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 20(6), pp. 691–707. doi:

10.1177/001872087802000607.

Driver and Vehicle Standards Agency (2017) *Improving the car driving test: report on consultation*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/608857/improving-the-car-driving-test-response-to-consultation.pdf (Accessed: 30 September 2018).

Duchowski, A. T. (2002) ‘A breadth-first survey of eye-tracking applications’, *Behavior Research Methods, Instruments, and Computers*, 34(4), pp. 455–470. doi: 10.3758/BF03195475.

Dukic, T. *et al.* (2005) ‘Effect of button location on driver’s visual behaviour and safety perception’, *Ergonomics*. Taylor & Francis Group Ltd, 48(4), pp. 399–410. doi: 10.1080/00140130400029092.

Dukic, T., Hanson, L. and Falkmer, T. (2006) ‘Effect of drivers’ age and push button locations on visual time off road, steering wheel deviation and safety perception’, *Ergonomics*. Taylor & Francis , 49(1), pp. 78–92. doi: 10.1080/00207540500422320.

Dul, J. and Weerdmeester, B. (2003) *Ergonomics For Beginners*. CRC Press. doi: 10.4324/9780203212097.

Ebrahimi, D. and Kunov, H. (1991) ‘Peripheral vision lipreading aid’, *IEEE Transactions on Biomedical Engineering*, 38(10), pp. 944–952. doi: 10.1109/10.88440.

Ecker, R. *et al.* (2009) ‘pieTouch: A Direct Touch Gesture Interface for Interacting with In-Vehicle Information Systems’, *Proceedings of the 11th*

International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '09, (May), p. 1. doi: 10.1145/1613858.1613887.

Ege, E. S., Cetin, F. and Basdogan, C. (2011) 'Vibrotactile Feedback in Steering Wheel Reduces Navigation Errors during GPS-Guided Car Driving', in *IEEE World Haptics Conference*. Istanbul, Turkey: IEEE. doi: 10.1109/WHC.2011.5945563.

Eggemeier, F. T. *et al.* (1991) 'General considerations concerning workload assessment in multi-task environments', in Lamos, D. L. (ed.) *Multiple Task Performance*. London: Taylor & Francis, pp. 207–216.

Elliott, D. *et al.* (2001) 'A century later: Woodworth's (1899) two-component model of goal-directed aiming', *Psychological Bulletin*, 127(3), pp. 342–357. doi: 10.1037/0033-2909.127.3.342.

Elvik, R. (2006) 'Laws of accident causation', *Accident Analysis and Prevention*, 38, pp. 742–747. doi: 10.1016/j.aap.2006.01.005.

Engström, J., Johansson, E. and Östlund, J. (2005) 'Effects of visual and cognitive load in real and simulated motorway driving', *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2 SPEC. ISS.), pp. 97–120. doi: 10.1016/j.trf.2005.04.012.

Eriksson, M. and Papanikotopoulos, N. P. (1997) 'Eye-tracking for detection of driver fatigue', *Proceedings of Conference on Intelligent Transportation Systems*, pp. 314–319. doi: 10.1109/ITSC.1997.660494.

Eye Tracking Inc. (2011) *What is Eye Tracking?* Available at: http://www.eyetracking.com/About-Us/What-Is-Eye-Tracking (Accessed: 9

October 2018).

Fabre-Thorpe, M. (2011) ‘The characteristics and limits of rapid visual categorization’, *Frontiers in Psychology*. Frontiers, 2, p. 243. doi: 10.3389/fpsyg.2011.00243.

Fei Li, F. *et al.* (2002) ‘Rapid natural scene categorization in the near absence of attention’, *Proceedings of the National Academy of Sciences*, 99(14), pp. 9596–9601. Available at: www.pnas.orgcgidoi10.1073pnas.092277599 (Accessed: 9 September 2018).

Feng, F., Liu, Y. and Chen, Y. (2017a) ‘A computer-aided usability testing tool for in-vehicle infotainment systems’, *Computers & Industrial Engineering*. Pergamon, 109, pp. 313–324. doi: 10.1016/J.CIE.2017.05.019.

Feng, F., Liu, Y. and Chen, Y. (2017b) ‘Effects of Quantity and Size of Buttons of In-Vehicle Touch Screen on Drivers’ Eye Glance Behavior’, *International Journal of Human-Computer Interaction*, pp. 1–14. doi: 10.1080/10447318.2017.1415688.

Findlay, J. M. and Gilchrist, I. D. (2003) *Active vision : the psychology of looking and seeing*. Oxford University Press. Available at: https://books.google.co.uk/books?hl=en&lr=&id=ZnrnCwAAQBAJ&oi=fnd&pg=PR7&dq=Findlay+%26+Gilchrist,+2003&ots=QNZslVZaHH&sig=kdozyJB5vdvuo8t0wpR9kUh_Wb0#v=onepage&q=Findlay %26 Gilchrist%2C 2003&f=false (Accessed: 30 September 2018).

Fitts, P. M. (1954) ‘The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement’, *Journal of Experimental Psychology*, 47(6), pp. 381–391. doi: 10.1037/h0055392.

Fitts, P. M., Jones, R. . and Milton, J. . (1950) ‘Eye movements of aircraft pilots during instrument-landing approaches’, *Aeronautical Engineering Review*, 9(2), pp. 24–29.

Francois, M. *et al.* (2016) ‘Automotive HMI design and participatory user involvement: Review and perspectives’, *Ergonomics*, 60(4). doi: 10.1080/00140139.2016.1188218ï.

Frey, B., Southern, C. and Romero, M. (2011) ‘Brailletouch: Mobile Texting for the Visually Impaired’, in *Proceedings of the 6th International Conference on Universal Access in Human-computer Interaction: Context Diversity - Volume Part III*, pp. 19–25.

Fuller, R. (2005) ‘Towards a general theory of driver behaviour’, *Accident Analysis and Prevention*, 37(3), pp. 461–472. doi: 10.1016/j.aap.2004.11.003.

Funkhouser, D. and Chrysler, S. T. (2007) *ASSESSING DRIVER DISTRACTION DUE TO IN-VEHICLE VIDEO SYSTEMS THROUGH FIELD TESTING AT THE PECOS RESEARCH AND TESTING CENTER 6. Performing Organization Code 13. Type of Report and Period Covered Unclassified*. Texas. Available at: http://www.ntis.gov (Accessed: 13 December 2018).

Gärtner, U., König, W. and Wittig, T. (2001) ‘Evaluation of manual vs. speech input when using a driver infomation system in real traffic’, *Proceedings of the First International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, (August), pp. 7–14. Available at: http://drivingassessment.uiowa.edu/DA2001/02_Gartner_Wittig.pdf.

Geiser, G. (1985) ‘Man Machine Interaction in Vehicles’, *ATZ 87*, pp. 74–77.

Gellatly, A. . and Dingus, T. A. (1998) ‘Speech Recognition and Automotive Applications: Using Speech to Perform in-Vehicle Tasks’, *In Proceedings of the human factors and ergonomics society annual meeting*, 42(17), pp. 1247–1251.

Gill, J. (2000) ‘Which Button? Designing user interfaces for people with visual impairments’. London: Royal National Institute for the Blind.

Gill, K. *et al.* (2013) ‘Digital reader vs print media: the role of digital technology in reading accuracy in age-related macular degeneration.’, *Eye (London, England)*. Nature Publishing Group, 27(5), pp. 639–43. doi: 10.1038/eye.2013.14.

Global Industry Analysts (2018) *Automotive Infotainment Systems: A Research Brief*. Available at: https://strategyr.com/MarketResearch/Automotive_Infotainment_Systems_Market_Trends.asp (Accessed: 26 June 2018).

Godley, S. T., Triggs, T. J. and Fildes, B. N. (2002) ‘Driving simulator validation for speed research’, *Accident Analysis and Prevention*, 34, pp. 589–600. Available at: www.elsevier.com/locate/aap (Accessed: 6 November 2018).

Godthelp, H., Milgram, P. and Blaauw, G. J. (1984) ‘The development of a time-related measure to describe driving strategy’, *Human Factors*, 26(3), pp. 257–268.

Goodale, M. A. and Milner, A. D. (2005) *Sight unseen : an exploration of conscious and unconscious vision*. 2nd Editio. Oxford, UK: Oxford University Press.

Goodman, M. J. *et al.* (1999) ‘Using Cellular Telephones in Vehicles: Safe or Unsafe?’, *Transportation Human Factors*. Lawrence Erlbaum Associates, Inc. , 1(1), pp. 3–42. doi: 10.1207/sthf0101_2.

Green, P. *et al.* (2003) *Typical values for driving performance with emphasis on the standard deviation of lane position: A summary of the literature*. Ann Arbor, MI.

Greenberg, J. *et al.* (2003) ‘Driver Distraction: Evaluation with Event Detection Paradigm’, *Transportation Research Record: Journal of the Transportation Research Board*, 1843(January), pp. 1–9. doi: 10.3141/1843-01.

Greene, M. R. and Oliva, A. (2009) ‘The Briefest of Glances: The Time Course of Natural Scene Understanding’, *Psychological Science*. SAGE PublicationsSage CA: Los Angeles, CA, 20(4), pp. 464–472. doi: 10.1111/j.1467-9280.2009.02316.x.

Greenstein, J. S. (1997) ‘Pointing Devices’, *Handbook of Human-Computer Interaction*. North-Holland, pp. 1317–1348. doi: 10.1016/B978-044481862-1.50121-7.

Gribble, P. L. *et al.* (2002) ‘Hand-eye coordination for rapid pointing movements Arm movement direction and distance are specified prior to saccade onset’, *Exp Brain Res*, 145, pp. 372–382. doi: 10.1007/s00221-002-1122-9.

Grudin, J. (2001) ‘Partitioning DigitalWorlds: Focal and Peripheral Awareness in Multiple Monitor Use’, in *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM, pp. 458–465. doi: 10.1145/365024.365312.

Gugerty, L., Rakauskas, M. and Brooks, J. (2004) ‘Effects of remote and in-person verbal interactions on verbalization rates and attention to dynamic spatial scenes’, *Accident Analysis and Prevention*, 36, pp. 1029–1043. doi: 10.1016/j.aap.2003.12.002.

