Look Here! Measuring the Attentional Demand of Near-Future Full Windshield Vehicle Displays

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Abstract

Driving a road vehicle is a task which requires and demands visual attention. Despite this, information on a vehicle's state, the road environment, or the entertainment features have commonly been conveyed to the driver via visual means because the information can quickly be received and responded to as desired by the driver.

Current vehicle displays commonly consist of digital displays presented in the centre console (between the two front seats, under the windshield), and at the instrument cluster (above the steering wheel). Such displays are sometimes referred to as Head-down Displays (HDDs) as they encourage the driver to look down and within the vehicle. The attentional demand and corresponding distraction arising from HDDs is a longstanding component of research largely due to safety concerns. Conducting secondary tasks with such displays (where the driver performs a task in addition to primary task of driving e.g., changing the vehicle's climate controls) is associated with degraded driving performance and therefore an increased crash risk.

More recent developments in display technology have led to the inclusion of Head-up Displays (HUDs) within vehicles. These displays present imagery in a translucent form over the road environment typically by reflecting or projecting graphics onto the windshield or another treated glass component. Since they position information closer to the drivers' view of the road environment, they are considered to encourage more beneficial attentive behaviours than HDDs, by ensuring the driver is looking up and out of the vehicle towards the road ahead. HUDs within road vehicles are expected to expand in size so that information can be presented across the whole windshield; these are commonly referred to as a full Windshield Displays (WSDs). Presently, the types of tasks that have been investigated on these displays have been limited. Equally, the attentional demand of these novel displays needs to be ascertained, as well as how this varies when imagery has the potential to be located across the whole windshield.

Consequently, this thesis aimed to: establish the demand of near-future ecologically valid tasks on windshield displays, develop approaches to investigate visual demand, and ascertain how this demand varies when imagery is presented across expansive windshield locations. A series of four driving simulator-based studies were conducted to address these aims.

The first study examined twenty-six participants using an after-market HUD device at the Virginia Tech Cogent Lab. Participants completed tasks on the display which contained components likely to be within the interfaces of near-future HUDs or WSDs (text reading and menu navigation). The analysis showed interactions between task type and the task complexity significantly impacted driver eye-movement and specific longitudinal measures of driving performance. Thus, the exact attributes of the tasks presented on a HUD appear to influence the display's attentional demand.

The second study used two after-market HUD devices to simulate display imagery appearing across the windshield. Twenty-six participants were recruited, and a visually demanding task was used to begin to assess visual demand across windshield displays. The measures showed that increasing display eccentricity resulted in poorer driving performance, thereby indicating greater demand.

The third study recruited sixty participants to expansively investigate the impact of display imagery presented in fifty-one display locations. The WSD was simulated using projection. An innovative approach was developed to establish how long a driver could make a continuous glance to these locations before unsafe driving occurred. Graphical depictions of these time thresholds were produced for several dependent measures; they illustrate the visual demand implications of displays across the windshield area.

The final study recruited eighteen participants to compare three display locations (two windshield displays and a HDD). Two display tasks were used to establish how drivers manage their engagement with these displays. The observed interactions indicated that drivers were more enticed to attend to the windshield displays than the HDD.

Overall, this thesis demonstrates novel approaches to assessing visual demand across display positions. It concludes that windshield display demand is dependent on display location eccentricity and the nature of the task being displayed. The outcome of this demand depends on how drivers respond to these features. Finally, future work and the future of vehicle displays is discussed.

Publications

The work in this thesis has generated two academic publications:

Topliss, B. H., Pampel, S. M., Burnett, G., & Gabbard, J. L. (2019). Evaluating head-up displays across windshield locations. In *11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 244-253.

Topliss, B. H., Harvey, C., & Burnett, G. (2020). How long can a driver look? Exploring time thresholds to evaluate head-up display imagery. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 9-18.

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List of Abbreviations

AOI – Area of Interest

AR – Augmented Reality

FT – Feet

FWSD – Full Windshield Display

HDD – Head-down Display

HUD – Head-up Display

IVIS – In-Vehicle Information System

KMH – Kilometres per Hour

M/S – Metres per Second

MS – Milliseconds

Min TTC – Minimum Time to Collision

MPH – Miles per Hour

NDRT – Non-Driving Related Task

PC – Personal Computer

RQ – Research Question

SA – Situational Awareness

SD – Standard Deviation

SDDQ – Susceptibility to Driving Distraction Questionnaire

SDLP – Standard Deviation of Lane Position

SR – Steering Reversal

SSQ – Simulation Sickness Questionnaire

TEORT – Total Eyes-Off Road Time

TOR – Take-Over Request

TTC – Time to Collision

VR – Virtual Reality

WSD – Windshield Display

3D – Three Dimensional

1 Introduction

1.1 Background

Driving is a complex and demanding task, and the increasing prominence of technology in vehicles has the potential to capture a drivers' attention away from this task. Naturally, this has led to distraction becoming a prominent topic of research (Ito, Atsumi, Uno, & Akamatsu, 2001).

Distracted driving is common. A roadside observation study from St Albans, UK, found that 16.8% of the 10,984 observed drivers were engaged in an observable secondary task (an activity in addition to driving) (Sullman, Prat, & Tasci, 2015). However, a review of the 100-car naturalistic study indicates engagement in secondary tasks can reach almost as high as 40% (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Critically, these distractions are closely associated with undesirable outcomes including, greater variations in speed (Rakauskas, Gugerty, & Ward, 2004), and slower braking responses (Hancock & Ranney, 1999). The risk of a crash, or a near-crash, significantly increases during common in-vehicle secondary activities such as the use of a phone or eating (Klauer et al., 2014). Conducting secondary tasks has been confirmed as one of the most frequent contributing factors in crashes and near-crashes in naturalistic on-road data (Klauer, et al., 2006). Furthermore, confidence in dealing with distractions does not necessarily relate to better driving performance (Lesch & Hancock, 2004).

1.2 Eye Movement While Driving

Driving is considered to be a predominantly visual-manual task and therefore, the appropriate allocation of visual attention in particular is fundamental to effective driving performance (Shinar, 2008; Foley, 2009).

Drivers tend to look towards elements of the environment they either aim to approach or avoid (Rogers, Kadar, & Costall, 2005), which is likely indicative of planning movements for subsequent actions (Land & Hayhoe, 2001). However, the location of a driver's focus of attention whilst driving can vary due to numerous factors. For example, studies have shown that driver eye-movements and behaviours are influenced by: driving experience (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), cognitive load (Harbluk, Noy, Trbovich, &

Eizenman, 2007) and fatigue (Wang, Yang, Ren, & Zheng, 2006). Greater available visual information (e.g., in a daylight scenario) is associated with better dual-task driving performance compared to lower light conditions with less visual predictability (Broeker et al., 2020). A drivers' eyes being focused off the road environment, is closely associated with an increased crash risk (Victor et al., 2015; Liang, Lee, & Yekhshatyan, 2012) and due to the associations made by research such as Green, (1999c) and Victor et al., (2015), visual distractions are often evaluated according to eyes-off-road time. Within the field of driving, this is commonly assessed with eye-tracking devices and monitoring of whether a driver is looking towards the road environment or towards another task. These methods and their application to the current work are further discussed below (Chapter 2).

1.3 Driving Distraction and Demand

In order to fully understand the attentional demand caused by windshield display imagery, a full definition of distraction must be specified. The Paperback Oxford English Dictionary defines the word 'distract' as to *"prevent someone from concentrating on something"* (Waite, 2012). However, further definitions and classifications have been discussed specifically within the area of driving in order to ensure consistency across research.

Importantly, distraction needs to be distinguished from inattention. Generally, authors consider driver distraction to be one form of driver inattention (Young & Regan, 2007), therefore distraction leads to inattentive driving but inattentive driving may not be caused by a distraction (Pettitt, Burnett, & Stevens, 2005). More specifically, inattention occurs when the driver fails to attend (e.g., due to fatigue), thus there is diminished attention to safety critical driving activities (Lee, Young, & Regan, 2009). In contrast, distraction requires engagement in an explicit activity which demands attention away from the primary driving task (e.g., texting on a mobile device) (Lee et al., 2009).

Beyond this basic description, a true definition of driver distraction should also incorporate several other factors. Importantly, a source of distraction can originate both internally and externally to the vehicle (Pettitt et al., 2005; Young & Regan, 2007).Young & Regan (2007) further argue that a definition of distraction should incorporate the results of the distraction. Specifically, that an event or object may only be classed as a distraction when it causes a driver to insufficiently allocate attention to the driving task; if no detrimental effect occurs and driving performance does not degrade, then no distraction has occurred.

Equally, distraction can also be specified by type according to the modality of attention which the distraction is interfering with. Young, Regan, and Hammer (2003) discuss four distinct types of distraction: Visual, Auditory, Biomechanical/Physical and Cognitive. Visual distraction encompasses three further types. The first is when the drivers view of the road is obscured, the second is when the driver focuses on another visual element (instead of the road ahead), and the third is visual inattentiveness. This third type is sometimes described as ‘looking but not seeing’; it occurs when a high perceptual load prevents the detection of hazards even when a driver is looking towards the hazard (Mack, 2003; Murphy & Greene, 2016; Mancero, Wong, & Amaldi, 2007). Auditory distraction occurs when a driver focusses their attention on auditory signals, such as a radio or phone. Biomechanical distraction is when a driver removes their hands or feet from the control points of a vehicle to physically manipulate another object rather than the physical tasks required when driving, such as maintaining the steering wheel position. Finally, cognitive distraction is described by the authors (Young et al., 2003) as any thought processing which consumes enough attention to disrupt navigation and safe driving performance. Commonly, a source of distraction may incorporate multiple of these types, they may also exhibit them simultaneously. As an example, a touch-screen device would have the potential to exemplify all four of these forms. A notification noise could lead to auditory distraction, a visual notification could cause a visual distraction, dismissing the message could cause biomechanical/physical distraction since it requires a manual touch, and further thoughts on the messages’ content could cause a cognitive distraction.

An expansive definition of driver distraction, which incorporates all of these elements, is detailed by Pettitt et al., (2005); it includes the impact of the distraction, the agent, the mechanism and the type. Driver distraction is considered to have occurred when *“A driver is delayed in the recognition of information necessary to safely maintain the lateral and longitudinal control of the vehicle (impact) due to some event, activity, object or person within or outside of 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 combination thereof (type).”* (Pettitt et al., 2005).

Applying this to the present work: a Head-up Display (HUD) or Windshield Display (WSD) would not to be considered a distraction unless it sufficiently demands attention away from the driving task in a manner to cause a negative effect on the driving task. Therefore, whether or not a task on a display leads to distraction is further complicated by numerous interacting factors including driving experience, the current road environment, and task complexity (Young & Regan, 2007). There are many elements such as the vehicle design, road design and the driver's characteristics which all influence the attentional demands that are placed on drivers and how they respond to it (Dukic, Hanson, & Falkmer, 2006). Thus, for this work the aim was to specifically examine the attention HUD and WSD imagery demands from drivers, and whether this demand is likely to lead to driving distraction. Commonly, the demand from secondary tasks and displays is assessed by monitoring their impact on driving performance, eye-tracking, and subjective scales (Silva, 2014; Tsimhoni & Green, 2001; Desmet & Diependaele, 2019) as well as specialised procedures such as peripheral detection tasks (Milicic & Lindberg, 2009). The equipment and approaches used within the present thesis are discussed below (section 2.2).

1.4 Vehicle Displays

Despite the significance of visual attention whilst driving, numerous in-vehicle systems rely on visual displays to convey information to the driver. This largely originated from the development of in-vehicle navigation systems where the use of a visual displays enabled large, detailed amounts of information to be conveyed almost instantly to the driver, despite distraction concerns (Takasaki & Wasielewski, 1989; Dingus & Hulse, 1993). As vehicles have developed the in-vehicle systems have expanded, now commonly including climate controls and entertainment devices, which can encourage drivers to engage with non-driving related tasks (NDRTs). See Figure 1 for common sources of visual information within road vehicles.

Subsequently, there have been suggestions that certain information should be prioritised and its position on visual displays should vary according to that prioritisation (Olaverri-Monreal, Lehsing, Trubswetter, Schepp, & Bengler, 2013). For instance, the drivers' speed is commonly presented in the instrument cluster just below the driver's view of the road due to its prioritisation, whereas the radio is presented further away in the centre console, since it is not crucial for effective vehicle control (see Figure 1). Generally, displays presented within the vehicle are referred to as Head-down Displays (HDDs) in the literature, since they encourage drivers to keep their head down and look within the vehicle. Despite these considerations around positioning, visual distraction is still a primary safety concern.

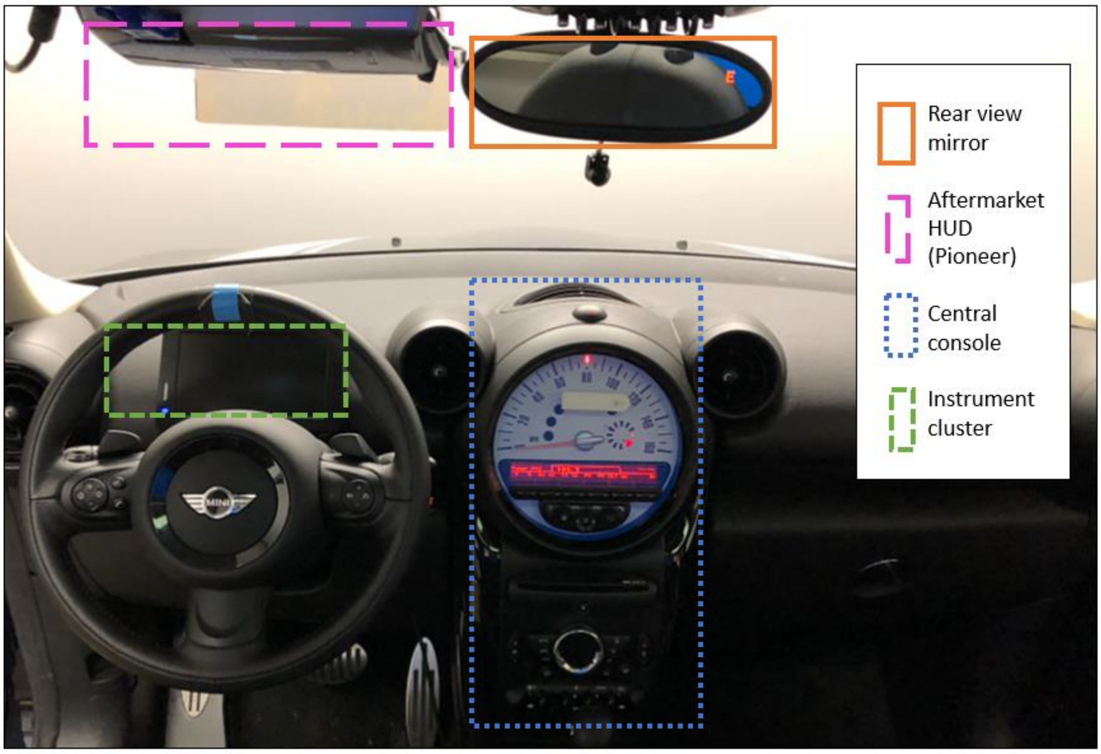

Figure 1. Common sources of visual information within a vehicle. Photo taken from the driving simulator used with Study 1 (Chapter 3).