Haddon, W. (1999) ‘The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptively based’, *Injury Prevention*, pp. 231–236. doi: 10.1136/ip.5.3.231.

Haigney, D. E., Taylor, R. G. and Westerman, S. . (2000) ‘Concurrent mobile (cellular) phone use and driving performance: task demand characteristics and compensatory processes’, *Transportation Research Part F: Traffic Psychology and Behaviour*, 3(3), pp. 113–121.

Harbluk, J. L. *et al.* (2007) ‘Using the Lane-Change Test (LCT) to Assess Distraction: Tests of Visual-Manual and Speech-Based Operation of Navigation System Interfaces’, in *Driver Assessment Conference*, pp. 16–22. doi: 10.17077/drivingassessment.1208.

Harbluk, J. L., Noy, Y. I. and Eizenman, M. (2002) ‘The impact of cognitive distraction on driver visual behaviour and vehicle control’. Available at: https://trid.trb.org/view/643031 (Accessed: 19 July 2018).

HARMAN (2013) *HARMAN delivers leading-edge, next-generation infotainment system for Mercedes-Benz*. Available at: https://news.harman.com/releases/harman-delivers-leading-edge-next-generation-infotainment-system-for-mercedes-benz (Accessed: 13 October 2018).

Harrington, K. J., Burnett, G. E. and Georgiou, O. (2018) ‘Exploring the Use of Mid-Air Ultrasonic Feedback to Enhance Automotive User Interfaces’, in *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. doi: 10.1145/3239060.3239089.

Harrison, B. L. *et al.* (1995) ‘Transparent layered user interfaces: An evaluation of a display design to enhance focused and divided attention’, in *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM Press/Addison-Wesley Publishing Co, pp. 317–324.

Hart, S. G. and Staveland, L. E. (1988) ‘Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research’, *Advances in psychology*, 52, pp. 139–183.

Harvey, C., Stanton, N. A., Pickering, C. A., McDonald, Michael, *et al.* (2011) ‘Context of use as a factor in determining the usability of in-vehicle devices’, *Theoretical Issues in Ergonomics Science*. Taylor & Francis Group , 12(4), pp. 318–338. doi: 10.1080/14639221003717024.

Harvey, C., Stanton, N. A., Pickering, C. A., McDonald, Mike, *et al.* (2011a) ‘In-Vehicle Information Systems to Meet the Needs of Drivers’, *International Journal of Human–Computer Interaction*, 27(6), pp. 505–522. doi: 10.1080/10447318.2011.555296.

Harvey, C., Stanton, N. A., Pickering, C. A., McDonald, Mike, *et al.* (2011b) ‘To twist or poke? A method for identifying usability issues with the rotary controller and touch screen for control of in-vehicle information systems’, *Ergonomics*, 54(7), pp. 609–625. doi: 10.1080/00140139.2011.586063.

Harvey, C. and Stanton, N. A. (2012) ‘Trade-off between context and objectivity in an analytic approach to the evaluation of in-vehicle interfaces’, *IET Intelligent Transport Systems*, 6(3), p. 243. doi: 10.1049/iet-its.2011.0120.

Hassanpoor, H., Fallah, A. and Raza, M. (2012) ‘New role for astroglia in learning: formation of muscle memory’, *Medical hypotheses*, 79(6), pp. 770–773. doi: 10.1016/j.mehy.2012.08.025.

Hatfield, J. and Chamberlain, T. (2005) *THE EFFECTS OF IN-VEHICLE AUDIOVISUAL DISPLAY UNITS ON SIMULATED DRIVING*. Sydney. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.507.9024&rep=rep1&type=pdf (Accessed: 13 December 2018).

Heinrich, H. W. (1931) ‘Industrial Accident Prevention. A Scientific Approach.’, in *Industrial Accident Prevention. A Scientific Approach.* New York & London : McGraw-Hill Book Company, Inc. Available at: https://www.cabdirect.org/cabdirect/abstract/19432701767 (Accessed: 12 May 2019).

Hendy, K. C., Hamilton, K. M. and Landry, L. N. (1993) ‘Measuring Subjective Workload: When Is One Scale Better Than Many?’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 35(4), pp. 579–601. doi: 10.1177/001872089303500401.

Hettinger, L. J. *et al.* (1990) ‘Vection and simulator sickness’, *Military Psychology*, 2(3), p. 171.

Hocherman, S. (1993) ‘Proprioceptive guidance and motor planning of reaching movements to unseen targets', *Experimental Brain Research*. Springer-Verlag, 95(2), pp. 349–358. doi: 10.1007/BF00229793.

Hollnagel, E. (1998) *Cognitive reliability and error analysis method : CREAM*. Elsevier. Available at: https://books.google.co.uk/books?hl=en&lr=&id=-Y4MI8cMSpMC&oi=fnd&pg=PP1&dq=Hollnagel,+E.+(1998).+Cognitive+reliability+and+error+analysis+method+(CREAM).+New+York:+Elsevier+Science+Inc.&ots=ETcUr1dDsy&sig=nwaasE4DTncRdTbUATNrFb_hgeE#v=onepage&q=Hollnagel (Accessed: 12 May 2019).

Horberry, T. *et al.* (2006) 'Driver distraction: The effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance', *Accident Analysis and Prevention*, 38(1), pp. 185–191. doi: 10.1016/j.aap.2005.09.007.

Horng, W.-B. *et al.* (2004) 'Driver fatigue detection based on eye tracking and dynamic template matching', in *IEEE International Conference on Networking, Sensing and Control*, pp. 7–12. doi: 10.1109/ICNSC.2004.1297400.

Horrey, W. J. and Wickens, C. D. (2004a) 'Driving and Side Task Performance: The Effects of Display Clutter, Separation, and Modality', *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 46(4), pp. 611–624. doi: 10.1518/hfes.46.4.611.56805.

Horrey, W. J. and Wickens, C. D. (2004b) *The Impact of Cellular Phone Conversations on Driving: A Meta-Analytical Approach*.

Horrey, W. J. and Wickens, C. D. (2007) 'In-Vehicle Glance Duration: Distributions, Tails, and Model of Crash Risk', *Transportation Research Record: Journal of the Transportation Research Board*, 2018, pp. 22–28. doi:

10.3141/2018-04.

Horrey, W. J., Wickens, C. D. and Alexander, A. (2003) ‘THE EFFECTS OF HEAD-UP DISPLAY CLUTTER AND IN-VEHICLE DISPLAY SEPARATION ON CONCURRENT DRIVING PERFORMANCE’, in *PROCEEDINGS of the HUMAN FACTORS AND ERGONOMICS SOCIETY 47th ANNUAL MEETING*. doi: 10.1177/154193120304701610.

Horrey, W. J., Wickens, C. D. and Consalus, K. P. (2006) ‘Modeling drivers’ visual attention allocation while interacting with in-vehicle technologies’, *Journal of Experimental Psychology: Applied*, 12(2), pp. 67–78. doi: 10.1037/1076-898X.12.2.67.

Huestegge, L. and Böckler, A. (2016) ‘Out of the corner of the driver’s eye: Peripheral processing of hazards in static traffic scenes’, *Journal of Vision*, 16(2), p. 11. doi: 10.1167/16.2.11.

iMotions (2017) *SMI and Apple: What It Means for the Future of Eye Tracking*. Available at: https://imotions.com/blog/smi-apple-eye-tracking/ (Accessed: 13 October 2018).

Iris Tech (no date) *Rods and Cones*. Available at: https://iristech.co/blue-light/rods-and-cones-3/?lang=en (Accessed: 23 September 2018).

ISO 14198 (2012) ‘Road vehicles — Ergonomic aspects of transport information and control systems — Calibration tasks for methods which assess driver demand due to the use of in-vehicle systems’. ISO. Available at: https://www.iso.org/obp/ui/fr/#iso:std:iso:ts:14198:ed-1:v1:en (Accessed: 12 May 2019).

ISO 15007-1 (2014) *Road vehicles — Measurement of driver visual behaviour with respect to transport information and control systems — Part 1: Definitions and parameters*. doi: 10.1007/s11367-011-0297-3.

ISO 15007-2 (2014) *Road vehicles — Measurement of driver visual behaviour with respect to transport information and control systems — Part 2: Equipment and procedures*.

ISO 16673 (2017) *ISO 16673 - Occlusion method to assess visual demand due to the use of in-vehicle systems*.

ISO 2575 (2010) *Road vehicles — Symbols for controls, indicators and tell-tales*.

Ito, T. and Miki, Y. (1997) 'Japan's Safety Guidelines on In-Vehicle Display Systems', in *MOBILITY FOR EVERYONE. 4TH WORLD CONGRESS ON INTELLIGENT TRANSPORT SYSTEMS*. Berlin. Available at: https://trid.trb.org/view/540720 (Accessed: 24 November 2018).

Itoh, K. *et al.* (2004) 'Evaluation of a Voice-Activated System Using a Driving Simulator', *SAE Technical Paper*. doi: https://doi.org/10.4271/2004-01-0232.

Jahn, G. *et al.* (2005) 'Peripheral detection as a workload measure in driving: Effects of traffic complexity and route guidance system use in a driving study', *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(3), pp. 255–275. doi: 10.1016/j.trf.2005.04.009.

Jamson, A. H. *et al.* (2004) 'Speech-based email and driver behaviour: Effects of an in-vehicle message system interface', *Human Factors*, 46(4), pp. 625–639.

Jamson, A. H. and Merat, N. (2005) ‘Surrogate in-vehicle information systems and driver behaviour: Effects of visual and cognitive load in simulated rural driving’, *Transportation Research F*, 8(2), pp. 79–96.

Janelle, C. M., Singer, R. N. and Williams, A. M. (1992) ‘External distraction and attentional narrowing: Visual search evidence’, *Journal of Sport and Exercise Psychology*, 21(1), pp. 70–91.

Japan Automobile Manufacturers Assosciation (2004) *Guideline for In-vehicle Display Systems-Version 3.0*. Available at: http://www.jama-english.jp/release/release/2005/In-vehicle_Display_GuidelineVer3.pdf (Accessed: 12 December 2018).