One potential remedy for visual distraction issues are Head-up Displays (HUDs), because they enable drivers to maintain visual attention at least towards the road environment, since the display imagery is located over the forward road view (Ablaßmeier, Poitschke, Wallhoff, Bengler, & Rigoll, 2007) (see Figure 2 for an example). Thus, drivers may be better equipped to respond to the road environment as required if using a HUD compared to a HDD. Therefore, it is sometimes assumed these displays have the potential to maintain the benefits of visual displays, whilst also diminishing the distraction concerns (for a literature review see section 2.3 for concerns and 2.4 for benefits).

HUD devices originated from the aviation community, and were generally used to assist pilots in highly time sensitive situations, and included items such as gunsights, speed, horizon lines and navigation information (Banbury, 1992). Within road vehicles HUDs typically consist of digital imagery being displayed or projected on a transparent medium over the drivers' forward view (Betancur, Villa-Espinal, Osorio-Gómez, Cuéllar, & Suárez, 2018). The introduction of HUD technology has been more recent to road vehicles, but they are already implemented in vehicles on the roads today (Normile & Ulitskaya, 2021). An example is presented in Figure 2. An inspection of these current displays reveals commonly repeated elements including: short-term navigational information, current speed, incoming calls, lane keeping, distance to vehicles to ahead, cruise control settings, gear position and traffic sign recognition (Normile & Ulitskaya, 2021). Thus, at the present time they typically provide additional driving related information, with some features moving towards productivity (e.g., phone call information).

Figure 2. An example of a current HUD in and Audi Q4 E-Tron 2021. It contains speed information and navigation information, including a screen-fixed Augmented Reality (AR) arrow.

HUDs within road vehicles must be resilient to vibration, changes in temperature and humidity, all whilst remaining bright and clear enough to be legible over the road environment (Van Derlofske, Pankratz, & Franey, 2020). Aftermarket in-vehicle HUDs tend to use a separate sheet of combiner screen, similar to the type used in teleprompters or in aviation applications (Nichol, 2015). It is a transparent piece of glass or film which is attached to the windscreen or in front of the user (an example is seen within Figure 1). The display imagery is created using some form of projection system or screen which is then reflected by the combiner, thereby becoming visible to the user over their forward view (Nichol, 2015). However, the size of these is limited either by the observer needing to move their head to view the full imagery, which is potentially inappropriate in road vehicle applications, or they are limited by the size of the combiner.

Currently, in-built vehicle windscreens are commonly constructed from two laminated glass layers, so generally HUD imagery is intended to reflect off the inner glass surface. However, this can lead to a secondary ‘ghost’ image occurring due to reflections off the outer glass surface in addition to the inner surface. To prevent this, manufactures have varied the shape of the interior glass adhesive (commonly polyvinyl butyral) into a more wedged shape, so that the two reflections combine, or closely overlay (Pankratz, Diepholz, & Vanderlofske, 2021). Unfortunately, this only works at limited viewing angles so it is not suitable for drivers of all heights and some will still see the double imaging regardless (Van Derlofske et al., 2020). Furthermore, the skewing of light makes it an unsuitable approach for large HUD displays where the windscreen curves drastically, in these instances the issue cannot be sufficiently corrected using this approach (Van Derlofske et al., 2020). Moreover, many current devices can be disrupted if the driver is wearing polarised glasses, and temperature management is a further common issue in the devices’ durability (Van Derlofske et al., 2020). Technology is continuing to develop and find solutions to some of these problems (e.g., Jackin et al., 2023; Mareška, Kordová, & Míka, 2022).

1.4.1 The Future of Vehicle Displays

Authors have argued for a more human-centred (Pauzie, 2015) and holistic view of in-vehicle displays (Van Derlofske, Pankratz, & Franey, 2020). Thus, taking a Human Factors approach, as used within this thesis, is an ideal perspective to take on future vehicle displays, since it emphasises the importance of human interactions with systems (Wogalter, Hancock, & Dempsey, 1998).

Based on the literature, there are several upcoming developments in HUDs. First, HUDs appear likely to expand in size so they have the potential to present imagery across the whole windscreen (Häuslschmid, 2018; Osterwald, 2013). These are commonly referred to as a Windshield Displays (WSDs) or Full Windshield Displays (FWSDs) and would provide a larger platform to present different information, of varying priority, to the driver in a more optimal position than a HDD. Equally, these displays could be present on the other surfaces or windows within the vehicle (Yontem, Li, Chu, Meijering, & Skrypchuk, 2021). Furthermore, while displays are currently able to vary the depth of the imagery somewhat according to driver preference, some speculate that this could become more expansive. For example, particular interface features could be presented to the driver at different depths (Haeuslschmid & Shou, 2015) or at the same depth as real-world environmental elements.

Secondly, there is an emphasis on the implementation of Augmented Reality (AR) to these systems (e.g., Zhang, Yang, Zhang, Zhang, & Sun, 2021; Tönnis, Klinker, & Plavšic, 2009). Riegler, Riener and Holzmann (2021) conducted a systematic review of AR literature within the driving field. Their work demonstrates there was a large increase in the amount of research papers on this topic around 2013, with further increases in its prominence from there. Commonly within driving research, AR is described according to whether the point of reference for the imagery is within the real-world environment (external to the vehicle) or whether it is on the screen (Smith, Gabbard, et al., 2021). For example, most current AR HUD imagery is 'screen-fixed', so that the imagery appears to be attached to the windshield or the transparent display surface (see Figure 2 for an example of a screen-fixed arrow on a HUD within a current vehicle). However, developing tracking technology has enabled future concepts to explore AR applications where the imagery perceptively appears to be attached to something within the real-world environment (e.g., Riegler, Riener, & Holzmann, 2019c). Within the aviation industry this is commonly referred to as a 'conformal' HUD (e.g., Goteman, Smith, & Dekker, 2007), or otherwise as 'world-fixed' within driving research. Both approaches to AR would benefit from larger scale HUDs or WSDs so that the imagery and information can be presented in a manner that is proximate or corresponds with the real-world environment as the driver sees it.

Mekni & Lemieux (2014) define AR as having three characteristics. First, it combines the real and virtual, secondly it is interactive in real time, and thirdly it is registered in 3D space. Thus, in combination it can vary, or 'augment', a drivers' perception of reality. It has applications across various areas within the driving field. Prospective AR devices have largely been combined with HUDs or WSDs to insert road signs (Rane, Kim, Marcano, & Gabbard, 2016), crash warning systems (Kim, Wu, Gabbard, & Polys, 2013), navigation directions (Medenica, Kun, Paek, & Palinko, 2011), or highlight safety critical elements within the environment such as a pedestrians in order to ensure they are noticed (Kim, Isleib, & Gabbard, 2016). This display content may also vary with the increasing levels of automation in vehicles (Ayoub, Zhou, Bao, & Yang, 2019) which, while not the focus of this work, is reflected upon (see sections 7.3 and 7.7.2). Prospective work is also investigating AR being used to remove content from a viewer's visual environment, which is called diminished reality (DR) (e.g., Cheng, Yin, Yan, Gugenheimer, & Lindlbauer, 2022). If applied to driving this could help reduce motion sickness, highlight important features of the environment (by hiding others) or allow part of the vehicle to become translucent (Lindemann & Rigoll, 2017).

All these prospective AR displays could have the ability to further support a driver's performance. However, they must be designed conscientiously, otherwise they risk further disruption (Ma, Jia, Hong, Kwok, & Yan, 2021). Furthermore, new developments in technology are required to effectively employ AR systems within vehicles. Blankenbach, (2019) argues that increasing the field of view of the displays to at least 60x40 degrees would be needed within cities, and a luminance of 40000cd/m2, so that content is clearly visible even against bright buildings. Prototypes of such devices have used cameras which are able to capture landmarks in the road environment for augmentation, whilst also capturing and correcting distortion caused by the windscreen (Wu, Blaicher, Yang, Seder, & Cui, 2009), but much more development is needed for real-world applications.

This thesis is relevant to the development of AR displays primarily through the investigation of larger windshield displays and the impact of display imagery location. This is discussed in more detail in Chapter 7 (section 7.7.1).

Finally, a more immediate likely progression of HUDs is that information and tasks which are currently displayed on in-vehicle displays (HDDs) could move to a HUD or WSD in order to benefit from the advantages that windshield displays appear to offer; which include improved driving performance and visual behaviours (e.g., Liu & Wen, 2004) (see Chapter 2, section 2.2). As with AR, the implementation of new tasks and information will likely lead to the size of windshield displays increasing and therefore a similar pattern of prioritising information may occur (as with any vehicle display, see section 1.4); with critical information being positioned nearer to the driver's forward view and less critical being positioned further away (for concepts see, Haeuslschmid et al., 2016).

Since this thesis aims to investigate the demand of near-future windshield displays, it focuses primarily on two speculative progressions of windshield displays which are likely to be present within the near-future. Namely: the expansion in size of HUDs, and their presentation of tasks and information which commonly reside on HDDs within current vehicles, since no or minimal technological development is required for these factors to be implemented within vehicles imminently. Other concepts which are likely to be relevant to future displays (such as world-fixed AR, autonomous vehicles, and expansive display depth) are not primarily addressed within this work in order to effectively focus on and explore the demand of near-future displays. Throughout this work, the term 'windshield display' is used to describe any display (HUD, WSD or FWSD) which displays imagery on the windshield of a road vehicle.

1.5 Research Aims and Questions

The present work aimed to investigate the demand imposed on drivers by Head-up Displays (HUDs) and Windshield Displays (WSDs) when used as near-future display in road vehicles.

The research primarily uses driving simulators in order to examine the impact on driving performance and visual behaviour. Specifically, the research addressed three core research questions (RQs):

RQ1) How do drivers respond to the attentional demand imposed by near-future tasks on a windshield display?

RQ2) How does demand vary across windshield display locations?

RQ3) What approaches may be developed to help investigate windshield display demand?

1.6 Structure of Thesis

The structure of the thesis is summarised in the Figure below (Figure 3). The thesis contains four empirical studies to address the primary research questions.

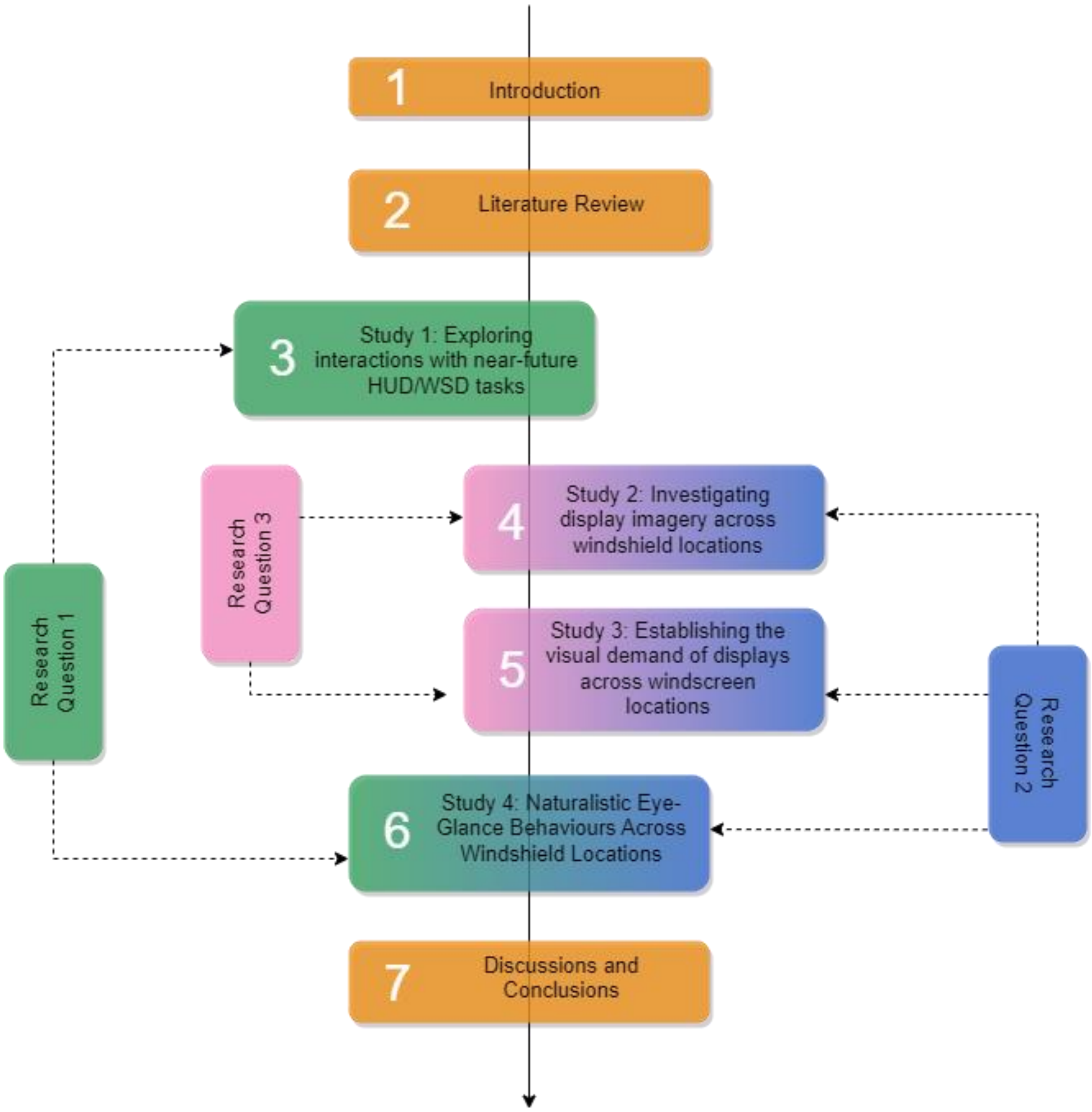

Figure 3. Structure of the Thesis

Chapter one introduces the thesis, including the primary background, the rationale, the aims and objectives, as well as the details of the thesis structure.

Chapter two contains a thorough review of the literature including: the equipment used within the research area and throughout the thesis, previous work on vehicle displays, the benefits and concerns of HUDs and WSDs, the assessment approaches to displays, and the location of vehicle displays. It reviews considerations around this previous work and how the present work responds.

Chapter three details the first explorative study which aimed to start addressing the first research question. It used simulated near-future tasks on an aftermarket HUD device and was conducted at the Cogent Lab driving simulator at the Virginia Polytechnic Institute and State University. It highlights the importance of task nature and complexity when analysing vehicle displays.

Chapter four describes the second empirical study which begins exploring the second and third research question, using an aftermarket HUD and a driving simulator to examine the impact of imagery location across a windscreen.

Chapter five depicts an expansive third empirical study further exploring the importance of imagery location, by examining tasks conducted in 51 locations across a windscreen. The study addresses research questions two and three. The results of this work visually depict how different imagery locations variably impact visual demand.

Chapter six recounts a final driving simulator study which examines a menu task and an intentionally unsuitable game task across several display locations in order to address the first and second research questions.

Chapter seven discusses the research as a whole: synthesising the overall results, evaluating the approach, and proposing future work.

2 Literature Review and Related Work

2.1 Chapter Introduction

This chapter reviews previous literature and related work on, vehicle display research, HUDs and WSDs. First, common equipment and methods used within the research area are reviewed. Secondly, the chapter examines the features which make windshield displays advantageous or disadvantageous within the context of a road vehicle. Thirdly, the current assessment approaches and recommendations for vehicle displays are considered, with reflections on their applications to HUDs and WSDs. Finally, previous work on display location is reviewed. The chapter is organised into five main sections which are summarised in the figure below (Figure 4).

Figure 4. An overview of the literature review topics.

Conclusions on each section are also included throughout as well as a chapter summary at the end (section 2.7).

2.2 Equipment and Methods for Display Research

The demand incurred by a task, interaction or display during driving can be measured using several techniques and pieces of apparatus. The present research uses driving simulators, eye-tracking glasses, and various display techniques, in order to investigate the research questions outlined in the previous chapter. This section reviews the methods and human factors considerations involved with using this equipment. It also discusses the key decisions which were made regarding their use within the thesis.

2.2.1 Driving Simulators

When wanting to study driving on-road studies, which use an instrumented real vehicle, appear as an attractive methodology since they provide the most realism and therefore appear highly ecologically valid. Ecological validity refers to the ability to generalise results from a controlled experiment to natural behaviour in the real world (Schmuckler, 2001; Kihlstrom, 2021; Holleman, Hooge, Kemner, & Hessels, 2020). Typically, these studies are conducted within an instrumented vehicle on a test-track or a participant’s personal vehicle may be instrumented to monitor more naturalistic driving conditions in real-world scenarios. However, the evaluation of driving distraction and display demand is most commonly assessed using driving simulators due to their numerous benefits over on-road studies.

2.2.1.1 The Advantages of Driving Simulators

The exact nature of driving simulators can vary greatly, from a full vehicle cab with a motion base and 360-degree screens, to a PC based simulator with desktop controls. Despite this, safety is considered a primary advantage to using any form of driving simulator. When implementing a secondary task, in addition to the primary task of driving, a participants’ driving performance is liable to drop, making the use of a real vehicle and the subsequent risks involved, sometimes ethically inappropriate (De Winter, van Leeuwen, & Happee, 2012). In contrast, conducting these tasking within a driving simulator is much safer.

Furthermore, the use of a simulator allows for much greater control. Various road environments and conditions such as weather, traffic behaviour, road layout can be eliminated or implemented as required. These factors may otherwise confound studies or be difficult to implement if the study was conducted with a vehicle on-road. Equally, this level of control can be easily standardised across participants and between experimental conditions, thereby making the process more efficient (Carsten & Jamson, 2011).

Temporary additions to the vehicle such as novel interaction devices, screens and cameras can be easily incorporated into a driving simulator, and without concerns over safety (Carsten & Jamson, 2011). This is a prominent advantage to the present research where novel displays must be replicated. Some of the techniques which are commonly used to replicate these displays (see section 2.2.3.1), would not be possible unless conducted within a driving simulator.

Moreover, whereas instrumented vehicles can lead to cumbersome data collection, with the behaviour of other traffic and lane markers being particularly difficult to monitor, driving simulators enable researchers to expansively and sensitively examine numerous driving measures without these concerns (De Winter et al., 2012).

Finally, the prominence of driving simulators means they are largely accessible and not overly costly for researchers to use (Weinberg & Harsham, 2009).

2.2.1.2 The Disadvantages of Driving Simulators

Despite these copious advantages, driving simulators do suffer from some limitations.

2.2.1.2.1 Simulation Sickness

Some participants may experience discomfort when using a simulator, which is commonly referred to as simulation sickness (Mourant & Thattacherry, 2000). Seemingly, this is caused by conflicting movement sensory cues (Reason & Brand, 1975). For example, when the participant views video images which indicate they are moving (such as on the screens of a driving simulator), but the vestibular system does not indicate motion. A participant experiencing simulation sickness may exhibit a number of symptoms of varying severity including headaches, eye strain, nausea, vomiting, dizziness and disorientation. Simulation sickness can negatively impact a participant’s well-being as well as the results of a simulation study. For example, participants may attempt to avoid certain stimuli or tasks that exacerbate the discomfort, and therefore are unable to respond or behave as they would when naturally driving a vehicle within a real environment (Burnett, Harvey, & Donkor, 2017). Numerous factors have been shown to influence simulation sickness though, vehicle behaviour, the environment, interface design and participant individual differences all appear to play a role (see Burnett et al., 2017, for a summary).

Within the studies conducted for this thesis, measures were taken to ensure that simulation sickness was prevented wherever possible. Within the recruitment process, participants were warned about simulation sickness and were asked to not volunteer if they had conditions which make simulation sickness more likely, or conditions which may make the simulator unsafe for them. This included severe motion sickness, migraines, epilepsy, dizziness and pregnancy (see Appendix B, C, D, E). Furthermore, the information sheets and/or consent forms further highlighted the potential for simulation sickness (see Appendix B, C, D, E). The experimenter was always present throughout the studies (either monitoring within the same room or via video or via a window from a control room) in order to observe the participants for indications of discomfort. All the simulators used within the studies were made using real vehicle cabs which may somewhat appease simulation sickness as it provides a visual reference point (Burnett, Irune, & Mowforth, 2007). Where possible, air circulation was also increased using the in-vehicle fan system for the participants' comfort. Participants always performed a familiarisation drive, which gave participants the opportunity to experience the simulation and judge whether they were comfortable. The drives designed within all the studies did not last for longer than ten to fifteen minutes, so that any discomfort could regularly dissipate, and participants could easily and regularly speak to the experimenter if they required a break or would prefer to stop the procedure. The Simulation Sickness Questionnaire (SSQ) (Kennedy, Norman, Berbaum, & Lilienthal, 1993) (Appendix A) was used throughout all of the studies to record how participants were feeling and help them express anything they were feeling.

2.2.1.2.2 Driving Simulator Fidelity and Validity

Largely, other issues with simulators result from attempting to replicate a real-world driving experience. As mentioned previously, driving simulators can vary greatly, particularly in their physical components. Typically, driving simulators are classified according to their level of fidelity, that is broadly speaking, the degree to which the real-world system is replicated (Liu, Macchiarella, & Vincenzi, 2008). Regarding simulators this concept of fidelity can be further split according to physical or psychological fidelity (Liu et al., 2008). Physical fidelity encompasses many elements such as visuals (e.g., a graphical road environment), audio, motion, interaction mechanics, the vehicle cab and so on. Their physical characteristics such as their positions, size and shape should mimic the real-world equivalent as closely as possible for high fidelity. Thus, the sensory information from the simulated vehicle and the simulated environment will result in physical sensation comparable to the real-world (Greenberg & Blommer, 2011). Psychological fidelity addresses the degree to which the simulation results in the same psychological experience as the real-world system (Liu et al., 2008). Closely linked is perception fidelity, which refers to the degree to which the user perceives it as real (Young, Regan, & Lee, 2009). Thus, for high psychological fidelity the same level of workload, stress and motivation would be implemented in the simulated environment, as in the real situation (Liu et al., 2008; Ranney, 2011). Especially pertinent to driving research is the psychological concept of risk perception. Within real-world driving, drivers are motived by risk, and other psychological factors, to drive safely and consistently. The clear safety of driving simulators, whilst a benefit, may result in inconsistent driving performances (Ranney, 2011).

Closely linked to the concept of fidelity is validity. In addition to the previously discussed ecological validity, absolute and relative validity are also commonly mentioned in relation to driving simulators. Absolute validity refers to the absolute value of an effect being equivalent in reality (Kaptein, Theeuwes, & Van Der Horst, 1996). For example, a change in speed due to a traffic calming measure would result in the exact same change in speed (e.g., 10mph lower) in the simulator as it would on a real road. In contrast, simulators generally have relative validity (Mullen, Charlton, Devlin, & Bedard, 2011), which refers to proportional values (Kaptein et al., 1996). Thus, a change in speed would be proportional to what would occur in the real world, for example a 10% drop in speed. Driving simulators are often evaluated to ensure that at least relative validity is established. An example of this, which considered distracted driving specifically, is the work from Knapper, Christoph, Hagenzieker and Brookhuis (2015) who compared speed variance in a simulator and on-road during distracted driving. The authors found that during distracted driving the measures varied in the same direction on the road and in the simulator, thus the authors found suggestive evidence of relative validity.

Generally, higher fidelity is strived for with the hope of higher validity as a result. Classically, this relationship was found to be true, with high-fidelity simulators generally resulting in more secure validity (Kaptein et al., 1996). However, more recent work indicates that the relationship between high fidelity and validity is not simple (Wynne, Beanland, & Salmon, 2019) and that actually high-fidelity is unnecessary for appropriate validity (Park, Allen, Rosenthal, & Fiorentino, 2005). Some authors have found that even simple tasks could be used to imitate the driving task effectively. For example, Morgenstern, Wögerbauer, Naujoks, Krems, and Keinath (2020) examined the box task method, which involves asking participants to maintain a box's size by turning a steering wheel, and found the task comparable to commonly used driving tasks.

In summary, limited fidelity and validity are some of the most prominent limitations of driving simulation methods. Both are likely to be present considerations in any simulation study, thus it is most important to understand not whether they are present, but rather know and appreciate how they may influence results (Greenberg & Blommer, 2011).

2.2.1.3 Driving Simulation Measures

The data collected from a simulator is commonly used to assess driving performance. The measures can be categorised into two groups: lateral and longitudinal driving performance (e.g., Tönnis, Lange, & Klinker, 2007). Lateral measures consist of measures which identify the cars positioning in the lateral plane. These include measures such as steering reversals, lane position and distance to lane exceedance. Longitudinal measures instead monitor the drivers position in the longitudinal plane including speed, acceleration, distance to lead vehicles, and response times. As discussed in the previous chapter, if a secondary element, for example a display, is demanding enough it may have a detrimental impact on driving performance. Thus, driving performance measures with different displays may be compared in order to assess the impact on driving performance and therefore driving safety. As a result, driving performance measures are critical to many research topics, including those investigated here. Notably, driving performance measures are often difficult to define with various terms being used throughout the literature (Savino, 2009; Green, 2013; SAE International, 2015) and each of them being variably interpreted (Young et al., 2016). Therefore, where driving performance was assessed within this work, the details of the measures are discussed within the relevant chapters.

Additionally, the present work applies an approach commonly referred to as a ‘car following task’ (e.g. Fiorani, 2007); participants followed a simulated lead vehicle throughout their driving procedures within all of the studies reported here. The exact driving behaviours this car exhibited varies and is expanded upon within each studies’ description. It was included throughout this work as it imposed a consistent need for the participants to maintain good longitudinal driving performance across all the studies (participants had to try and ensure they did not collide). The car following task also served as a sensitive method of analysing longitudinal driving performance throughout the studies (as distance and time to the lead vehicle could be assessed continuously through the drives). Furthermore, it provided some indication of situational awareness as described below.

Situational Awareness (SA) is an increasingly common term within the driving research literature (e.g., Walker et al., 2008). SA is defined as an understanding of the environment’s state, so the observer can perceive and comprehend what is present, as well as predict upcoming states (Endsley, 1995). SA is commonly assessed with the Situational Awareness Global Assessment Technique (SAGAT), which is problematic since it requires an environment to be paused and relies on the explicit recall of the observer in order to determine their understanding of the situation in its current state. More recently, Briggs, Hole and Turner (2018) inspected driver situational awareness by monitoring their ability to detect unexpected events with a concurrent conversation task, or without. The authors concluded that drivers may use a schema driven strategy to SA when distracted by a secondary task, and as a result are less receptive to unexpected events in a driving scenario. While a specific measure of SA was not incorporated into the present studies, the ‘car following task’ (where a lead vehicle varied its speed) was present within all of the studies. While not a wholly unexpected event, driving performance in relation to this lead vehicle should be somewhat reflective or indicative of the drivers’ SA.

2.2.1.4 Driving Simulation Conclusions

The significant prominence of driving simulators in the area is a testament to their strength (Boyle & Lee, 2010). As a result of reviewing this information on methodology and the benefits of using driving simulators, they were selected as the primary approach in order to study and address the research questions. Images of the driving simulators used within the studies are present below (Figure 5).

Figure 5. All the driving simulators used within the studies. A) used with study 1, B) used within study 2 and C) used within studies 3 and 4.

2.2.2 Eye-Tracking Devices

Attentional demand is commonly assessed by monitoring visual behaviours using eye-tracking equipment, with eye-movements and fixations being indicative of how a persons' visual attention is being allocated, and therefore able to indicate how demanding an element may be (Duchowski, 2017; Carter & Luke, 2020; Poole & Ball, 2006). When the eye is open, light enters the eye's structure through the pupil and the cornea, then the lens focuses this light onto the retina at the back of the eye. Light is primarily focused onto a small central area of the retina called the fovea, where there is a dense collection of sensitive photoreceptors which capture a detailed image of what the eye is directed to (Carter & Luke, 2020). Since the fovea is small, the eyes move frequently to generate information about the entire visual field. The basic eye-movements generally recorded include data on the fixations and saccades. Fixations occur when the eyes are fixed on a visual target and remain stable, whereas saccades are the fast eye-movements which reposition the fovea to a new aspect of the visual environment (Duchowski, 2017).