Jenness, J. W. *et al.* (2002) ‘Effects of manual versus voice-activated dialing during simulated driving.’, *Perceptual and motor skills*, 94(2), pp. 363–379. doi: 10.2466/pms.2002.94.2.363.

Jex, H. R., McDonnell, J. D. and Phatak, A. V. (1966) ‘A Critical Tracking Task for Manual Control Research’, *IEEE Transactions on Human Factors in Electronics*, HFE-7(4), pp. 138–145. doi: 10.1109/THFE.1966.232660.

Jin, Z. X., Plocher, T. and Kiff, L. (2007) ‘Touch screen user interfaces for older adults: button size and spacing’, in *Proceedings of the 4th International Conference on Universal Access in Human Computer Interaction: Coping with Diversity*, pp. 933–941. doi: 10.1007/978-3-540-73279-2.

Johnson, E. A. (1965) ‘Touch display—a novel input/output device for computers’, *Electronics Letters*, 1(8), p. 219. doi: 10.1049/el:19650200.

Jordan, P. W. (1998) *An Introduction to Usability*. CRC Press.

Julesz, B. (1984) ‘A brief outline of the texton theory of human vision’, *TINS*, pp. 41–45. Available at: https://ac.els-cdn.com/S0166223684802751/1-s2.0-S0166223684802751-main.pdf?_tid=06d15563-3a82-42ae-9c07-16189bb528f5&acdnat=1544959354_76348fc45e09843cbe8d5806804c9ac9 (Accessed: 16 December 2018).

Kane, S. K. *et al.* (2008) ‘Slide Rule: Making mobile touch screens accessible to blind people using multi-touch interaction techniques’, *Proceedings of the 10th International ACM SIGACCESS conference on Computers and accessibility (Assets ’08)*. Halifax, Nova Scotia, Canada: ACM, pp. 73–80. doi: 10.1145/1414471.1414487.

Kane, S. K., Wobbrock, J. and Ladner, R. (2011) ‘Usable gestures for blind people: understanding preference and performance’, *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI ’11*, 37(3), pp. 413–422. doi: 10.1145/1978942.1979001.

Kaptein, N., Theeuwes, J. and Van Der Horst, R. (1996) ‘Driving Simulator Validity: Some Considerations’, *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies , 1550, pp. 30–36. doi: 10.3141/1550-05.

Kass, S. J., Cole, K. S. and Stanny, C. J. (2007) ‘Effects of distraction and experience on situation awareness and simulated driving’, *Transportation Research Part F*, 10, pp. 321–329. doi: 10.1016/j.trf.2006.12.002.

Kennedy, R. S. *et al.* (1993) ‘Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness’, *The International Journal of Aviation Psychology*, 3(3), pp. 203–220.

Kim, H. H. *et al.* (2011) ‘Effect of Touch-key Sizes on Usability of Driver Information Systems and Driving Safety’, *Journal of Korean Institute of Industrial Engineers*. Korean Institute of Industrial Engineers, 37(1), pp. 30–40. doi: 10.7232/JKIIE.2011.37.1.030.

Kircher, K. *et al.* (2014) *Secondary Task Workload Test Bench-2TB Final Report*. Linkoping. Available at: www.vipsimulation.se (Accessed: 25 November 2018).

Kirkpatrick, A. *et al.* (2018) *Web Content Accessibility*. Available at: https://www.w3.org/TR/WCAG21/.

Klauer, S. G. *et al.* (2006) ‘The Impact of Driver Inattention On Near Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data’. doi: DOT HS 810 594.

Van Kleunen, L. *et al.* (2017) ‘Design Considerations for a Large Display Touch Application in Informal Education’, in Hammond, T., Adler, A., and Prasad, M. (eds) *Frontiers in Pen and Touch*. Springer, Cham, pp. 217–226. doi: 10.1007/978-3-319-64239-0_16.

Kobayashi, M. *et al.* (2011) ‘Elderly User Evaluation of Mobile Touchscreen Interactions’, in *INTERACT: Part 1*, pp. 83–99. Available at: https://link.springer.com/content/pdf/10.1007/978-3-642-23774-4_9.pdf (Accessed: 10 December 2018).

Koch, C. (2004) *The Quest for Consciousness: A Neurobiological Approach*. Englewood, CO: Roberts and Company. Available at: https://jrqwq1tbn01.storage.googleapis.com/MTkzNjIyMTA0Nw==01.pdf (Accessed: 9 September 2018).

Konstantopoulos, P., Chapman, P. and Crundall, D. (2010) ‘Driver’s visual attention as a function of driving experience and visibility. Using a driving simulator to explore drivers’ eye movements in day, night and rain driving’, *Accident Analysis and Prevention*. Elsevier Ltd, 42(3), pp. 827–834. doi: 10.1016/j.aap.2009.09.022.

Koppinen, A. (2000) ‘Design challenges of an in-car communication system UI’, *Personal Technologies*. Springer-Verlag, 4(2–3), pp. 165–170. doi: 10.1007/BF01324123.

Krol, K. *et al.* (2015) ‘Too taxing on the mind! Authentication grids are not for everyone’, in *International Conference on Human Aspects of Information Security, Privacy, and Trust*. Springer, pp. 71–82. doi: 10.1007/978-3.

Kujala, T. (2013) ‘Browsing the information highway while driving: Three in-vehicle touch screen scrolling methods and driver distraction’, *Personal and Ubiquitous Computing*, 17(5), pp. 815–823. doi: 10.1007/s00779-012-0517-2.

Kujala, T. and Saariluoma, P. (2011) ‘Effects of menu structure and touch screen scrolling style on the variability of glance durations during in-vehicle visual search tasks’, *Ergonomics*, 54(8), pp. 716–732. doi: 10.1080/00140139.2011.592601.

Kujala, T. and Salvucci, D. D. (2015) ‘Modeling visual sampling on in-car displays: The challenge of predicting safety-critical lapses of control’, *International Journal of Human Computer Studies*, 79, pp. 66–78. doi: 10.1016/j.ijhcs.2015.02.009.

Kurniawan, S. H. *et al.* (2006) ‘Personalising web page presentation for older people’, *Interacting with Computers*, 18, pp. 457–477. doi:

10.1016/j.intcom.2005.11.006.

Labiale, G. (1996) ‘Complexity of in-car visual messages and drivers’ performances’, in *Vision in vehicles 5*, pp. 187–194.

Lamble, D. *et al.* (1999) *Cognitive load and detection thresholds in car following situations: safety implications for using mobile (cellular) telephones while driving*, *Accident Analysis and Prevention*. Available at: www.elsevier.com/locate/aap (Accessed: 9 September 2018).

Land, M. F. (2006) ‘Eye movements and the control of actions in everyday life’, *Progress in Retinal and Eye Research*, 25(3), pp. 296–324. doi: 10.1016/j.preteyeres.2006.01.002.

Lansdown, T. C., Brook-Carter, N. and Kersloot, T. (2004) ‘Distraction from multiple in-vehicle secondary tasks: vehicle performance and mental workload implications’, *Ergonomics*. Taylor & Francis Ltd , 47(1), pp. 91–104. doi: 10.1080/00140130310001629775.

Large, D. R. *et al.* (2015) ‘Applying NHTSA task acceptance criteria to different simulated driving scenarios’, *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI ’15*, pp. 117–124. doi: 10.1145/2799250.2799254.

Large, D. R. *et al.* (2016) ‘Grouping icons to ease the visual burden of search and select pointing tasks during interactions with in-vehicle touchscreen HMIs’, *Human Factors in Complex Systems*.

Lasch, A. and Kujala, T. (2012) ‘Designing browsing for in-car music player: effects of touch screen scrolling techniques, items per page and screen orientation on driver distraction', in *Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Portsmouth, NH, USA: ACM, pp. 41–48. doi: 10.1145/2390256.2390262.

Lauber, F., Böttcher, C. and Butz, A. (2014) 'You've Got the Look: Visualizing Infotainment Shortcuts in Head-Mounted Displays', in *Automotive User Interfaces and In-Vehicle Applications*. doi: 10.1145/2667317.2667408.

Lauber, F., Follmann, A. and Butz, A. (2014) 'What You See Is What You Touch : Visualizing Touch Screen Interaction in the Head-Up Display', *Proceedings of the 2014 conference on Designing interactive systems*, pp. 171–180. doi: 10.1145/2598510.2598521.

Lee, J. D. *et al.* (2001) 'Speech-based Interaction with In-vehicle Computers: The Effect of Speech-based E-mail on Drivers' Attention to the Roadway', *Human factors*, 43, pp. 631–640.

Lee, J. D. and Kantowitz, B. H. (2005) 'Network analysis of information flows to integrate in-vehicle information systems', *International journal of vehicle information and communication systems*, 1(2), pp. 24–43.

Lee, P. N. and Triggs, T. J. (1976) 'THE EFFECTS OF DRIVING DEMAND AND ROADWAY ENVIRONMENT ON PERIPHERAL VISUAL DETECTIONS', in *Australian Road Research Board Conference Proc*, pp. 7–12.

Lee, S. C., Hwangbo, H. and Ji, Y. G. (2016) 'Perceived Visual Complexity of In-Vehicle Information Display and Its Effects on Glance Behavior and Preferences', *International Journal of Human-Computer Interaction*. Taylor &

Francis, 32(8), pp. 654–664. doi: 10.1080/10447318.2016.1184546.

Lee, S. and Zhai, S. (2009) ‘The Performance of Touch Screen Soft Buttons’, in *CHI*. ACM, pp. 309–318. Available at: http://delivery.acm.org/10.1145/1520000/1518750/p309-zhai.pdf?ip=82.9.199.45&id=1518750&acc=ACTIVE SERVICE&key=BF07A2EE685417C5.9530128DD756F5CF.4D4702B0C3E38B35.4D4702B0C3E38B35&__acm__=1536496061_52f7bb5c289fb9f91d2b10c14d47ee28 (Accessed: 9 September 2018).

Lenneman, J. K. *et al.* (2009) ‘Differential effects of focal and ambient visual processing demands on driving performance’, pp. 306–312.

Liang, Y. and Lee, J. D. (2010) ‘Combining cognitive and visual distraction: Less than the sum of its parts’, *Accident Analysis and Prevention*, 42, pp. 881–890. doi: 10.1016/j.aap.2009.05.001.