Eye-tracking apparatus can vary greatly depending on its application but perhaps the most common method of monitoring eye movement in eye-tracking uses corneal reflections (Duchowski, 2017). The corneal reflections, also known as Purkinje reflections (Cornsweet & Crane, 1973) are the result of the eye's structure and layers, and as such, can be used to help determine eye-movement. Typically, an infrared red light is shone into the eye and the reflections from the eye-structures are detected to surmise the movement of the eye. The use of infrared means normal vision is not disrupted. Using solely this approach enables the detection of movement but not eye-movement relative to a real-world environment (Young & Sheena, 1975); consequently using only this method it would not be possible to determine exactly where a participant is looking. Traditionally, to overcome this limitation, participants would be fixed to an eye-tracking device, such as a table-mounted stand with a chin and head-rest (Young & Sheena, 1975). These face the criticism that the unusual situation or discomfort of the device may cause participants to adapt their behaviours.

A modern approach to locating where a participant is looking is through the use of video-based data (Duchowski, 2017). The pupil can be detected in addition to the corneal reflections (Poole & Ball, 2006) so that in combination, the eye's orientation in space can be isolated. Eye-tracking measurements which can achieve this are referred to as 'point of regard' measurements (Duchowski, 2017). Much greater flexibility is enabled by this approach, for example, the eye-tracking device need not be in contact with the participant and could instead be remote and placed on a desktop, enabling much more natural behaviour and head movement. Point of regard measures are generally used when visual items or elements which the participants may look to, require identification and are relevant to the investigation. Thus, it is highly relevant to the present work. Eye-tracking within the driving field is commonly interested in the extent to which a driver is looking to an Area of Interest (AOI) (e.g., Trösterer, Meschtscherjakov, Wilfinger, & Tscheligi, 2014; Barnard & Lai, 2010). Particularly prevalent in the literature are assessments on how much the driver looks towards the forward road environment (e.g., Mourant & Ge, 1997) or towards a display. In order to best line-up the eye-movement to the real-world environment (or a simulated one), some form of calibration is normally required. This involves the participant looking towards a known location in the environment, then the point of regard is established by measuring the positions of the corneal reflections and the location of the pupil (Duchowski, 2017). Multiple calibration points are generally used to ensure the device can monitor the user from the extremes of all likely viewing angles (Duchowski, 2017).

2.2.2.1 Eye-Tracking Equipment Limitations

Despite the improvements in the technology, there are still limitations to this equipment. Glasses or contact lenses, have the potential to confuse these eye-tracking systems because the light reflected from the lenses may be interpreted as corneal reflections (Carter & Luke, 2020). Modern eye-tracking glasses claim that contact lenses specifically should not interrupt these processes (Mele & Federici, 2012), however, the lenses can distort the shape of the wearer's pupil, and as a result the video-based software can still have detection issues. Equally, the head-mounted eye-tracking equipment is also commonly designed to look like eye-wear and as a result wearing both can be difficult (Tobii Pro, n.d.). Pupil detection can also be impeded by the participant's eye-lid if they are particularly sleepy and they partially occlude the pupil (Carter & Luke, 2020). Other areas of darkness such as from make-up or eye-lashes may also be mistakenly detected as part of the pupil (Carter & Luke, 2020; Schnipke & Todd, 2000; O'Brien, 2009). The performance of the infra-red light is also paramount to good eye-tracking. If a participant's glasses have a tint or anti-glare coating or a strong prescription, the infrared light might not illuminate the eye enough for accurate detection (Carter & Luke, 2020). Furthermore, the lighting conditions of the study, or changes in lighting conditions, have the potential to further disrupt these detection processes (Zhu, Fujimura, & Ji, 2002; Carter & Luke, 2020).

Although eye-tracking is a prevalent measure of demand and distraction, it is important to appreciate that eye-movement is only indicative of visual attention. Whilst the eye may be towards the forward road environment a driver may fail to notice an important visual cue or hazard due to inattentional blindness (Mancero, Wong, & Amaldi, 2007); looking does not mean seeing (see section 1.3). Furthermore, this can become exacerbated by increased visual load (meaning greater visual information in the environment) (Murphy & Greene, 2016) thereby highlighting the importance of appropriate visual displays and the present research.

Additionally, it is important to note that eye-tracking focuses on foveal vision, i.e., where the eye is centrally focused, and where light is reflected onto the fovea. However, visual information can also be acquired through peripheral or ambient vision since light is also reflected on to the other areas of the retina from around where the eye is focussing. These peripheral areas are not as dense in photoreceptors, so peripheral vision is not as accurate as foveal. However, this form of visual uptake is not directly monitored by eye-tracking (Duchowski, 2017). Research into these two forms of vision and their relevance in driving has shown the importance of foveal vision in critical driving behaviours such as hazard detection (Horrey, Wickens & Alexander, 2003). However, there is also strong evidence that peripheral vision has an important role within driving (Wolfe, Dobres, Rosenholtz, & Reimer, 2017). Research has shown that drivers are able to use their peripheral vision to detect a car ahead braking (Lamble, Laakso, & Summala, 1999; Summala, Lamble, & Laakso, 1998) when they are looking to a vehicle display. Peripheral vision also is important for a driver’s perception of speed (so a wide angle of view within a driving simulator is also preferable) (Pankratz et al., 2021). Research has also indicated that drivers are able to maintain their lane position using their peripheral vison when they are forced to look towards an in-vehicle display, though their ability to do this depends on where their foveal vision is focused and how much driving experience they have (Summala, 1998; Heikki Summala, Neiminen, & Punto, 1996). Finally, looking at HUDs in particular, aviation research has indicated that peripheral vision may be used to extract useful information such as airspeed as presented from a HUD (Ziv, 2016). How drivers employ their peripheral vision when using HUDs and WSDs will be a feature present throughout this work.

2.2.2.2 Eye-Tracking Equipment Benefits and Implementation within the Current Work

Within the current work, SMI eye-tracking glasses were used in some manner within all studies. They use a combination of forward video, pupil detection and corneal reflection to monitor eye-movement relative to the simulated driving environments. Eye-tracking glasses were used rather than fixed non-contact eye-tracking equipment so that large head movements could be followed (which might otherwise obscure the eyes from an eye-tracking device positioned in front of the participants). Large head movements may be expected from drivers when they are looking to side-mirrors or, as in the present work, when drivers are asked to attend to displays across a myriad of locations within the vehicle and across the windscreen. Fortunately, eye-tracking glasses are becoming increasingly compact, thereby allowing these natural head movements to be performed comfortably (Paletta, Santner, Fritz, Mayer & Schrammel, 2013). Therefore, eye-tracking glasses are well suited to the work conducted within this thesis. An example of the eye-tracking glasses is available in Figure 6.

Figure 6. SMI Eye-tracking glances as used within study 4.

As mentioned previously, eye-tracking data is often reviewed in terms of AOIs. Where AOI boundaries should be located, is somewhat debated (Orquin, Ashby, & Clarke, 2016). For the present work the edge of the AOIs were placed at the boundaries of the environmental elements in order to prevent false positive fixations. Due to the head movement of the drivers, their forward visual scene changed throughout the studies. Therefore, in order to study AOIs, each visual intake collected by the eye-tracking glasses was manually assigned with the appropriate AOI for analysis. Driving research also commonly uses the term 'glance' to refer to a driver looking to an AOI (Smith, Gabbard, & Conley, 2016). As defined for the present work, a glance can include multiple fixations and saccades, but a new glance is considered to have started when the participant fixates on a new feature of the environment or blinks (Smith et al., 2016)(see section 3.3.4 for more details).

2.2.2.3 Eye-Tracking Conclusions

Overall, despite the difficulties associated with the effective capture of eye-tracking measures, it provides a highly insightful view of how drivers may be distributing their visual attention. The visual behaviours of drivers are highly associated with driving performance (Green, 1999c; Victor et al., 2015) and so eye-tracking is a valuable tool to driving research, and therefore it was used in this work.

2.2.3 Head-Up Displays (HUDs) and Windshield Displays (WSDs)

Although HUDs are implemented within some modern vehicles, researchers often need to replicate them within the context of an instrumented vehicle or driving simulator which does not have an integrated HUD/WSD.

2.2.3.1 Display Equipment used to Research HUDs and WSDs

One approach is to use real world HUDs which are intended to be fitted to vehicles post manufacturing (e.g., Smith, Streeter, Burnett, & Gabbard, 2015). For example, within the current work Pioneer after-market HUDs were used to display imagery and tasks in the first two studies (see Figure 7). These consist of a projection system mounted to the vehicle’s interior roof, and a combiner glass folding down in a similar position to a sun visor. The display would present imagery to the driver just above the horizon line, though this position is dependent on the exact angle of the combiner glass and the driver’s eye-line. Using this approach benefits from potentially appearing more real to participants and an example of this is visible in Figure 7.

Figure 7. A Pioneer HUD attached to the ceiling of the vehicle cab. The combiner screen is visible as a clear rectangle near the top of the windshield. The projection system is positioned flat against the vehicle’s roof.

A second approach is to use reflection. Some after-market HUD devices reflect pre-designed LCD boards onto a windshield. Alternatively, mobile devices can be used to reflect imagery on to the windshield (e.g. Burta, Szabo, & Gontean, 2021). If a static driving simulator is being used (so there is no concern over space usage at the front of the vehicle cab) LCD displays can be laid flat on the floor of the experiment space, or projectors can be positioned in order to reflect display imagery to the driver in a manner which would be impossible within the confines of a real-world vehicle cab (e.g., Liu, 2003). This approach can be adjusted in order to examine HUD imagery in various locations based on how a display is reflected, though some positions may be limited by the presence of the vehicle cab.

Another approach, when using a driving simulator, is projection. Display imagery can be projected over the road environment (e.g., Flannagan & Harrison, 1994; Gerber, Schroeter, Xiaomeng, & Elhenawy, 2020). Thus, whilst one or multiple projectors are creating the road environment, additional projectors show the display imagery over the same surface (see Figure 8). Thus, the road environment and display imagery exist on the same plane in 3D space. This approach was used in the final two studies of the current work and benefits from high flexibility, meaning presenting imagery across multiple areas could easily be achieved with minimal modification to the driving simulator set-up. Within these studies the projection surface was approximately three metres in front of the drivers' seated position; therefore, the HUD imagery's position emulated the focal depth seen in real-world HUDs and the focal depth commonly investigated within research (e.g., Merenda, Smith, Gabbard, Burnett, & Large, 2016; Tonnis, Sandor, Klinker, Lange, & Bubb, 2005; Smith et al., 2016).

Figure 8. A projector positioned on top of the driving simulator cab to present a simulated HUD over the also projected driving environment.

Finally, virtual reality (VR) is an evolving approach commonly used to investigate vehicle technology which is currently in early development or otherwise difficult to implement using other simulation techniques. This involves the participant wearing a headset over their eyes in order to view a completely virtual simulated 3D environment. Riegler, Riener, and Holzmann (2019b) proposed the use of VR in order to quickly prototype and conduct research on automated vehicles and windshield displays. The authors detail the required construction, hardware and the justification for each element. The result is a relatively lower-cost yet higher-fidelity approach to such research (compared to desktop simulators). Riegler, Song, and Riener (2022) continued this work, and have also introduced approaches to investigating display interfaces by enabling participants to interact with display contents and components within VR vehicle environments. For example, they enabled participants to move around and change the colours of features to be presented on a windshield display.

Thus, this approach is particularly suited to investigating AR or highly complex graphical imagery on vehicle displays.

2.2.3.2 What HUDs and WSD Present within Research

In order to examine HUDs, research has generally implemented some form of imagery or task on the display. In some instances, the imagery does not require direct interaction from the driver, but simply provides information which could suggest to the driver a change of behaviour or change in their vehicle management. For example, common warnings on car's functioning, 'low washer fluid' (Carl Jörgen Normark, Tretten, & Gärling, 2005), or speed and status information (Ablaßmeier et al., 2007). Beyond basic information, some highlight or augment environmental features, as viewed by the driver, in an attempt to further aid them in the driving task. This includes elements such as drive path support, distance to other vehicle support, an indication of future navigation directions, repeating road signs and the detection of critical road events (e.g., Pauzie, 2015; Zhang, Yang, Zhang, Zhang, & Sun, 2021; Liu, 2003; Kim, Wu, Gabbard, & Polys, 2013; Medenica, Kun, Paek, & Palinko, 2011; Liu & Wen, 2004; Osterwald, 2013). With the development of more autonomous vehicles, HUDs have also been examined assuming the driver is not responsible for vehicle control. For example, Gerber et al., (2020) investigated drivers watching TV shows on mobile devices and HUDs (see section 7.7.2).

Alternatively, research is conducted where the HUD or WSD imagery requires interaction or a response from the driver. For example, visual search tasks, where participants are required to look towards the display and search to find a particular target. For these tasks participants are often then required to respond in a particular manner as evidence that they have completed the task (e.g., a button press or verbal response). These can include looking through words, text or characters (e.g., Smith et al., 2015; Smith, Gabbard, Burnett & Doutcheva, 2017; Smith et al., 2016; Weinberg, Harsham, & Medenica, 2011) or shapes (e.g., identifying the biggest circle, Wilschut, Rinkenauer, Brookhuis, & Falkenstein, 2008; Hensch et al., 2020). Similarly, there have been time-sensitive detection tasks (e.g., Summala et al., 1996; Lamble et al., 1999) where the participant is required to almost constantly and continually attend to the display in order to successfully complete the task. For example, naming aloud when a '4' or '7' appears in rapidly alternating characters (Summala et al., 1998). These approaches were adapted in the second and third study of the current work, more detailed information on these is available in the relevant chapters (Chapters 4 and 5). Other tasks included text comprehension tasks, which require reading aloud or for the driver to comment on a characteristic of the text, for example whether it was semantically correct or not (Hensch et al., 2020; Tsimhoni, Green, & Wantanabe, 2001; Schartmüller et al., 2021).