Little, K. and Hannen, M. (1993) ‘Longbow Apache Controls and Displays Management’, *American Helicopter Society Specialists Meeting*, pp. 6–7.

Ljung, M. (2002) *DREAM-Driving Reliability and Error Analysis Method*. Linköping University. Available at: http://www.diva-portal.org/smash/get/diva2:19361/FULLTEXT01.pdf (Accessed: 12 May 2019).

Lui, Y. . (2001) ‘Comparative study on the effects of auditory, visual and multi-modality displays on drivers’ performance in advanced traveller information systems’, *Egonomics*, 44(4), pp. 425–452.

Macdonald, W. A. and Hoffmann, E. . (1980) ‘Review of relationships between steering wheel reversal rate and driving task demand', *Human Factors*, 22(6), pp. 733–739.

Maciej, J. and Vollrath, M. (2009) 'Comparison of manual vs. speech-based interaction with in-vehicle information systems', *Accident Analysis and Prevention*, 41(5), pp. 924–930. doi: 10.1016/j.aap.2009.05.007.

Maclean, K. E. (1999) 'Application-Centered Haptic Interface Design', in Srinivasan, M. and Cutkosky, M. (eds). MIT Press. Available at: http://cdr.stanford.edu/touch/workshop/ (Accessed: 9 September 2018).

Maglio, P. P. and Campbell, C. S. (2000) 'Tradeoffs in Displaying Peripheral Information', in *CHI*, pp. 241–248. Available at: https://interruptions.net/literature/Maglio-CHI00-p241-maglio.pdf (Accessed: 14 October 2018).

Maguire, M. C. (1999) 'A review of user-interface design guidelines for public information kiosk systems', *Int. J. Human-Computer Studies*, 50, p. 243. Available at: http://www.idealibrary.comon (Accessed: 9 September 2018).

Malcolm, R. (1984) 'Pilot disorientation and the use of a peripheral vision display', *Aviation, Space, and Environmental Medicine*.

Maltz, M., Shinar, D. and -Gurion, B. (1999) 'Eye Movements of Younger and Older Drivers', *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 41(1), pp. 15–25. doi: 10.1518/001872099779577282.

Mankoff, J. *et al.* (2003) 'Heuristic Evaluation of Ambient Displays', in *CHI*. Ft. Lauderdale: ACM. Available at: http://www.cs.cmu.edu/~io/publications/old-pubs/test.pdf (Accessed: 16 December 2018).

Martens, M. and van Winsum, W. (2000) ‘Measuring distraction: the peripheral detection task’, *TNO Human Factors, …*, (March 2016), pp. 1–7. Available at: http://www-nrd.nhtsa.dot.gov/departments/Human Factors/driver-distraction/PDF/34.PDF.

Martens, M. and Winsum, W. Van (2001) ‘Effects of speech versus tactile driver support messages on driving behavior and workload’, *SAE technical papers*, pp. 6–80. Available at: https://pdfs.semanticscholar.org/d162/f70339ecaaddea423dae839b18c19c3a7efc.pdf (Accessed: 29 July 2018).

Mattes, S. (2003) ‘The Lane Change Task as a Tool For Driver Distraction Evaluation’, *Quality of work and products in enterprises of the future*, pp. 1–30. Available at: http://people.usd.edu/~schieber/docs/MATTES2003-powerpoint.pdf.

Matthews, T. L. *et al.* (2006) *Evaluating Glanceable Visuals for Multitasking*. Available at: http://www.eecs.berkeley.edu/Pubs/TechRpts/2006/EECS-2006-173.html (Accessed: 16 December 2018).

Matthews, T. L. (2007) *Designing and Evaluating Glanceable Peripheral Displays*. University of California at Berkeley. Available at: http://www.eecs.berkeley.edu/Pubs/TechRpts/2007/ (Accessed: 4 August 2018).

May, A., Ross, T. and Osman, Z. (2005) ‘The design of next generation in-vehicle navigation systems for the older driver’, *Interacting with Computers*, 17(6), pp. 643–659. doi: 10.1016/j.intcom.2005.09.004.

Mayhew, D. R. *et al.* (2011) ‘On-road and simulated driving: Concurrent and discriminant validation', *Journal of Safety Research*. Elsevier Ltd, 42(4), pp. 267–275. doi: 10.1016/j.jsr.2011.06.004.

McCarthy, J. ., Sasse, M. . and Riegelsberger, J. (2004) 'Could I have the Menu Please? An Eye Tracking Study of Design Conventions', *People and computers XVII—Designing for society*, (May), pp. 401–414.

McDonald, J. E., Dayton, T. and McDonald, D. R. (1988) 'Adapting menu layout to tasks', *International Journal of Man-Machine Studies*, 28(4), pp. 417–435.

McGehee, D. V., Mazzae, E. N. and Baldwin, G. H. S. (2000) 'Driver Reaction Time in Crash Avoidance Research: Validation of a Driving Simulator Study on a Test Track', in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, pp. 320–323. doi: 10.1177/154193120004402026.

McGookin, D., Brewster, S. and Jiang, W. (2008) 'Investigating touchscreen accessibility for people with visual impairments', *Proceedings of the 5th Nordic conference on Human-computer interaction building bridges - NordiCHI '08*, p. 298. doi: 10.1145/1463160.1463193.

Mclaughlin, A. C., Rogers, W. A. and Fisk, A. D. (2009) 'Using Direct and Indirect Input Devices: Attention Demands and Age-Related Differences', *ACM Trans Comput Hum Interact*, 16(1), pp. 1–15. doi: 10.1145/1502800.1502802.

McWilliams, T. *et al.* (2018) 'Assessing Driving Simulator Validity: A Comparison of Multi-Modal Smartphone Interactions Across Simulated and Field Environments'. Available at: https://trid.trb.org/view/1497139 (Accessed: 1 October 2018).

Medenica, Z. *et al.* (2011) *Augmented Reality vs. Street Views: A Driving Simulator Study Comparing Two Emerging Navigation Aids*. Available at: http://www.oskar.easyjapanese.org/doc/fp495-medenica.pdf (Accessed: 9 October 2018).

Medical Dictionary (no date) *Motor Learning*. Available at: http://medical-dictionary.thefreedictionary.com/motor+learning (Accessed: 22 June 2016).

Metz, B., Schömig, N. and Krüger, H.-P. P. (2011) 'Attention during visual secondary tasks in driving: Adaptation to the demands of the driving task', *Transportation Research Part F: Traffic Psychology and Behaviour*. Elsevier Ltd, 14(5), pp. 369–380. doi: 10.1016/j.trf.2011.04.004.

Michon, J. A. (1993) *Generic Intelligent Driver Support*. Washington DC: Taylor and Francis.

Miller, G. A. (1956) 'THE PSYCHOLOGICAL REVIEW THE MAGICAL NUMBER SEVEN, PLUS OR MINUS TWO: SOME LIMITS ON OUR CAPACITY FOR PROCESSING INFORMATION 1', *The Psychological Review*, 63(2), pp. 81–97. Available at: https://pure.mpg.de/rest/items/item_2364276/component/file_2364275/content (Accessed: 16 December 2018).

Miura, T. (1986) 'Coping with situational demands: A study of eye movements and peripheral vision performance', *Vision in vehicles*.

Monterey Technologies Inc. (1996) *Resource Guide for Accessibility: Design of Consumer Electronics*. Washington DC.

Mourant, R. R. and Rockwell, T. H. (1970) 'Mapping Eye-Movement Patterns to the Visual Scene in Driving: An Exploratory Study', *Human Factors: The Journal of Human Factors and Ergonomics Society*, 12(1), pp. 81–87. doi: 10.1177/001872087001200112.

Neggers, S. and Bekkering, H. (2000) 'Ocular Gaze is Anchored to the Target of an Ongoing Pointing Movement', *The American Physiological Society*, pp. 639–651. Available at: www.physiology.org/journal/jn (Accessed: 13 December 2018).

NHTSA (2013) *Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices*, *Docket No. NHTSA-2010-0053*. doi: NHTSA-2010-0053.

NHTSA (2015) *Distracted Driving*. Available at: https://www.nhtsa.gov/risky-driving/distracted-driving.

NHTSA (2017) '2016 Fatal Motor Vehicle Crashes: Overview', *Traffic Safety Facts: Research Note (DOT HS 812456)*, (October), pp. 1–9. doi: DOT HS 812 456.

Nikolic, M. I. and Sarter, N. . (2001) 'Peripheral visual feedback: A powerful means of supporting effective attention allocation in event-driven, data-rich environments', *Human Factors*, 43(1), pp. 30–38.

Nordgren, P. (2007) *Development of a touch screen interface for Scania Interactor*. Available at: http://www8.cs.umu.se/education/examina/Rapporter/PederNordgren.pdf (Accessed: 24 November 2018).

Nothdurft, H. C. (2000) 'Salience from feature contrast: Variations with texture density', *Vision Research*, 40(23), pp. 3181–3200. doi: 10.1016/S0042-6989(00)00168-1.

Nuthmann, A. and Malcolm, G. L. (2016) 'Eye-guidance during scene search: The role color plays in central and peripheral vision', *Journal of Vision*, 16(2016), p. 490. doi: 10.1167/16.2.3.doi.

Nymark, M. and Zhang, J. (2010) *Balancing HMI Design and Requirements Engineering*. KTH Industrial Engineering and Management. Available at: http://kth.diva-portal.org/smash/get/diva2:460079/FULLTEXT01.pdf (Accessed: 12 May 2019).

O'Brian, J. (2015) *Tech Time Machine: Car Tech*. Available at: http://mashable.com/2015/01/05/car-tech-ces/#h0HvY.FPRaqK (Accessed: 27 June 2018).

Oliva, A. and Torralba, A. (2006) 'Chapter 2 Building the gist of a scene: the role of global image features in recognition', *Progress in Brain Research*. Elsevier, 155, pp. 23–36. doi: 10.1016/S0079-6123(06)55002-2.

Oliveira, J. *et al.* (2011) 'Blind People and Mobile Touch-based Text-Entry: Acknowledging the Need for Different Flavors'. Available at: http://di.ciencias.ulisboa.pt/~tjvg/amc/phd/files/afp053-oliveira.pdf.