Beyond these examples, the exact task is often specialised to investigate the specifics of the research (e.g., detection response times, Haeuslschmid, Forster, Vierheilig, Buschek, & Butz, 2017). Some researchers have also begun to include tasks which are often present within other vehicle displays, such as navigating menus (e.g., Angelini et al., 2016), although further work in this area is needed, and is addressed within the first study of this thesis (Chapter 3). Others have included potential future display developments, such as providing visual feedback from touch screen keyboards (Lauber, Follmann, & Butz, 2014).

The studies within the present work use various tasks, some of which emanate from the principal task forms detailed above; each of them is described and justified in the relevant chapters.

2.2.3.3 HUD and WSD Conclusions

Which particular approach or equipment is used to study HUDs or WSDs is largely dependent on the exact research questions being addressed. WSDs or large HUDs do not currently exist within real road vehicles and as such have to be simulated. Within the present work several approaches are used to simulate WSDs and the success and limitations of these are reviewed in the relevant chapters.

2.2.4 Conclusions

This section reviewed the common methods of assessing demand within the area of driving. It discussed their benefits and limitations and also addressed how some of them will be employed within this thesis.

2.3 The Concerns around HUDs and WSDs

As discussed previously (Chapter 1) HUDs and WSDs are generally considered beneficial within vehicles since they enable the driver to maintain their visual attention towards the external environment. However, since their implementation within aircraft there have been concerns over the nature of HUDs.

This section collects some of the primary concerns and reviews how they are influential to the area.

2.3.1 Attentional Tunnelling and Capture

Early research from the aviation community has long held concerns over the exact implementation of HUDs. For example, Foyle, Stanford, Beverly and McCann (1991) conducted a simulation study researching how pilots responded to HUDs displaying altitude whilst also following a path along the terrain. Whilst the authors found the presence of the HUD aided altitude maintenance, they also found that its presence resulted in poorer path following along the terrain. Foyle et al., (1991) concluded that the participants were unable to efficiently process both the HUD (altitude) information and the terrain information simultaneously. Thus, a trade-off in task performance between whatever is supported by the HUD (e.g., altitude maintenance) and other primary controls (e.g., following a path along the terrain) is liable to occur. Similarly, McCann et al., (1993) conducted a study using a PC to simulate a HUD and a runway. The authors looked at whether people could focus on both the HUD and the world environment simultaneously. The authors found that responses to cues were fastest when part of the same perceptual group, meaning the visual information sources were both on the HUD or both on the runway. Participants were slowest when shifting attention between stimuli on a HUD to stimuli within the real world. Thus, HUDs which aim to inform a driver or pilot about the real-world environment may suffer from slower responses. However, the authors do argue that this issue could be reduced by more advanced displays which are capable of incorporating the display stimuli within the world itself. These concepts have since been developed into the world-fixed AR concepts which are being researched today (e.g., Schneider et al., 2019; Riegler, Riener & Holzmann, 2019c).

A similar study was conducted by Hagen et al., (2005) but applied to an on-road study. Participants were asked to drive a vehicle along a runway while a HUD displayed the vehicle's speed as digital numbers. Whilst the presence of the HUD appeared to improve speed maintenance it also appeared to worsen their lane position performance. Thereby demonstrating that this concern is present within both aviation contexts and road vehicles.

In review, the above authors concluded that the results they were observing were likely due to an effect commonly known as attentional tunnelling, cognitive tunnelling, or attentional capture (Foyle, McCann, Sanford, & Schwirzke, 1993; Hagen et al., 2005; Prinzel & Risser, 2004; Ward & Parkes, 1994). Broadly, this is where a person focuses their attention on one stimuli or channel of information within their environment at the expense of others (Wickens, 2005). Thus, within the previously described work, participants focused on the HUD and the information it was conveying, at the expense of environmental information, thereby resulting in poorer performances on measures which were dependent on that environmental information. For example, the results of Hagen et al., (2005) indicates that participants were maintaining their speed performance (as it was displayed on the HUD) at the expense of their lane positioning (which required participants to attend to the road environment). Arguably this phenomenon is particularly dangerous within an automotive context because road environments are complex and ever-changing and therefore, efficient scanning behaviours (looking across the whole road environment) are required for effective driving performance (Konstantopoulos, Chapman, & Crundall, 2010).

Attentional tunnelling appears to be influenced by numerous factors. Liu (2003) conducted a simulation study using a simulated HUD appearing at the bottom of a car windshield. The HUD displayed various information including current speed in digits, and road signs for response tasks. The author found that drivers attending to the HUD in low load driving conditions (where there were wider lanes, straighter curves, fewer oncoming vehicles and fewer roadside buildings which were further from the road edge) led to minimal variation in their lateral driving position. The author concluded this may be due to cognitive capture (McCann et al., 1993), and more specifically, that the participants were inefficient when switching attention between the HUD and the primary driving task, so they minimally corrected their lateral road position. However, in the higher driving workload condition (narrow lanes, more curves, more vehicles and more buildings) the tunnelling effect diminished, thereby demonstrating that the drivers were able to prioritise the driving task in certain situations, when driving demand was high. The tunnelling effects also appears to be influenced by display position (Foyle et al., 1993), this is discussed in greater detail within the section below (section 2.6).

Overall, the concern with tunnelling is that even though a driver's visual attention is towards the road environment, they may miss particular cues and hazards that are present within the road environment if they are entirely focused on the HUD or WSD.

2.3.2 Obscuration, Clutter and Legibility

HUD legibility, or the ease by which a HUD's imagery can be interpreted, is determined both by the HUD itself, and the environment in which it is used. Largely, for a display to have good basic legibility, it needs to display information large enough, bright enough and at a high enough resolution to suit the environment in which it is shown. For HUDs, results generally suggest that a high luminance is required (luminance contrast of 7:1) and font sizes may need to be larger than typical display recommendations in order to ensure text legibility (Wan & Tsimhoni, 2021). This concept is closely linked to obscuration and clutter which are discussed below.

Display clutter is a concern with any display. While not commonly defined, an interface may be considered 'cluttered' when it is too information dense, where the information is inefficiently organised, or where too much information is irrelevant (see Moacdieh & Sarter, 2015) and this results in an ineffective performance with the system from the user. Particularly important with HUDs is that an overabundance of stimuli can come from both the HUD and the environment which it overlays, making relevant information perceptibly difficult to discern. Ward and Parkes (1994) argued that background complexity (in the environment outside the vehicle) is a significant concern regarding the legibility and therefore the effectiveness of HUDs. This is a particularly prominent concern in road vehicles (compared to aircraft) due to the complexity of the external visual scene, which is also constantly changing. Ward, Parkes, and Crone (1995) found that background complexity did deteriorate HUD legibility, but positioning the HUD over the road minimised this effect. Horrey, Wickens and Alexander (2003) similarly caution that placing a HUD too close to a driver's forward view, and therefore over pertinent driving information, could lessen a driver's ability to respond to unexpected traffic events.

Considering obscuration: display elements on a HUD can be presented over the drivers' view of the road and, as a result they, have the potential to cover or disguise potentially important cues from the environment (Ward & Parkes, 1994) (see Figure 9). Currently, this limitation is not too prevalent within road vehicle HUDs due to their limited size. However, with the expansion of windshield displays, it may become a more prominent concern. The impact of this limitation is lessened by several design elements currently employed within HUDs. First, they typically present information or imagery in a translucent manner, so vital visual information should still be discernible through the display imagery (although this may impact display legibility). Furthermore, the level of translucency can also be adaptable (Kim et al., 2013). Kim et al., (2013) also found that participants preferred slimmer warning bar graphics over the thicker ones, largely due to concerns that the imagery would occlude their view. Thus, drivers appear aware of this concern, and ideal placement and clear design is likely more important than large graphics (Kim et al., 2013).

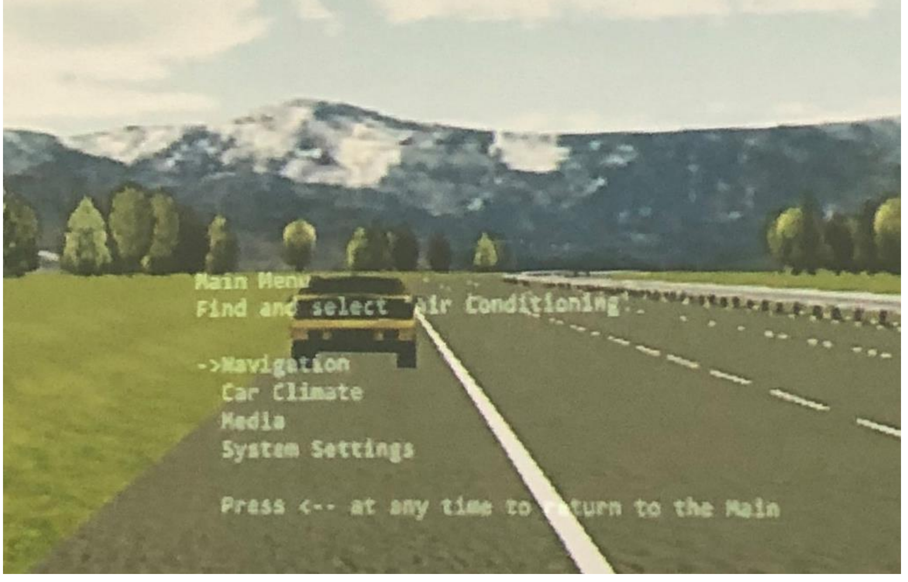

Figure 9. An example of simulated HUD text overlaying a simulated road environment. The words 'Find and select air conditioning' are over the rear of the yellow lead car demonstrating obscuration and legibility issues.

Oh, Ko and Ji (2016) more recently researched this topic of HUD legibility by asking participants to watch real-world footage of a car journey. Whilst watching, participants simultaneously completed a tracking task, which imitated the driving task, using a desktop steering wheel and pedals. Participants were also asked to complete a secondary task using a simulated HUD which appeared over the real-world footage. When cued, participants had to press the right or left button on the steering wheel in response to whether certain criteria were met (e.g., whether the vehicle speed displayed by the HUD was above the speed limit). Importantly the authors also manipulated what they referred to as 'superimposition' or the number of objects in the real-world which the simulated HUD overlayed. Oh, Ko and Ji, (2016) found that a greater number of overlayed objects resulted in greater glance durations to the simulated HUD. Thus, the background complexity likely impacted readability and consequently resulted in potentially unsafe driving behaviours (longer glances away from the road environment). The elderly participants (65+ years) were even more susceptible, with the higher background complexity resulting in poorer secondary task accuracy, longer task response times and longer glance durations than the younger participants. Furthermore, the HDD resulted in better response times and glance times than the HUD, with this sample of older participants, when there was a greater number of overlayed objects. Thus, their findings indicate that a HUD with poor legibility due to background conflict, will result in similar behavioural interaction as a HDD, in elderly populations. Despite this, the HUD resulted in better visual behaviours and response times than the HDD when there was lower background complexity, regardless of age. However, more work would be needed to confirm these findings. Since Oh, Ko and Ji, (2016) simulated a HUD over pre-recorded footage, additional distinguishing visual cues may be missing (e.g., depth, parallax), which may have resulted in poorer readability of the HUD beyond what would occur in real environments. Also, participants may have looked to the displays for longer than they would within a real vehicle or within a full driving simulation due to the lower perceived risk. Finally, text information may be particularly susceptible to this issue (Oh et al., 2016). In summary, the background environment over which the HUD is presented has the potential to interrupt a driver's interaction with it, however, more research is needed to appreciate the impact within real-world environments. Naturally, this is somewhat dependent on the positioning of the HUD or WSD which is discussed in greater detail below (section 2.4).

Additionally, new research on HUD design and legibility may negate these issues entirely. Research on both head-worn displays and HUDs has similarly concluded similarly that colours around the blue-end of the spectrum result in more robust legibility (Gattullo, Uva, Fiorentino, & Gabbard, 2015), and remain more recognisably the intended colour (Merenda et al., 2016). Furthermore, work has demonstrated that text, or similarly complex stimuli, is best displayed using a 'billboard' style, where the information is presented on a block which partially obscures the background, in order to maintain legibility (Gabbard, Swan, & Hix, 2006; Riegler, Riener, & Holzmann, 2019a). However, this would require careful design in order to not cause obscuration issues as described above. Technological developments may also mean these displays can improve a driver's view of their environment. For example, Stanton, Plant, Roberts, Allison and Howell (2020) found that a HUD aided pilot awareness in degraded visual environments due to weather conditions.

2.3.3 Novelty

In addition to the previously discussed concerns, it should be mentioned that for many drivers a HUD or WSD remains a new and unfamiliar method of display, and this element alone may impact responses to it. For example, Kiefer (1991) found that drivers sub-optimally glanced to the HUD more than was necessary and for long periods when they first encountered it. Ward and Parkes (1994) similarly argue that a human-centred approach must be taken to the introduction of new technologies in order to not risk distracting a driver's attention. Thus, research such as this is vital, and the beneficial use of HUDs may require familiarisation, training and adaptation in order to reduce this impact (Liu, 2003).

2.3.4 Conclusions

In summary, whilst HUDs and WSDs pose an exciting opportunity to convey visual information to drivers in a less detrimental manner than other vehicle displays (e.g., HDDs), they are still fallible. Concerns over, obscuration, tunnelling and legibility are particularly prominent throughout the area.

2.4 The Benefits of HUDs and WSDs

Despite the concerns highlighted above, other research has demonstrated that HUDs and WSDs have the potential to be beneficial when applied to road vehicles.

2.4.1 Driving Performance

Throughout driving display research, the use of HUDs has resulted in better driving performance than other visual display methods. Starting from early research, HUDs demonstrated potential, particularly in displaying driving relevant information. Sojourner and Antin (1990) conducted a video-based study in order to review the impact of a HUD digital speedometer on hazard detection. Participants viewed a video of a forward driving view and throughout had to respond to any navigational errors, speeding errors, or hazards (a pre-created stimuli which looked like a child's green ball). Thus, participants were required to monitor multiple forms of information, as occurs whilst driving. The speedometer varied across conditions: in half, a simulated HUD overlaid the video displaying a digital speedometer, in the other half, a more typical speedometer was available on a separate screen (a HDD). The authors found that participants responded significantly quicker to the hazard when using the HUD. Participant detection of navigation and speed errors were high across the two speedometer conditions. Thus, the HUD enabled participants to effectively monitor speed and navigation whilst also remaining highly vigilant to hazards. Liu (2003) conducted a simulation study using a simulated HUD appearing at the bottom of the windshield. The HUD displayed various information including current speed, and road signs. The author found that the road sign information on the HUD led to faster responses to the road environment than when the information was only presented on road signs in the environment. Similarly, Liu and Wen (2004) conducted a driving simulation study on commercial lorry drivers comparing the use of HUDs and HDDs. The two displays showed the same information in the same layout including logistic, navigational, road condition (warnings), vehicle condition and road sign information. However, participants demonstrated better speed control (lower speed variation) when using the HUD.