Olsson, S. and Burns, P. C. C. (2000) 'Measuring driver visual distraction with a peripheral detection task', *NHTSA Driver Distraction Internet Forum*, (Online paper). doi: http://dx.doi.org/10.1097/JCP.0b013e3182a59409.

Orphanides, A. K. and Nam, C. S. (2017) 'Touchscreen interfaces in context: A systematic review of research into touchscreens across settings, populations, and implementations', *Applied Ergonomics*. Elsevier Ltd, 61, pp. 116–143. doi: 10.1016/j.apergo.2017.01.013.

Oviedo-Trespalacios, O. *et al.* (2017) 'Risk factors of mobile phone use while driving in Queensland: Prevalence, attitudes, crash risk perception, and task-management strategies', *PLOS ONE*. Edited by B. Podobnik. Public Library of Science, 12(9), p. e0183361. doi: 10.1371/journal.pone.0183361.

Owsley, C. *et al.* (1999) 'Older Drivers and Cataract: Driving Habits and Crash Risk', *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*. Oxford University Press, 54(4), pp. M203–M211. doi: 10.1093/gerona/54.4.M203.

Palinko, O. *et al.* (2010) 'Estimating Cognitive Load Using Remote Eye Tracking in a Driving Simulator', in *Proceedings of the 2010 symposium on eye-tracking research & applications*, pp. 141–144.

Palmer, L. *et al.* (2017) 'Predicting the Perceptual Demands of Urban Driving with Video Regression', in *In Applications of Computer Vision (WACV)*. IEEE, pp. 409–417. Available at: http://discovery.ucl.ac.uk/1565215/1/PalmerBialkowski_PerceptualLoad_WACV2017.pdf (Accessed: 13 October 2018).

Parhi, P., Karlson, A. K. and Bederson, B. B. (2006) 'Target size study for one-handed thumb use on small touchscreen devices', *Proceedings of the 8th conference on Human-computer interaction with mobile devices and services - MobileHCI '06*, p. 203. doi: 10.1145/1152215.1152260.

Parkes, A. M. and Coleman, N. (1990) 'Route guidance systems: A comparison of methods of presenting directional information to the driver', *Contemporary ergonomics*, pp. 480–485.

Patten, C. J. *et al.* (2006) ‘Driver experience and cognitive workload in different traffic environments’, *Accident Analysis & Prevention*, 38(5), pp. 887–894.

Pauzie, A. (2008) ‘A method to assess the driver mental workload: the Driving Activity Load Index (DALI) Special Issue-selected papers from HCD 2008 A method to assess the driver mental workload: The driving activity load index (DALI)’, *IET Intelligent Transport Systems*, 2(4), pp. 315–322. doi: 10.1049/iet-its:20080023.

Pavlidis, I. *et al.* (2016) ‘Dissecting Driver Behaviors Under Cognitive, Emotional, Sensorimotor, and Mixed Stressors’, *Scientific Reports*. Nature Publishing Group, 6(1), p. 25651. doi: 10.1038/srep25651.

Paxion, J., Galy, E. and Berthelon, C. (2014) ‘Mental workload and driving’, *Frontiers in Psychology*. Frontiers, 5(1344), pp. 1–11. doi: 10.3389/fpsyg.2014.01344.

Pettitt, M., Burnett, G. and Stevens, A. (2005) ‘Defining Driver Distraction’, in *World Congress on Intelligent Transport Systems*. doi: doi:10.1201/9781420007497.ch3.

Petzoldt, T., Bellem, H. and Krems, J. F. (2014) ‘The Critical Tracking Task’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 56(4), pp. 789–808. doi: 10.1177/0018720813501864.

Pickering, C. a., Burnham, K. J. and Richardson, M. J. (2007) ‘A research study of hand gesture recognition technologies and applications for human vehicle interaction', *3rd Institution of Engineering and Technology Conference*, pp. 1–15. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.135.7688&rep=rep1&type=pdf.

Pielot, M. *et al.* (2012) 'PocketMenu: Non-Visual Menus for Touch Screen Devices', in *MobileHCI*. San Francisco, CA: ACM, pp. 327–330. Available at: https://play.google.com/store/apps/details?id= (Accessed: 6 November 2018).

Pitts, M. J. *et al.* (2012) 'Visual–haptic feedback interaction in automotive touchscreens', *Displays*, 33, pp. 7–12. doi: 10.1016/j.displa.2011.09.002.

Plaue, C., Miller, T. and Stasko, J. T. (2004) *Is a Picture Worth a Thousand Words? An Evaluation of Information Awareness Displays*. Atlanta. Available at: https://smartech.gatech.edu/bitstream/handle/1853/52/04-02.pdf (Accessed: 16 December 2018).

Plaue, C. and Stasko, J. (2007) 'Animation in a Peripheral Display: Distraction, Appeal and Information Conveyance in Varying Display Configurations', *Proceedings of Graphics Interface*, pp. 135–142. Available at: https://www.cc.gatech.edu/~john.stasko/papers/gi07.pdf (Accessed: 16 December 2018).

Politis, I., Brewster, S. and Pollick, F. (2014) 'Speech Tactons Improve Speech Warnings for Drivers', in *Automotive User Interfaces and In-Vehicle Applications*, pp. 1–8. doi: 10.1145/2667317.2667318.

Poole, A. and Ball, L. J. (2006) 'Eye tracking in HCI and usability research', in *In Encyclopedia of human computer interaction*. IGI Global, pp. 211–219.

Proteau, L. *et al.* (1987) ‘On the type of information used to control and learn an aiming movement after moderate and extensive training’, *Human Movement Science*, 6(2), pp. 181–199.

Rakauskas, M. E., Gugerty, L. J. and Ward, N. J. (2004) ‘Effects of naturalistic cell phone conversations on driving performance’, *Journal of Safety Research*, 35(4), pp. 453–464. doi: 10.1016/j.jsr.2004.06.003.

Ranney, T. A. (2008) *Driver Distraction: A Review of the Current State-of-Knowledge*. Washington, DC. Available at: https://trid.trb.org/view/868221 (Accessed: 25 November 2018).

Ranney, T. A., Harbluk, J. L. and Noy, Y. I. (2005) ‘Effects of Voice Technology on Test Track Driving Performance: Implications for Driver Distraction’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 47(2), pp. 439–454. doi: 10.1518/0018720054679515.

Reed, M. P. and Green, P. A. (1999) ‘Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task’, *Ergonomics*. Taylor & Francis Group, 42(8), pp. 1015–1037. doi: 10.1080/001401399185117.

Regan, M. A., Lee, J. D. and Young, K. L. (2009) *Driver distraction : theory, effects, and mitigation*. CRC Press.

Reid, G. B. and Nygren, T. E. (1988) ‘The Subjective Workload Assessment Technique: A Scaling Procedure for Measuring Mental Workload’, *Advances in Psychology*. North-Holland, 52, pp. 185–218. doi: 10.1016/S0166-4115(08)62387-0.

Reyes, M. L. and Lee, J. D. (2004) ‘The Influence of IVIS Distractions on Tactical and Control Levels of Driving Performance Driver Monitoring of Inattention and Impairment Using Vehicle Equipment (DrIIVE) View project Motivations for speeding View project’, in *PROCEEDINGS of the HUMAN FACTORS AND ERGONOMICS SOCIETY 48th ANNUAL MEETING*. doi: 10.1177/154193120404801935.

Richter, H. *et al.* (2010) ‘HapTouch and the 2+1 State Model: Potentials of Haptic Feedback on Touch Based In-Vehicle Information Systems’, in *Proceedings of the Second International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI 2010)*, pp. 72–79. doi: 10.1145/1969773.1969787.

Rogers, W. A. *et al.* (2005) ‘Touch a Screen or Turn a Knob: Choosing the Best Device for the Job’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 47(2), pp. 271–288. doi: 10.1518/0018720054679452.

Rogers, Y., Payne, S. J. and Todd, P. M. (2010) ‘Projecting Instant Information In Situ: Can It Help Us Make More Informed Decisions?’, in *Ubiprojection Workshop, Pervasive ‘10*. Helsinki, Finland, pp. 39–42. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.230.8102&rep=rep1&type=pdf (Accessed: 16 December 2018).

Roscoe, A. H. (1987) ‘The practical assessment of pilot workload’. Advisory Group for Aerospace Research and Development.

Roscoe, A. H. and Ellis, G. A. (1990) *A subjective rating scale for assessing pilot workload in flight: A decade of practical use. No. RAE-TR-90019*.

Rubio, S. *et al.* (2004) ‘Evaluation of Subjective Mental Workload: A Comparison of SWAT, NASA-TLX, and Workload Profile Methods’, *Applied Psychology*. Wiley/Blackwell (10.1111), 53(1), pp. 61–86. doi: 10.1111/j.1464-0597.2004.00161.x.

Rümelin, S. and Butz, A. (2013) ‘How to make large touch screens usable while driving’, *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI ’13*, pp. 48–55. doi: 10.1145/2516540.2516557.

Rydström, A. *et al.* (2005) ‘Multifunctional systems in vehicles: a usability evaluation.’, *Proceedings of the Fourth International Cyberspace Conference on Ergonomics CybErg*. International Ergonomics Association Press, pp. 768–775. Available at: http://www.diva-portal.org/smash/get/diva2:1010799/FULLTEXT01.pdf (Accessed: 4 August 2018).

SAE 2119 (1997) *Manual Controls for Mature Drivers (J2119_199710)*. doi: https://doi.org/10.4271/J2119_199710.

Salvucci, D. D. *et al.* (2007) ‘iPod Distraction: Effects of Portable Music-Player Use on Driver Performance’, in *CHI Proceedings*. San Jose, CA: ACM, pp. 243–250. Available at: www.apple.com] (Accessed: 25 November 2018).

Salvucci, D. D. and Kujala, T. (2016) ‘Balancing Structural and Temporal Constraints in Multitasking Contexts’, in Papafragou, A. et al. (eds) *CogSci 2016 : Proceedings of the 38th Annual Conference of the Cognitive Science Society*. Austin, TX, pp. 2465–2470. doi: 10.1016/j.joep.2012.09.001.

Sanders, M. S. and McComick, E. J. (1993) *Human Factors in Engineering* *and Design*. 7th edn. New York, USA: McGraw-Hill.

Sasangohar, F., MacKenzie, I. S. and Scott, S. D. (2009) ‘Evaluation of Mouse and Touch Input for a Tabletop Display Using Fitts’ Reciprocal Tapping Task’, *Human Factors and Ergonomics Society Annual Meeting Proceedings*, 53(12), pp. 839–843. doi: 10.1518/107118109X12524442637787.

Sauras-Perez, P., Taiber, J. and Smith, J. (2014) ‘Variability analysis of in-car gesture interaction’, in *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE, pp. 777–780. doi: 10.1109/ICCVE.2014.7297657.

Schall, M. C. *et al.* (2012) *Distraction Detection and Mitigation Through Driver Feedback*, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. doi: 10.1177/0018720812462029.

Schepers, P. and Den Brinker, B. (2011) ‘What do cyclists need to see to avoid single-bicycle crashes?’, *Ergonomics*, 54(4), pp. 315–327. doi: 10.1080/00140139.2011.558633.

Schmidt, R. A. and Lee, T. (1999) ‘Motor control and learning: a behavioral emphasis’, *Human Kinetics*.

Sears, A. and Shneiderman, B. (1991) ‘High Precision Touchscreens: Design Strategies and Comparisons with a Mouse’, *International Journal of ManMachine Studies*, 34(4), pp. 593–613.

Seidler, K. S. and Wickens, C. D. (1992) ‘Distance and organization in multifunction displays’, *Human Factors*, 34(5), pp. 555–569.

Senders, J. W. *et al.* (1967) ‘The Attentional Demand of Automobile Driving’, *Highway Research Record*, (195), pp. 15–33. Available at:

https://trid.trb.org/view/663847 (Accessed: 6 November 2018).

Serafin, C. *et al.* (1993) ‘Car Phone Usability: A Human Factors Laboratory Test’, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. SAGE PublicationsSage CA: Los Angeles, CA, 37(3), pp. 220–224. doi: 10.1177/154193129303700302.

Sesto, M. E. *et al.* (2012) ‘Effect of touch screen button size and spacing on touch characteristics of users with and without disabilities’, *Human Factors*, 54(3), pp. 425–436. doi: 10.1177/0018720811433831.

Shechtman, O. *et al.* (2007) ‘The impact of intersection design on simulated driving performance of young and senior adults’, *Traffic Injury Prevention*, 8(1), pp. 78–86. doi: 10.1080/15389580600994321.

Sheridan, T. B. and Simpson, R. W. (1979) *TOWARD THE DEFINITION AND MEASUREMENT OF THE MENTAL WORKLOAD OF TRANSPORT PILOTS*. Available at: https://dspace.mit.edu/bitstream/handle/1721.1/67913/ftl_r_1979_04.pdf?sequence=1 (Accessed: 10 December 2018).

Sherrington, C. S. (1907) ‘ON THE PROPRIO-CEPTIVE SYSTEM, ESPECIALLY IN ITS REFLEX ASPECT’, *Brain*. Oxford University Press, 29(4), pp. 467–482. doi: 10.1093/brain/29.4.467.

Shneiderman, B. (1991) ‘Touch screens now offer compelling uses’, *IEEE Software*, 8(2), pp. 93–94. doi: 10.1109/52.73754.

Shneiderman, B. (2010) ‘Designing the user interface: strategies for effective human-computer interaction’. Pearson Education India.

Shusterman, R. (2011) 'MUSCLE MEMORY AND THE SOMAESTHETIC PATHOLOGIES OF EVERYDAY LIFE', 12(1), pp. 4–15. doi: 10.2478/v10038-011-0001-2.

Siebert, P. *et al.* (2002) 'The Effects of Telematics on Driver Distraction', *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. SAGE PublicationsSage CA: Los Angeles, CA, 46(22), pp. 1868–1870. doi: 10.1177/154193120204602219.

Silber, H. R. (2018) *THE EFFECTS OF FORMATIVE FEEDBACK ON DRIVER PERFORMANCE AND MODELING RISK USING DRIVER WORKLOAD DATA*. Available at: https://search.proquest.com/openview/6b7a6c694a0ded3e6c230b3ee0af73da/1?pq-origsite=gscholar&cbl=18750&diss=y (Accessed: 15 December 2018).

Smyth, T. N. and Kirkpatrick, A. E. (2006) 'A new approach to haptic augmentation of the GUI', in *Proceedings of the 8th international conference on Multimodal interfaces*. ACM, pp. 372–379. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.92.3859&rep=rep1&type=pdf (Accessed: 9 September 2018).

Sodhi, M., Reimer, B. and Llamazares, I. (2002) 'Glance analysis of driver eye movements to evaluate distraction', *Behavior Research Methods, Instruments, and Computers*, 34(4), pp. 529–538. doi: 10.3758/BF03195482.

Soechting, J. F. and Flanders, M. (1989) 'Sensorimotor Representations for Pointing to Targets in Three-Dimensional Space', *JOURNAL OF NEUROPHYSIOLOGY*, 62(2), pp. 582–594. Available at: http://wexler.free.fr/library/files/soechting %281989%29 sensorimotor representations for pointing to targets in three-dimensional space.pdf (Accessed: 12 December 2018).

Somervell, J. *et al.* (2002) *An evaluation of information visualization in attention-limited environments*, *IEEE TCVG Symposium on Visualization*. Available at: http://portal.acm.org/citation.cfm?id=509740.509775 (Accessed: 2 October 2018).

Sonderegger, A. and Sauer, J. (2009) 'The influence of laboratory set-up in usability tests: effects on user performance, subjective ratings and physiological measures', *Ergonomics*, 52(11), pp. 1350–1361. Available at: https://doc.rero.ch/record/24962/files/Sonderegger_Sauer2009.pdf (Accessed: 9 October 2018).

Spies, R. *et al.* (2009) 'Augmented interaction and visualization in the automotive domain', in *Human-Computer Interaction. Ambient, Ubiquitous and Intelligent Interaction*. Springer.

Stasko, J. *et al.* (2005) *Evaluating the InfoCanvas Peripheral Awareness System: A Longitudinal, In Situ Study*. Atlanta. Available at: https://smartech.gatech.edu/bitstream/handle/1853/5958/05-08.pdf?sequence=1&isAllowed=y (Accessed: 16 December 2018).

Statista (2015) *Connected cars as a share of total vehicles 2015-2025*. Available at: https://statista.com/statistics/275849/number-of-vehicles-connected-to-the-internet/ (Accessed: 26 June 2018).

Stern, E. B. and Davis, E. S. (2006) 'Driving simulators', *Driver Rehabilitation and Community Mobility*, pp. 223–235.

Stevens, A. *et al.* (2002) *Design guidelines for safety of in-vehicle information systems*, *Department of Transport, Local Government and the Regions*. Available at: http://www.transport-research.info/Upload/Documents/200607/20060728_165141_88073_UG340_Final_Report.pdf.

Stokes, A., Wickens, C. D. and Kite, K. (1990) *Display technology - Human factors concepts*, *NASA STI/Recon Technical Report A, 91*. Available at: http://adsabs.harvard.edu/abs/1990STIA...9127333S (Accessed: 23 September 2018).

Strayer, D. L. *et al.* (2016) 'Talking to your car can drive you to distraction.', *Cognitive research: principles and implications*. Springer, 1(1), p. 16. doi: 10.1186/s41235-016-0018-3.

Strayer, D. L. *et al.* (2017) *Visual and Cognitive Demands of Using In-Vehicle Infotainment Systems*. Washington, DC. Available at: https://aaafoundation.org/wp-content/uploads/2017/11/VisualandCognitive.pdf (Accessed: 25 November 2018).

Strayer, D. L. and Drews, F. A. (2004) 'Effects of cell phone conversations on younger and older drivers', *Human Factors and Ergonomics Society Annual Meeting Proceedings*, 47(16), pp. 1860–1864. Available at: http://www.ingentaconnect.com/content/hfes/hfproc/2003/00000047/00000016/art00006.

Strayer, D. L., Drews, F. A. and Johnston, W. A. (2003) 'Cell Phone-Induced Failures of Visual Attention During Simulated Driving', *Journal of Experimental*

Psychology: Applied, 9(1), pp. 23–32. doi: 10.1037/1076-898X.9.1.23.

Su, J. *et al.* (2010) 'Timbremap: Enabling the Visually-Impaired to Use Maps on Touch-Enabled Devices', in *CHI*. Available at: http://www.eecg.utoronto.ca/~ashvin/publications/timbermap.pdf (Accessed: 10 December 2018).

Summala, H., Nieminen, T. and Punto, M. (1996) 'Maintaining lane position with peripheral vision during in-vehicle tasks', *Human factors*, 38(3), pp. 442–451.

Sun, X., Plocher, T. and Qu, W. (2007) 'An Empirical Study on the Smallest Comfortable Button/Icon Size on Touch Screen', *Lecture Notes in Computer Science*, 4559/2007, p. Available at: http://link.springer.com/chapter/10.1007/978-3-540-73287-7_71.

Sweeny, T. D., Haroz, S. and Whitney, D. (2013) 'Perceiving group behavior: Sensitive ensemble coding mechanisms for biological motion of human crowds', *Journal of Experimental Psychology: Human Perception and Performance*, 39(2), pp. 329–337. doi: 10.1037/a0028712.

Taber, M. J. (2016) 'Use and Implications of Fidelity in Helicopter Underwater Egress Training', in *Handbook of Offshore Helicopter Transport Safety*. Woodhead Publishing, pp. 125–150. doi: 10.1016/B978-1-78242-187-0.00007-9.

Taveira, A. D. and Choi, S. D. (2009) 'Review Study of Computer Input Devices and Older Users', *International Journal of Human-Computer Interaction*. Taylor & Francis Group , 25(5), pp. 455–474. doi: 10.1080/10447310902865040.

Teichner, W. H. and Krebs, M. J. (1974) ‘Laws of visual choice reaction time.’, *Psychological Review*, 81(1), pp. 75–98. doi: 10.1037/h0035867.