Research from driving simulators has also indicated that, when conducting non-driving related tasks (NDRTs) on a visual display, using a HUD is preferable to other display positions (i.e., HDDs). Smith et al., (2016) conducted a simulator study comparing several measures of driving performance whilst participants conducted a visual search task on a HUD and a HDD. The authors found that while the display task impacted both lateral and longitudinal driving performance, in comparison to a baseline drive, participants were able to better maintain their performance when the task was on the HUD rather than the HDD. Thus, the HDD was more commonly detrimental to driving performance.

Other work has suggested that the benefits of HUDs is in some way negligible, as some drivers may be able to protect or prioritise the task of driving and therefore allocate appropriate glances to the road regardless of any displays or tasks. For example, Horrey, Wickens and Alexander (2003) conducted a driving simulator study looking into glance behaviours and responses to hazards (e.g. other vehicles moving out of lane) with three displays (two HUDs and one HDD). Digits appeared on the displays every 10 to 20 seconds and the participants had to read them aloud as quickly as possible, though they were instructed to maintain safe driving. There were no differences in lane deviation when drivers were interacting with the different displays (either HUD or HDD), thereby indicating that neither form of display was better than the other in terms of basic driving performance, and that HDDs may not always be damaging to certain measures. Despite this finding, which contradicts the typical perspective on these displays, the other results do indicate that using a HUD may be advantageous. Firstly, whilst participants maintained their basic driving performance when using the HDD, this occurred at the expense of the secondary task (Horrey, Wickens & Alexander, 2003). In other words, completing the task with the HDD resulted in longer response and completion times. Thus, the HDD was not as effectively conveying information. Secondly, during the HDD tasks there were increased response times to hazards compared to the HUDs. Therefore, indicating that the HUDs enabled drivers to maintain better hazard detection. The authors discussed that hazard detection is likely a mostly foveal task, thus a HUD display position, which encourages foveal vision towards the road, enabled some time-sharing of visual resources (Horrey, Wickens & Alexander, 2003; Horrey & Wickens, 2004).

Ultimately, the previous work suggests that HUDs are not as detrimental to driving performance when displaying visual information in comparison to HDDs. Even if HDDs are not consistently detrimental to all drivers, they do to some extent encourage glances within the vehicle and away from the road. Generally, the differences in driving performance that are observed from the use of HUDs are considered beneficial due to the location of the display and the subsequent visual behaviour it allows or encourages. The following section (section 2.4.2) discusses the visual behaviour benefits of HUDs and WSDs, whilst the later section (section 2.6) discusses the precise positioning of HUDs and the impact this has in more depth.

2.4.2 Visual Behaviours

As discussed previously (Chapter 1) most early research on HUDs has been from the field of aviation research. However, the primary benefit of HUD and WSDs, whether implemented within a road vehicle or an aeroplane, is that it allows the communication of information to the driver or pilot, but it should not physically interfere with their ability to monitor the outside environment (Hagen et al., 2005).

Typically, eye-movement studies have indicated that HUDs can remedy issues with visual attention whilst driving, by keeping the driver's visual focus towards the road environment. Early work on displays (Hada, 1994) compared an instrument cluster, a centre console and a HUD. Median glance durations were influenced by display position, with the centre console leading to the highest median glance duration (0.82 seconds) whilst the HUD (0.79 seconds) and instrument cluster (0.77 seconds), which were positioned closer to the drivers forward view, resulted in lower median glance durations. Thus, the intrinsic positioning of HUDs may have the potential to improve visual driving behaviours in comparison to a HDD in the centre console. Ablaßmeier et al., (2007), explored eye-tracking within a real vehicle on a test track. A HUD showing vehicle status information (e.g., vehicle speed) was compared to more typical HDDs. The authors found that participants glanced to the HUD for shorter time periods than the HDD, particularly in more complex driving scenarios (such as when there was another vehicle present). This again suggests that HUDs are beneficial, as drivers did not tend to look at the HUD (and away from the road) for long periods of time. One explanation for the reduced time may be due to the driver not requiring much eye-movement transition time. The driver can quickly look to the HUD and back to the road again due to their proximity, whereas there would be a greater delay with HDDs which are located within the vehicle. Medenica, Kun, Paek, and Palinko (2011) similarly researched personal navigation devices within HUDs by comparing a HDD and a simulated AR WSD within a driving simulator (a line in the sky was placed within the simulated world for the participants to follow as a navigational aid). Medenica et al., (2011) found that percentage glance dwell time to the road was significantly lower when the HDD was active and was highest for the simulated AR WSD, thereby also suggesting the WSD allowed for more visual focus towards the road. In total, both studies suggest that HUDs/ WSDs should reduce eye-off-road time.

HUDs also appear to have demonstrable visual benefits for older populations or those with sight deficits. For example, Mourant, Tsai, Al-Shihabi and Jaeger (2001) compared younger and older drivers in a driving simulator, whilst they interacted with displays which showed digits. The participants had to report the digits displayed. Older drivers (58+ years) were less efficient at retrieving information from the displays and also displayed more severe driving performance issues (they spent more time out of lane and their average lane position error was greater). However, if the digits were superimposed on the simulated road scene (as a simulated HUD), the older drivers were more accurate at relaying the information and at maintaining vehicle control. The age differences may be due to biological factors: when a driver shifts their gaze between two elements (such as a HDD and the road ahead) their eyes are required to accommodate, meaning the muscles pull the lens into a new shape, so that the new focal distance is pulled into focus. A HUD, compared to a HDD, is more able to locate digital imagery at a similar depth to the road environment, thereby minimising the amount of eye-accommodation required. Effective eye-accommodation can be more difficult for older populations (Sun et al., 1988), so reducing the need for extreme eye-accommodation will likely make perceiving information easier, as indicated by Mourant et al's. (2001) study. Furthermore, minimising eye accommodation by using HUDs is a major advantage for all populations (Ablaßmeier et al., 2007), as it can reduce potential discomfort and fatigue that is sometimes caused by adjusting focal depth (Gabbard, Mehra, & Swan, 2019) and viewing 3D elements (Lambooij, Ijsselsteijn, Fortuin, & Heynderickx, 2009). See section 2.6.5 for further research on display depth.

More recent work on expansive WSDs has shown similarly positive visual behaviours when presenting AR imagery. Zhang, Yang, Zhang, Zhang, and Sun (2021) conducted a driving simulation study using a simulated AR WSD which highlighted particular environmental elements such as pedestrians, lane markings, vehicles, road signs and it displayed arrows on the road to indicate upcoming navigational directions. The authors found that drivers spent less time looking to the environmental elements when they were highlighted by the display than when the display imagery was not present. The authors concluded from this that the display aided the quick perception of these environmental elements. Furthermore, the drivers also allocated more attention to the front visual field when the display was active. The authors concluded that with the WSD, drivers were more able to effectively allocate their attention. However, the increased focus on the front visual field could also be indicative of tunnelling (see section 2.3.1), but this is difficult to decipher.

Overall, the work presented here demonstrates that the characteristics of HUDs have the potential to improve upon the visual behaviours of drivers when compared to HDDs. However, much of the information presented by the HUDs in the research in this section likely only required a quick glance to comprehend (e.g., they displayed vehicle speed). Other work has suggested that comprehending more complex information or tasks may lead to different visual behaviours to those discussed above. For example, the previously mentioned study by Smith et al., (2016) also compared the visual behaviour of drivers completing a text visual search task on a HDD and a HUD. The authors found the HUD resulted in what would generally be considered less desirable visual behaviours (longer glances). This finding is supported by more recent work such as Hensch et al., (2020), who also found that a HUD resulted in significantly longer eyes-on-display times than a HDD during partially automated driving. However, regardless of glance behaviour, Smith et al., (2016) found that participants actually maintained a better driving performance with the HUD compared to the HDD and completed the tasks quicker. Thus, whilst drivers may perform visual behaviours with a HUD which are typically considered undesirable, this may not necessarily impact driving performance as would be expected due to the fundamentally different and unique attributes of HUDs. This study is discussed in greater depth below when considering the assessment and recommendations concerning HUDs (section 2.5).

2.4.3 Task Performance

In addition to the previously discussed benefits of HUDs, drivers also appear to respond to and complete the tasks presented on these displays faster than HDDs. This effect was present within many of the previously discussed studies. For example, Smith et al., (2016) found that participants completing the same visual search task on a HUD and on a HDD, completed the task faster with the HUD, and significantly so during high and medium levels of task complexity.

As discussed above Liu and Wen (2004) investigated commercial lorry drivers using HUDs and HDDs. Participants experienced the displays in both high and low load driving conditions, meaning there were variations in lane width, curves, the number of other vehicles and buildings in order to make the driving task more complex. One task required participants to respond to a warning signal presented on the display and the authors found that drivers were significantly faster when using the HUD regardless of driving complexity.

Smith, Streeter, Burnett and Gabbard (2015) compared visual search tasks on a HUD and a HDD. Participants had to find target letters in a grid, or in a continuous text format. No difference in driving response times were found between HDD and HUD, yet task performance was faster with the HUD compared to the HDD.

In summary, these studies indicate that the same task presented on a HUD and a HDD typically results in the HUD task being completed quicker.

2.4.4 Future Benefits

Whilst not a primary focus of the present thesis, other windshield display research is exploring the potential benefits of future technology to aid specific driving functions. For example Tönnis, Lange, and Klinker (2007) investigated the potential for an AR braking bar and drive path, where AR imagery highlights the lane boundaries, upcoming curves and potential stopping distances available to the driver. The results indicated that the augmented braking bar was preferable and supported driving performance without imposing additional mental workload.

Similarly, an on-road test track study was conducted using a HUD to inform drivers of potential pedestrian collisions (Kim, Anon, et al., 2016). The authors compared a baseline (no warning) and traditional warning (the word ‘brake’ appeared on the HUD) and a virtual shadow warning, which indicated to drivers the movement and location of the pedestrian. Whilst both warning systems resulted in better driving performances, the virtual shadow resulted in smoother braking in drivers presumably because it enabled the drivers to better determine the pedestrian’s location. However, two participants were excluded from the analysis because they ignored the HUD entirely. These participants self-reported that this was because they did not want to rely upon the display and instead believed in their own abilities to effectively detect participants. Thereby demonstrating the difficulties which can arise around the acceptance of novel technology.

Looking even further forward, these displays may have beneficial roles in increasingly automated vehicles. In SAE level 0-2 automated vehicles (which are currently present on the roads) there may be assistive features (e.g., adaptive cruise control) but the driver is still responsible for monitoring the driving environment, and therefore the same concerns around attentional demand are present (see J3016 SAE International, 2021). However, in future vehicles, drivers will likely be able to relinquish control of the vehicle's movements to the automated system. For SAE level 3 this is conditional, and the driver may need to regain control of the vehicle. However, for prospective higher levels (SAE level 4 and 5) highly automated driving may occur where the driver can fully engage with other activities within the vehicle, and in these instances windshield displays may have different roles and benefits (for full definitions of automated vehicles see J3016 SAE International, 2021). As a result, display research within this area is more focussed on NDRTs (such as entertainment and productivity features) and this is reflected in the research trends (Riegler et al., 2021). Within this context it may also be important to inform the users within the vehicle of the vehicle's upcoming behaviours in order to maintain comfort and trust (Dandekar, Mathis, Berger, & Pfleging, 2022). Equally, there is increasing focus on creating a positive user experiences when interacting with these displays (e.g., Riegler, Wintersberger, Riener, & Holzmann, 2019; Riegler, Riener, & Holzmann, 2022b). A windshield display could help during these use-cases. Future directions in this area are also discussed in section 7.7.

Overall, these topics are beyond the scope of this thesis. However, there are many prospective benefits windshield displays may pose once in-vehicle technology has advanced to those levels.

2.4.5 Conclusions

HUDs generally benefit as visual displays largely due to their location proximal to the driver's forward road view, but this is still dependent on thoughtful implementation to ensure that the common concerns regarding these displays do not prevail and disrupt driving.

2.5 Current Assessment Guidelines and Display Recommendations

The integration of visual displays within vehicles has naturally resulted in assessment criteria and guidelines in order to judge whether or not they are suitable for use within a vehicle given the safety concerns. The present section describes several of the current guidelines and assessment techniques used to ensure that in-vehicle displays are not too attentionally demanding, and how these relate to the present work.

2.5.1 Guidelines and Recommendations

First considering general recommendations for vehicle displays. These can incorporate both the characteristics of the display and the nature of the information systems they contain. All emphasise the need for vehicle displays to not interrupt effective and safe driving performance.

For example the Alliance of Automobile Manufactures (AAM, 2006; AAM, 2003) stated a range of principles over five sections which should be followed to ensure effective and safe vehicle displays. Sections one, two and four are particularly relevant to the topic of visual display demand, so are detailed here. The first section covers how displays are installed within the vehicle, including safely installing displays in a manner that does not obstruct a drivers view of the road or the vehicle's controls. This section also states that information on visual displays should be relevant to the driving task and that any particularly intensive information should be positioned close to the diver's forward sight line (AAM, 2003). This concept of information positioning is particularly pertinent to the current work and is discussed further below (section 2.6). The second section highlights principles relating to the presentation of information via visual displays. This includes the criteria: displays should not produce uncontrollable sounds, they should provide driving information which is timely and accurate, the form of the information should abide by industry standards, and finally, tasks should be completable using sequential glances. The fourth, and final section listed here, details system behaviour principles. Relevant to the present work are the statements which dictate that, visual information which is unnecessarily distracting (e.g., continuously moving images/text) should not be included; anything unsuitable to conduct whilst driving should be made inaccessible to the driver, and in the instance of any vehicle errors which could impact safety, the driver should be notified. Sections three and five consider system interaction methods and communication about the system (e.g., instructions) respectively, which are outside of the present work's focus and as such are not detailed here.

These principles were also adopted or modified by others making recommendations in the area, such as the National Highway Traffic Safety Administration (NHTSA 2012; NHTSA, 2010) who directly incorporated many of the AAM principles from sections one, two and four directly into their report. They also entirely excluded certain secondary tasks from being conducted whilst driving, since they are considered too demanding. These include text entry of more than 6 button presses, monitoring automatically scrolling text and watching video that is non-driving related. However, NHTSA also exclude many of the AAM principles regarding display installation, and display instructions, regarding them not appropriate for their specific guidelines (NHTSA, 2012).

The Japan Automobile Manufacturers Association (JAMA, 2004) also reiterates many of the principles stated by the organisations mentioned above, though has stricter specifics on what information can be presented. For example, they explicitly prohibit the use of video and scrolling text (like others) but also state that news updates, addresses, telephone numbers and hotel/restaurant information should not be available to the driver. They also state that a display should show no more than 31 characters at once, though argue that the value ‘120’ or unit ‘km’ would be considered one character, making the definition of ‘character ‘difficult to interpret.

Finally, the European guidelines (Commission of the European Communities, 2008) are also largely adapted from the previous recommendations. Relevant to the present thesis are the principles on information presentation which emphasise: the need for drivers to attain information quickly in brief glances, the displays to follow any international or national standards, produce no uncontrollable sounds, be accurate and timely, and prioritise safety relevant information. Also relevant are the principles on system behaviour which include criteria such as: restricting visual information which is likely to cause distractions, prevent the system from interfering with the primary task of driving, and inform the driver of any malfunctions which could impact safety.

Throughout these guidelines there is a primary intention that by following the recommendations the in-vehicle displays being developed will not interrupt the primary driving task. This is a sentiment that of course applies to HUDs and WSDs as well, however, these recommendations were often written with more traditional HDDs in mind. Some more specific recommendations regarding HUDs/WSDs are being developed from current research.

2.5.1.1 HUD/ WSD Guidelines and Recommendations

Ablaßmeier et al., (2007) conducted some field studies in order to investigate glance behaviours when looking to HUDs which displayed basic driving related information such as vehicle speed. The authors found that when presenting four icons it took participants an average of 4.9 seconds to comprehend all the information, and longer on roads containing curves. As a result, the authors recommend presenting no more than around four new items at a time on a HUD in order to not encourage detrimental glance behaviour. Similarly, Burnett and Donkor (2012) suggest that up to five or six symbols may be used depending on other design elements. Park and Im (2020) also suggest that fewer than six symbols should be used based on subjective workload measures. However, as with the JAMA (2004) recommendations on characters, deciding what exactly constitutes one icon can quickly become complicated in interface design.

Variance in legibility on HUDs and WSDs (see section 2.3.2) means that researchers have recommended larger text and images for windshield displays than on HDDs. Haeuslschmid, Forster, Vierheilig, Buschek and Butz (2017) found that stimuli sizes needed to be greater at the periphery than in central locations, ideally being larger than 0.8 degrees of the visual area for effective detection and response. Wan and Tsimhoni (2021) conducted a study specifically investigating ideal luminance and text size for HUDs. They argue that text presented with HUDs needs to be double the minimum text size used for other standard vehicle displays in order to maintain legibility.

Others have focused on recommendations for how to prioritise information within a HUD or WSD context. Haeuslschmid, Shou, O'Donovan, Burnett and Butz, (2016) began creating a design space to support the development of windshield applications, which specifically considers the locations of different driving related information. For example, ambient information such as current time, date or weather would be best suited at the top edge of the windscreen whilst crash warnings would suit being positioned 2.5 degrees above the driver's line of sight. Therefore, adding more specificity over previous recommendations simply stating a principle such as *"Information with higher safety relevance should be given higher priority"* (Commission of the European Communities, 2008).

Finally, NHTSA (2016) also released further design recommendations specifically for HUDs. The report emphasises that current HUDs should be used to present safety critical situations to the driver, or relevant navigation information. It lays out several guidelines, some examples include: driving related information should be prioritised and that no reference to other displays should be needed for interpretations and any use of indicators which regularly change in value should be limited. It also specifies some positioning recommendations which are surmised below (section 2.6).

2.5.2 Assessment of Vehicle Displays

Beyond these general recommendations, there has also been specific assessment criteria developed in order to evaluate whether certain in-vehicle systems are too demanding. Commonly, the evaluation of displays is conducted based on visual behaviours, since eyes-off-road time is indicative of demand and resulting driving performance deterioration (Green, 1999c).

One of the most prominent guidelines is Green's (1999b, 1999a) 15 second rule, which was conducted as preliminary work towards some standards: SAE J2364 and SAE J2365 (SAE International, 1998; SAE International, 1999). The 15 second rule focuses on the assessment of in-vehicle visual-manual devices aiming to aid navigation. The rule states that a task (such as selecting a destination) should take no more than 15 seconds for a driver to complete. Although, the background and justification of this rule has been detailed (Green, 1999a; Green, 1999b; Green 1999c) there a still several elements that require appraisal. First, the ideal measure of visual demand for an in-vehicle system is considered to be eyes-off-road time (Green, 1999c), rather than task time as used by this guideline. However, eye-off-road time was considered too costly as a measure during the rule’s development (Green, 1999a). Instead, task time was determined to be an appropriate measure as it is highly correlated with eyes-off-road time, whilst being easy to obtain and apply without specialist knowledge (Green, 1999c). Green (1999c) comments that whilst increasing eyes-off-road time clearly correlates with increase crash probability, there is no point of dramatic change in this relationship which would indicate an ideal threshold or cut-off point. As a result, the selection of 15 seconds as a limit, was the result of collating several sources (see Green, 1999a). This process, while it may be valid, is difficult to inspect or replicate. Since the development of this assessment approach, newer research has also shown that it may be inadequate. Green (1999a) commented that if a task took less than 15 seconds to complete whilst static (e.g., within a parked vehicle) it would pass the assessment and be considered safe to use whilst driving. Yet, subsequent work has found minimal correlation between this test conducted in static and dynamic environments (NHTSA, 2012). Thus, static tests are unlikely to inform how appropriate the device is for use whilst driving and overall, this test is now inappropriate.

The AAM (2003) constructed another prevalent set of assessment guidelines on in-vehicle displays. AAM specify that visual-manual tasks with a display should generally not incur glance durations of longer than 2 seconds, and that glance durations in total should not exceed 20 seconds. The authors defined this criterion by referring to the task of radio tuning. Radio tuning has been long been discussed when evaluating distraction within the literature, since there is ample data to compare to (e.g. Stutts, Reinfurt, Staplin, & Rodgman, 2001). Furthermore, it is representative of typical in-vehicle tasks and their complexities. As a result, it is commonly considered as a comparison or a reference visual-manual task that drivers do whilst driving and is socially accepted to not be too detrimental to basic driving performance.

JAMA (2004) similarly used time thresholds as indication of demand in the evaluation of displays. However, like their general guidelines, these were more strict than previous approaches, arguing that a driver should take no more than 8 seconds of total looking time to complete a task with a display.

Perhaps the most prevalent guidelines on visual demand, also use radio tuning as an analogy: the National Highway Traffic Safety Administration (NHTSA) guidelines (NHTSA, 2012). To develop these guidelines NHTSA reviewed pervious work on visual demand and in-vehicle displays (e.g. AAM, 2003;Green, 1999a; Green, 1999b) and internal experimentations. NHTSA (2012) justifies the creation of new guidelines by aiming to incorporate new research, make guidelines applicable to more vehicles and devices, as well as, improving on the assessment options. They argue that the drivers should be able to complete any non-driving-related visual-manual tasks in less than 2 second sequential glances that add up to no more than 12 seconds in total. NHTSA (2012) reached the 12 second value based on performance in a radio tuning task. By inspecting the distribution of performance times, they established that the 85th percentiles' performance time was 11.3 seconds, thereby making 12 seconds a more appropriate comparison threshold. Equally, the 2 second glance time was confirmed by this test as appropriate, since the mean glance duration to the radio ranged from 1.1 to 1.7 seconds. The authors emphasise that the eyes-off-road time should be monitored, rather than just time towards the device, in order to account for eye-tracking inaccuracies during testing.

To evaluate whether a device or display meets any of this criteria (NHTSA, 2010; AAM, 2003; JAMA,2004) the guidelines generally specify two methods. The first, the glance test, uses eye-tracking and monitors participants driving a simulated vehicle within a highway environment whilst interacting with the device or display that is being tested. NHTSA (2012) are particularly meticulous in describing the procedures and equipment required. For example, they enumerate the characteristics of the required driving simulator, the distribution of participant ages and acceptance criteria. For this test they specify that ~85% of participants (21 out of 24), should have no more than 15% of their mean glances exceed the 2 second eyes-off-road glance time. This is to account for the distribution of individual differences to the 85th percentile. Equally, their total eyes off road time should not exceed 12 seconds. AAM (2003) and JAMA (2004) more simply suggest that the total time a driver looks at the display should not exceed their criteria times (see above) when eye-tracking.

The second evaluation method is the occlusion procedure. Occlusion goggles are worn by the participant which incorporate mechanical or digital shutters that block the participants' sight. NHTSA (2012) suggest a shutter open time of 1.5 seconds and a closed time of 1 second, so that the goggles rapidly open and close to mimic a driver glancing to and from a display. As the driver does not begin with their eyes towards the road during the procedure, 0.5 seconds was subtracted from the 2 second glance recommendation, to account for the time a driver would normally take to transition their vision to and from the road environment. Within a stationary vehicle simulator, or mock-up, the participant should complete a task with the device being tested, with the limited vision provided by the occlusion goggles. If they are able to complete the task with these restrictions, the task is considered to be not too visually demanding. Similarly, AAM (2003) suggest an opening time of 1.5 seconds followed by 1 seconds of closed time (also to imitate a drivers' glance patterns whilst driving) and that there should be a total of no more than 20 seconds of open time. JAMA (2004) also indicates that same open and close times should be used during their evaluation. However, they also state their criteria time of 8 seconds should be reduced to 7.5 seconds when using the occlusion procedure.

In summary, work within the area of display assessment has typically evaluated visual demand by measuring the length of time a driver's eyes are located off the road or towards the display. A summary off the assessment criteria is presented in Figure 10.

Perhaps most prevalent and rigorous are the NHTSA guidelines. However, they may have faults. For instance, Broström, Bengtsson and Aust (2016) demonstrated that individual differences in glance strategies between participants could determine whether a device passes or fails the NHTSA glance test. Furthermore, the simple road environment which is suggested within the assessment may encourage longer glances to the display because there is lower perceived risk from drivers (Fuller, 2005).

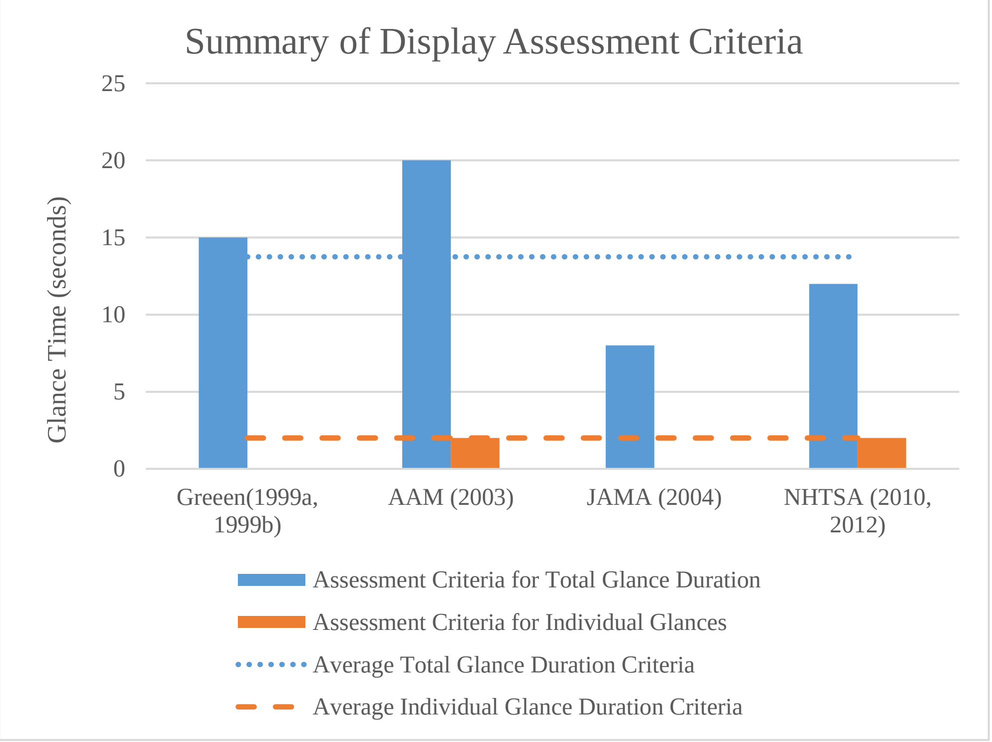

Figure 10. A chart summary of the display assessment criteria.

2.5.2.1 The Assessment of HUDs

Regarding the evaluation of HUDs specifically, NHTSA updated guidelines to address portable and aftermarket devices (NHTSA, 2013). Although, these guidelines mention HUDs specifically, they merely refer back to the methods and criteria already described (section 2.5.2) in order to evaluate them. Thus, they indicate that the same criteria and methods should be used to evaluate HUDs. However, there is evidence to suggest they are not sufficient for evaluating HUD interfaces. First, the work conducted to establish the time thresholds has commonly been done via comparisons to tuning a radio (AAM, 2003; NHTSA, 2010). Radios, and many other in-vehicle displays, are typically opaque and are located on the centre console, meaning that drivers are required to look into the vehicle to interact with them. In contrast, HUDs are located closer to the driver's view of the road environment or even over it, on a translucent surface. As a result, the transition time for driver to look at the display and back to the road is likely to be greatly reduced. Additionally, the length of time spent looking towards a HUD (and not to road) may be less detrimental due to drivers being able to better use their peripheral vision. With other displays the driver is looking into the vehicle, making it unlikely they will be able to monitor the road environment whilst also looking towards the display.

Furthermore, whilst eye-tracking devices may be usable to assess HUDs, the use of occlusion goggles (see section 2.5.2) may not be as appropriate. Occlusion goggles completely block the participants' view in an attempt to mimic the effect of looking between the road and at a HDD. However, when using a HUD a driver should retain some vision of the external road environment, particularly through their peripheral vision. Therefore, simulating looking at HUD by entirely blocking all vision is likely not suitable.

More recent research into the task of tuning a radio (Lee, Lee, Bärgman, Lee, & Reimer, 2018) which many of the assessments are based on, has indicated that it is a highly dangerous task to conduct whilst driving, creating between a 2.85-5 times increased crash risk compared uninterrupted driving. This suggests it should not be used as a reference task to suggest acceptable demand.