Thomas, P. *et al.* (2013) ‘Identifying the causes of road crashes in Europe.’, *Annals of advances in automotive medicine. Association for the Advancement of Automotive Medicine. Annual Scientific Conference*. Association for the Advancement of Automotive Medicine, 57, pp. 13–22. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24406942 (Accessed: 12 May 2019).

Törnros, J. E. B. and Bolling, A. K. (2005) ‘Mobile phone use-Effects of handheld and handsfree phones on driving performance’, *Accident Analysis and Prevention*, 37, pp. 902–909. doi: 10.1016/j.aap.2005.04.007.

Treisman, A. (1998) ‘Feature binding, attention and object perception’, *Philosophical Transactions of the Royal Society*, 353, pp. 1295–1306. Available at: https://royalsocietypublishing.org/doi/pdf/10.1098/rstb.1998.0284 (Accessed: 16 December 2018).

Tsimhoni, O., Smith, D. and Green, P. (2002) *Destination entry while driving: Speech recognition versus a touch screen keyboard*.

Tsimhoni, O., Smith, D. and Green, P. (2004) ‘Address Entry While Driving: Speech Recognition Versus a Touch-Screen Keyboard’, *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage UK: London, England, 46(4), pp. 600–610. doi: 10.1518/hfes.46.4.600.56813.

Tsimhoni, O., Yoo, H. and Green, P. (1999) *Effects of Visual Demand and In-Vehicle Task Complexity on Driving and Task Performance as Assessed by Visual Occlusion*. Available at:

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.526.4869&rep=rep1&type=pdf (Accessed: 13 October 2018).

Väänänen-Vainio-Mattila, K. *et al.* (2014) ‘User Experience and Expectations of Haptic Feedback in In-Car Interaction’, in *Proceedings of the 13th International Conference on Mobile and Ubiquitous Multimedia*. Melbourne, Australia, pp. 248–251. doi: 10.1145/2677972.2677996.

Vanderheiden, G. C. (1992) ‘White paper on the design of software application programs to increase their accessibility for people with disabilities’. Madison, USA: University of Wisconsin.

Victor, T. W., Harbluk, J. L. and Engström, J. A. (2005) ‘Sensitivity of eye-movement measures to in-vehicle task difficulty’, *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2 SPEC. ISS.), pp. 167–190. doi: 10.1016/j.trf.2005.04.014.

Violanti, J. M. and Marshall, J. R. (1996) *CELLULAR PHONES AND TRAFFIC ACCIDENTS: AN EPIDEMIOLOGICAL APPROACH*, *Accid. Anal. and Prev*. Available at: https://pdf.sciencedirectassets.com/271664/1-s2.0-S0001457500X00024/1-s2.0-0001457595000704/main.pdf?x-amz-security-token=AgoJb3JpZ2luX2VjELT%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FwEaCXVzLWVhc3QtMSJHMEUCIDJ61KIN8oqFcKgrH1NoZnuteszaWKCqcvVlA3EQzLS6AiEA7FxTVVVUSXtz2 (Accessed: 12 May 2019).

Vlaskamp, B. N. S. and Hooge, I. T. C. (2005) ‘Crowding degrades saccadic search performance’, *Journal of Vision*. The Association for Research in Vision and Ophthalmology, 5(8), pp. 956–956. doi: 10.1167/5.8.956.

Waloszek, G. (2000) *Interaction Design Guidelines for Touchscreen*

Applications, *Sap Design Guild*. Available at: http://www.sapdesignguild.org/resources/tsdesigngl/index.html (Accessed: 3 August 2018).

Wang, Y. *et al.* (2010) ‘The validity of driving simulation for assessing differences between in-vehicle informational interfaces: A comparison with field testing’, *Ergonomics*, 53(3), pp. 404–420. doi: 10.1080/00140130903464358.

Wang, Y. Z., Thibos, L. N. and Bradley, A. (1997) ‘Effects of refractive error on detection acuity and resolution acuity in peripheral vision’, *Investigative Ophthalmology and Visual Science*, 38(10), pp. 2134–2143.

Weinstein, L. F. and Wickens, C. D. (1992) ‘Use of Nontraditional Flight Displays for the Reduction of Central Visual Overload in the Cockpit’, *The International Journal of Aviation Psychology*. Lawrence Erlbaum Associates, Inc., 2(2), pp. 121–142. doi: 10.1207/s15327108ijap0202_4.

Weiser, M. and Brown, J. S. (1996) ‘Designing Calm Technology’, *PowerGrid Journal*, 1(1). Available at: http://www.ubiq.com/weiser/calmtech/calmtech.htm (Accessed: 30 September 2018).

Whitney, D. and Levi, D. M. (2011) ‘Visual crowding: a fundamental limit on conscious perception and object recognition.’, *Trends in cognitive sciences*. NIH Public Access, 15(4), pp. 160–8. doi: 10.1016/j.tics.2011.02.005.

Wickens, C. D. (1984) ‘Processing Resources in Attention’, in Parasurman, R. and Davies, R. (eds) *Varieties of Attention*. New York, USA: Academy Press, pp. 63–102.

Wickens, C. D. (2008) ‘Multiple Resources and Mental Workload’, *Human Factors*, 50(3), pp. 449–455. doi: 10.1518/001872008X288394.

Wickens, C. D. and Hollands, J. G. (1999) *Engineering Psychology and Human Performance*. 3rd Editio. Prentice Hall. Available at: http://webfiles.ita.chalmers.se/~mys/HumanAspects/WickensHollands/0_Wickens_Index_Preface.pdf (Accessed: 23 September 2018).

Wierwille, W. (1991) ‘Visual Adaptation of the Driver to High-Demand Driving Situations While Navigating with an in-Car Navigation System’, in Gale, A. G. (ed.) *Vision in Vehicles-III*. New York. Elsevier Ltd, pp. 79–87. Available at: https://trid.trb.org/view/347441 (Accessed: 9 October 2018).

Wierwille, W. (1993a) ‘Demands on driver resources associated with introducing advanced technology into the vehicle’, *Transportation Research Part C*, 1(2), pp. 133–142. doi: 10.1016/0968-090X(93)90010-D.

Wierwille, W. (1993b) ‘Visual and manual demands of in car controls and displays’, in Peacock, B. and Karwowski, B. (eds) *Automotive Ergonomics*. Taylor and Francis, pp. 299–313.

Wierwille, W. and Tijerina, L. (1998) ‘Modelling the relationship between driver in-vehicle visual demans and accident occurrence’, *Vision in vehicles*, 6, pp. 233–243. Available at: https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_242937_38 (Accessed: 19 July 2018).

Wilfinger, D. Meschtscherjakov, A. Perterer, N. and Tscheligi, M. (2012) ‘On the track: Comparing Distraction Caused by Interaction with Tertiary Interfaces with Cars on a Test Track’, in *Adjunct Proceedings of Automotive User*

Interfaces and In-vehicular Applications, pp. 99–102.

Williams, L. J. (1985) 'Tunnel Vision Induced by a Foveal Load Manipulation', *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 27(2), pp. 221–227. doi: 10.1177/001872088502700209.

Williams, L. J. (1995) 'Peripheral Target Recognition and Visual Field Narrowing in Aviators and Nonaviators', *The International Journal of Aviation Psychology*. Lawrence Erlbaum Associates, Inc. , 5(2), pp. 215–232. doi: 10.1207/s15327108ijap0502_6.

Wittmann, M. *et al.* (2006) 'Effects of display position of a visual in-vehicle task on simulated driving', *Applied Ergonomics*, 37, pp. 187–199. doi: 10.1016/j.apergo.2005.06.002.

Wolfe, B. *et al.* (2017) 'More than the Useful Field: Considering peripheral vision in driving', *Applied Ergonomics*. Elsevier Ltd, 65, pp. 316–325. doi: 10.1016/j.apergo.2017.07.009.

Wolfe, J. M. (1997) 'Guided Search 4.0: Current progress with a model of visual search', in Gancarz, G. (ed.) *Integrated Models of Cognitive Systems*, pp. 99–119. doi: 10.1007/978-94-011-5698-1_30.

Wolpert, D. M. and Flanagan, J. R. (2001) 'Primer Motor prediction', *Current Biology*, 11(18), pp. 729–732. Available at: https://www.cell.com/current-biology/pdf/S0960-9822(01)00432-8.pdf (Accessed: 13 December 2018).

Wong, J.-T. and Huang, S.-H. (2009) 'Modeling driver mental workload for accident causation and prevention', in *Proceedings of the Eastern Asia Society* *for Transportation Studies*.

Wood, C. *et al.* (2003) 'Inattentional Blindness While Driving', in *PROCEEDINGS of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. Public Policy Center, pp. 188–189. doi: 10.17077/drivingassessment.1119.

Woodworth, R. S. (1899) 'The accuracy of voluntary movement', *Psychological Review*, 3(3), pp. 743–752. doi: 10.1097/00005053-189912000-00005.

Wooldridge, M. *et al.* (1999) 'Comparison of driver visual demand in test track, simulator, and on-road environments.' Available at: https://www.researchgate.net/publication/239921357 (Accessed: 1 October 2018).

Yoon, S. H., Lim, J. H. and Ji, Y. G. (2015) 'Perceived Visual Complexity and Visual Search Performance of Automotive Instrument Cluster: A Quantitative Measurement Study', *International Journal of Human-Computer Interaction*. Taylor & Francis, 31(12), pp. 890–900. doi: 10.1080/10447318.2015.1069661.

Young, K. and Regan, Michael (2007) 'Driver distraction : A review of the literature', in Faulks, I. J. et al. (eds) *Distracted Driving*. Syndey, pp. 379–405. doi: 10.1201/9781420007497.

Zaharis, A. *et al.* (2010) 'User Authentication Method and Implementation Using a Three-Axis Accelerometer', in *MobiLight 2010*, pp. 192–202. Available at: http://wssl.inf.uth.gr (Accessed: 24 November 2018).

Zhang, H., Smith, M. R. H. and Witt, G. J. (2006) 'Identification of Real-Time Diagnostic Measures of Visual Distraction With an Automatic Eye-Tracking

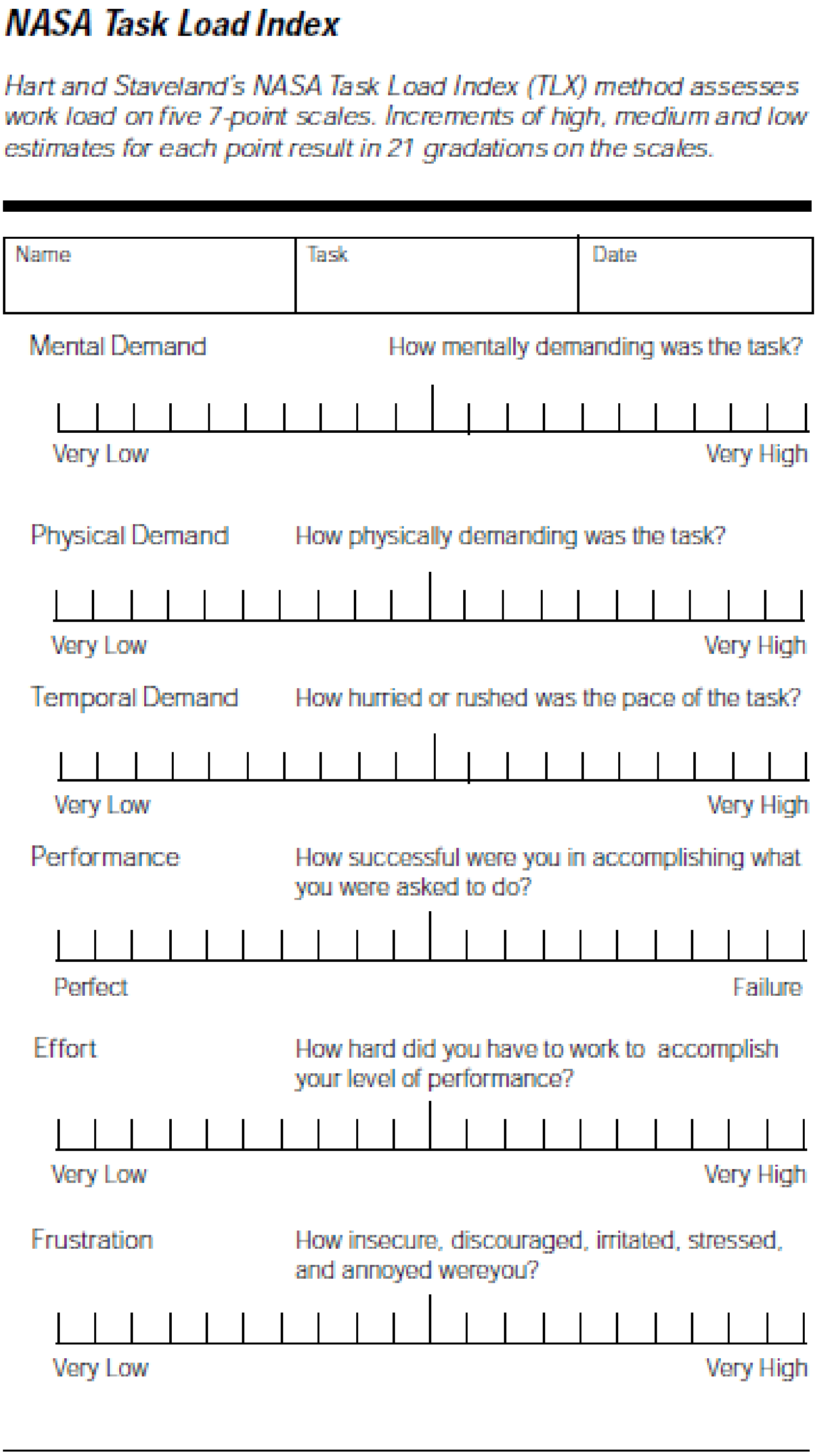
System', *Human Factors: The Journal of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, 48(4), pp. 805–821. doi: 10.1518/001872006779166307.

Ziefle, M. (2010) 'Information presentation in small screen devices: The trade-off between visual density and menu foresight', *Applied Ergonomics*, 41, pp. 719–730. doi: 10.1016/j.apergo.2010.03.001.

Zwahlen, H. T., Adams, C. C. and DeBals, D. P. (1987) 'Safety Aspects of CRT Touch Panel Controls in Automobiles', in *Vision in Vehicles II. Second International Conference on Vision in Vehicles*, pp. 335–344.

11 APPENDIX

11.1 NASA TLX QUESTIONNAIRE



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

11.2 DEMOGRAPHIC QUESTIONNAIRE FOR PARTICIPANTS

Gender: **Male** ☐ **Female** ☐

What is your age? …………………………

For how many years have you held a UK driving licence?

☐ Years

What is you approximate annual mileage?

☐ Miles

Are you left-handed or right-handed?

Left-handed ☐ Right-handed ☐

Do you own a touch screen device (e.g. smart phone or tablet)? If so, please give details if possible.

Yes ☐

No ☐

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

11.3 PRE AND POST TRIAL CONSENT FORMS

Pre-Trial Consent Form

Study title: Interaction mechanisms for in-vehicle displays

Researcher names: Ayse Eren

I confirm that I have read and understood the information sheet for the above study which I may keep for my records and have had the opportunity to ask any questions I may have.

I agree to take part in the above study and am willing to:

- ☐ Participate in a transport simulation activity
- ☐ Provide responses based on user experience of the simulator environment
- ☐ Be recorded in audio and/or video whist engaged in the study

I understand that my information* will be held and processed for the following purposes:

- ☐ Investigation into gain a better understanding of driver behaviour when interacting with in-vehicle displays
- ☐ Dissemination of research findings through academic publications and presentations

I confirm that I do not have the following:

- ☐ Severe motion/travel sickness; Migraine; Epilepsy; Dizziness; Blurred vision
- ☐ I am not pregnant

** Please note: Information from the study will be kept separately from participant details. It will not be possible to identify you from your responses to the study.*

I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without being penalised or disadvantaged in any way.

Name of participant (print name) ....

Signature of participant ....

Date ....

Post Trial Consent Form

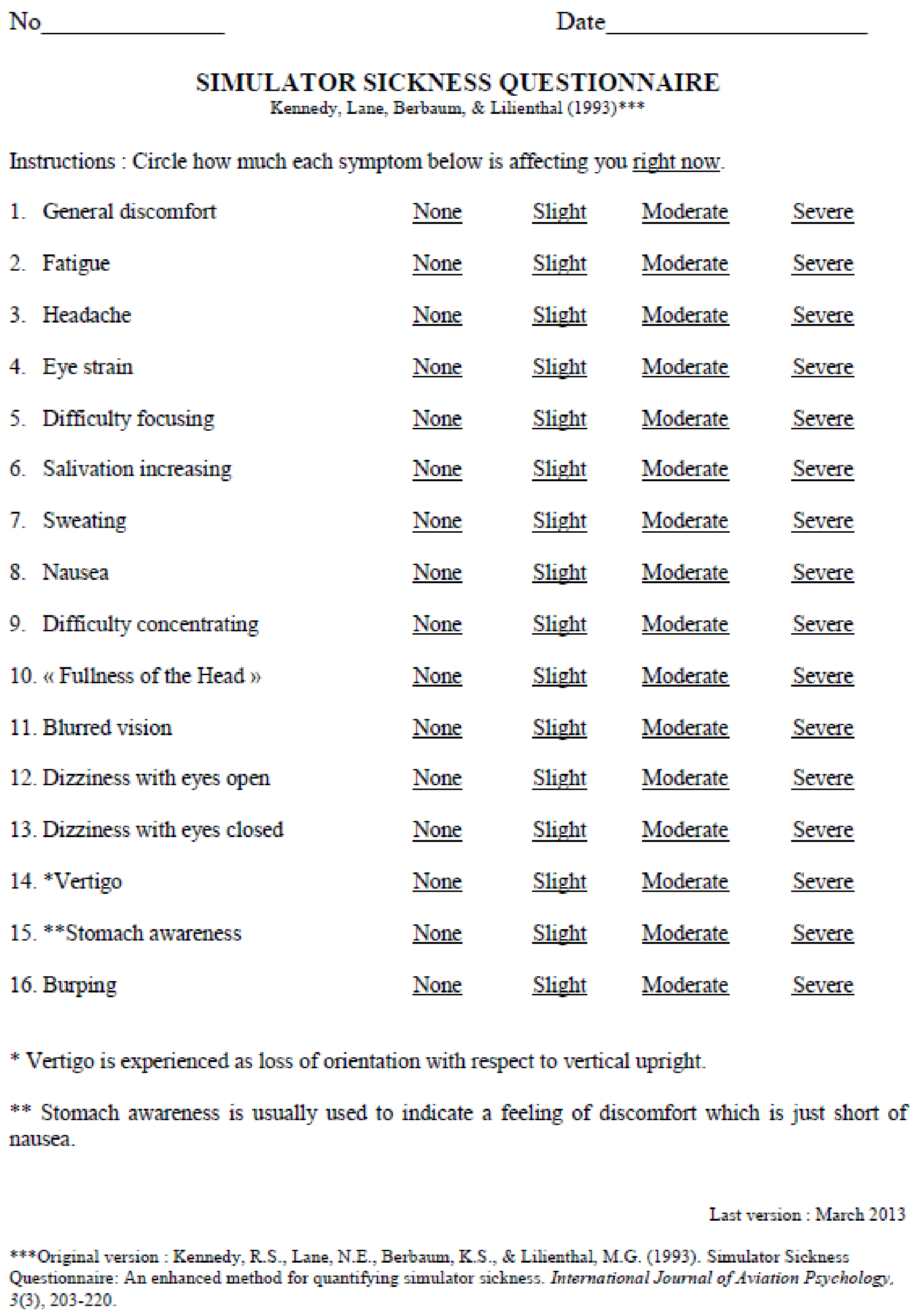
Thank you for participating in this experiment. Your time and effort is greatly appreciated.

Please sign below to confirm that you have received the £10 Amazon voucher.

Signed (participant)………………………………………………………

Date ……………………………………………………………………

11.4 SIMULATOR SICKNESS CHECKLIST



No_______________ Date_____________________

SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, *3*(3), 203-220.