Finally, Smith, Gabbard and Conley (2016) conducted a study specifically evaluating a HDD and a HUD using the eye-glance method outlined by NHTSA (2012). The displays showed lines of pseudo-text, which were made of characters and spaces. The participants had to identify a letter that appeared twice in a row, then search for that letter in the next section of text, and verbally state the number of times it appeared. Based on the results of the NHTSA (2012) eye glance test, the HDD performed better than the HUD. Since a sufficient number of participants completed the low complexity task on HDD within the 2 second glance duration criteria and the

12 second total criteria. All other combinations of conditions would have not met the NHTSA guidelines. Therefore, according to this method of evaluation, the HDD should be considered the least demanding display. However, the other results clearly indicated that this was not the case. Based on driving performance (both lateral and longitudinal) the HDD had a more negative effect. Furthermore, participants completed the medium and high complexity tasks with the HUD significantly more quickly than with the HDD. Overall, this indicates that, rather than the HDD being less visually demanding, the methods and criteria used to evaluate the HUD were not appropriate; they did not demonstrate the full picture. Thus, current methods of evaluating vehicle displays are not effectively applicable to HUDs.

2.5.3 Conclusions

Overall, the current display assessments, whilst broadly applying to HUDs and WSDs, do not always incorporate the specific nature of HUDs or WSDs into their foundation. In order to achieve this, a greater appreciation of the demand these displays incur is required. Hence, this thesis is intended to start developing the knowledge required, which in future work may then progress towards to creating new assessment criteria and recommendations. Possible future developments within this area, are also discussed in section 7.7).

Many of the principles discussed within this section (section 2.5) also include criteria on the ideal positioning of in-vehicle displays, though naturally these are often not applicable to HUDs or WSDs specifically. The next section reviews display positioning as a more direct focus.

2.6 The Location of Vehicle Displays

The influence of a display on a driver will depend upon its location, which is particularly prominent within the current work since a HUD or a WSD has the potential to present imagery anywhere on a windshield.

The ideal positioning of displays within a vehicle is complicated by ‘the eccentricity effect’ (Carrasco, Evert, Chang, & Katz, 1995). The best visual acuity is achieved when images are projected onto the fovea of a person’s eye, meaning targets are best identified when they are located in the centre of a person’s vision. The eccentricity effect is the phenomena which occurs as a target increases its distance away from this location. As the distance increases, the angle away from the centre of their vision, or eccentricity, also increases (see Figure 11). Increasing retinal eccentricity results in increased reaction times and errors in detecting targets (Carrasco et al., 1995). Typically, to counteract this effect observers will move their eyes towards a target so that it becomes focused on their fovea. Within the context of vehicle displays, this means a drivers' focal vision may be on the display whilst their ambient or peripheral vision is used to maintain their driving performance, or vice versa (see section 2.2.2.1). As the angular separation between the two tasks increases (between the display and the road ahead) performance is likely to degrade (Bhise & Rockwell, 1971).

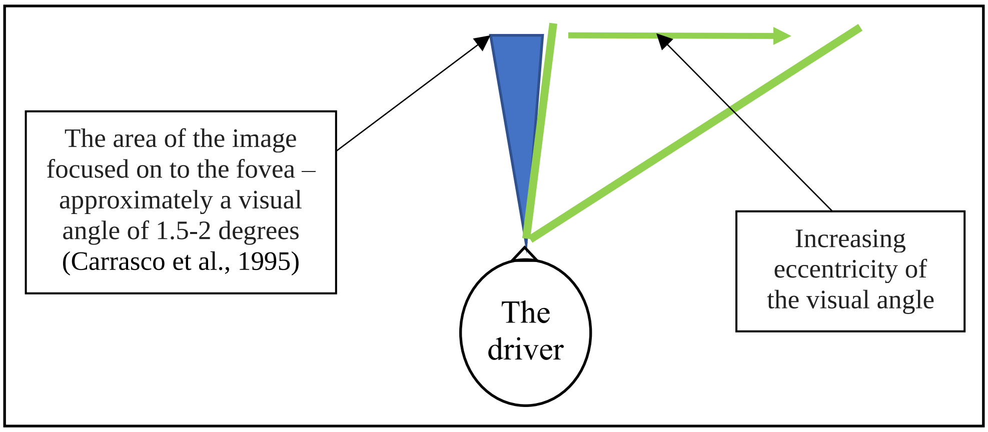

Figure 11. A top-down diagram illustrating visual angle and eccentricity.

Drivers typically focus on a point around 4-7 degrees below the horizon in order to effectively steer the vehicle (Land & Horwood, 1995). Thus, a driver's task performance with any display at a location distant from this is likely to be poorer (Carrasco et al., 1995), indicating that placing displays close to the focal point could be ideal. However, there are several clear issues with this positioning due to the driving context; if the display is close to the typical focus point, a display could obscure vital elements of the road environment and cause a deterioration in driving performance. Equally, presenting information in this location may risk distracting the driver. Thus, the discussion on ideal positioning of displays has long been debated.

2.6.1 Guidelines on Vehicle Display Positions and Locations

Some guidelines comment upon ideal display locations, which often emphasise the importance of placing visual displays close to a driver's forward view of the road. For example, Green, Levison, Paelke and Serafin (1994) state within their guidelines for visual displays "*Place commonly used displays, or those that are critical, close to the line of sight.*" The AAM recommend that HDDs should be positioned at an eccentricity of less than 30 degrees, whilst up to 40 degrees laterally would be acceptable (AAM, 2003). The Japan Automobile Manufacturers Association (JAMA) also produced recommendations that in-vehicle displays should conform to the driver's field of view, ideally within 30 degrees for passenger cars (JAMA, 2008).

Normark and Gärling (2011) conducted an extensive review of current guidelines on displays within vehicles. The review incorporated several elements including locations, colours, characters and graphics. Their review of display locations demonstrates persistent evidence that priority information should be presented as close as possible to the driver's typical line of sight.

2.6.2 Opaque Display Positions

Research on opaque displays has thoroughly evaluated the ideal positioning of screens throughout cars. Lamble, Laakso and Summala (1999) investigated the impact of a visual display at 10 locations within a vehicle interior and exterior, using two instrumented vehicles on a closed section of road. Participants had to report digits shown on the displays verbally. This task required constant visual attention, thereby ensuring participants were looking towards the display for the entire task duration. Simultaneously, participants had to brake if they detected that the lead car, which they were following, decelerated. Displays positioned at 17 degrees eccentricity (above the dashboard, to the right of the steering wheel) resulted in drivers performing best at the vehicle detection task. Curiously, when the display was positioned at the instrument cluster behind the steering wheel (21 degrees) the average time to respond to the lead vehicle was increased by 0.4 seconds, thereby suggesting that the instrument cluster is not in an ideal display location despite being consistently present within road vehicles. Notably, differences were evident between the upper and lower visual fields. Detection was faster when the display was positioned at the rear-view mirror (upper visual field, 42 degrees eccentricity) compared to the centre of the steering wheel (lower visual field) despite the steering wheel being at a lower eccentricity (34 degrees). One explanation for this is the varying attentional resolution of human sight. Research has established that the attentional resolution of the lower visual field is greater (He, Cavanagh, & Intriligator, 1996). Therefore, if displays are positioned higher, a driver may be able to respond more quickly to road environment stimuli since it'll appear in their lower visual field. Equally, when a display is positioned low within a driver's visual field they are required to use their upper visual field for hazard detection, which has lower attentional resolution (He et al., 1996).

Summala, Lamble, and Laakso (1998) used an almost identical set-up to Lamble, Laakso, and Summala (1999) although they enabled the leading vehicle to use their brake lights when decelerating. Their results corroborate Lamble, Laakso, and Summala's (1999) findings. A display placed in the lower windscreen at 16 degrees eccentricity resulted in the best lead car detection performance compared to a display at the instrument panel (27 degrees) or on the centre console (50 degrees). The authors concluded that, at least during daylight, brake lights on a decelerating car did little or nothing to aid detection when the driver is looking to the car's interior due to a HDD. Summala, Neiminen and Punto (1996) conducted a similar study comparing novices (< 5000km total driving experience) and experienced drivers (>30,000km total experience) again using an alternating digit task which required constant visual attention. Driving performance degraded when the display was positioned beyond 23 degrees for novices, but only became impaired for experienced drivers once the display was positioned at 38 degrees. Thus, highly peripheral vision may be sufficient for more experienced drivers to maintain vehicle control, but not for novices. In relation to display locations, this may indicate that novice drivers require displays to be presented at lower eccentricities to prevent lane deviation compared to experienced drivers. Thus, HUDs, which can be positioned at low eccentricities, may be particularly beneficial for novices.

Wittmann et al. (2006) conducted a simulator study with a particular focus on display location and vertical and horizontal eccentricity by testing seven display conditions. The authors manipulated the task difficulty on the display and measured the resulting driving performance. Participants were either free to allocate their attention as they wanted or were encouraged to focus on the display. Throughout, participants had to detect a red light at the end of the bonnet and respond with a brake press. Whilst participants had complete control over their attention, the duration of lane departures remained the same across the different display conditions. Thus, the participants appeared to protect the driving task and maintain vehicle control regardless of display tasks (as discussed by Horrey & Wickens, 2004). However, when attention was forcefully directed towards the display, position 'F' (which was at

5.2-5.7 degrees eccentricity and positioned similarly to a current HUD) resulted in significantly shorter reaction times to the red light compared to all other conditions. Thus, the display in this condition was determined to be best, followed by displays above the centre console and speedometer. Through collating their many variables, the authors determined that vertical eccentricity was more damaging (to duration of lane departure and reaction time to red light on bonnet) than horizontal. In total, the results support the concept that displays with lower eccentricity are best for the detection of changes in the environment and for maintaining basic vehicle control. Although, similarly to other studies (e.g., Lamble, Laakso & Summala, 1999) the displays tested were opaque, not translucent like HUDs. The authors also comment that more work is needed to define the exact points of safety and non-safety. They pose that 25-30 degrees could be considered a border area, which falls in line with the guidelines reported above (section 2.6.1). Interestingly, the authors also examined a display positioned at the rear-view mirror (43.3-50.6 degrees eccentricity). This rear-view mirror position resulted in significantly slower responses than the ‘F’ position (which imitated a typical HUD location) and several of the other display positions. Again suggesting that, even the sources of visual information which are accepted within driving may not be optimally placed.

Finally, Svärd, Bärgman, and Victor, (2021) conducted a driving simulation study investigating high eccentricity opaque displays (12, 40 and 60 degrees eccentricity). Each display showed a visual detection task (*“In which area did the circle change shape?”)* which participants had to respond to whilst driving. Participants also had to respond to critical event, where a lead vehicle suddenly braked ahead of them. The authors found that driver glance response times to the critical event was not related to display position. However, brake response time was longest when drivers were engaged with the higher eccentricity displays. Therefore, the high eccentricity display location degraded the participants’ ability to promptly respond to the critical event.

Although windshield displays vary greatly from the opaque displays used by the above studies, their work remains highly informative on how visual attention may vary based on display location. Particularly important are their findings on display eccentricity, upper and lower visual fields, and driving experience.

2.6.3 HUD and WSD Positions

To be located in a good position, HUD or WSD imagery needs to effectively communicate information to the driver, and it also needs to minimally detrimentally impact the primary task of driving. An early review specifically on HUDs within cars indicated that they are best positioned around 6 to 10 degrees below the driver's line of sight (Gish & Staplin, 1995). Generally, other work on HUDs since then has supported this approximation. For example, NHTSA (2016) recommend that a HUD should be positioned 5 degrees to the right (for left-hand drive vehicles) and 5 degrees below the centre line of a driver's view. Thus, they also consider and ideal positions to be above the steering wheel and below the driver's view of the horizon. This approximate visual area is indicated within a driving simulator (used within studies 3 and 4) below (Figure 12).

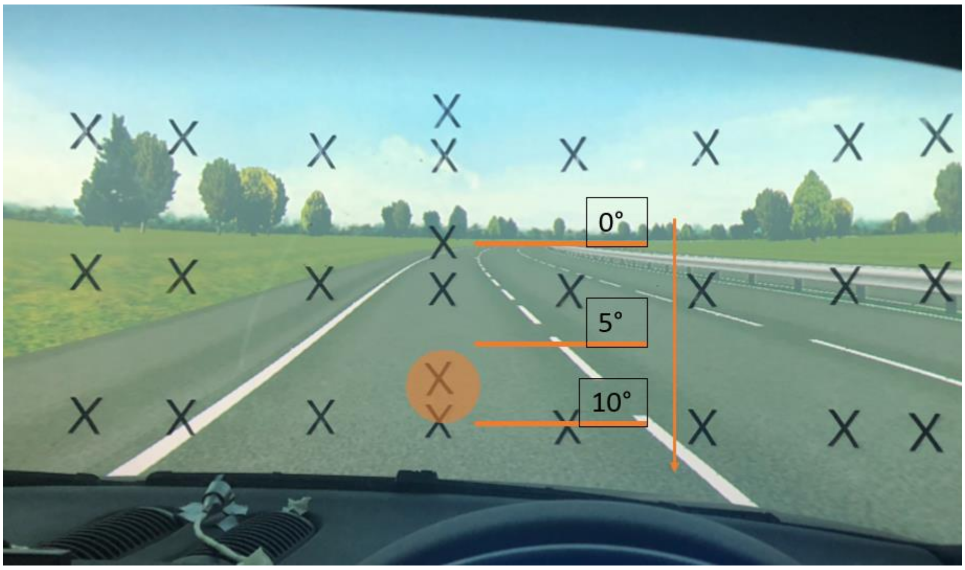

Figure 12. A visualisation of vertical eccentricity applied to the driving simulator used in studies 3 and 4. The horizon line, as created by the simulated road environment, is considered the drivers' default line of sight (0 degrees) and further downward eccentricities are marked. The orange circle indicates approximately where a vertically offset 6–10-degree HUD would be located. The 'X's were used as measurement markers.

Throughout the research area, HUD locations have been investigated using various measures. Wantanabe, Yoo, Tsimhoni and Green (1999) looked at the implementation of warning symbols on a HUD in a driving simulator. Drivers responded to the HUD by pressing a button whenever a warning triangle appear in one of 15 HUD locations. Drivers were also asked to press a button whenever they detected other pre-determined road events (e.g., a passing car). The fastest responses to the HUD occurred when it was positioned 5 degrees to the right of centre within the simulated environment. Similarly, Tsimhoni et al., (2000) investigated reading and detection tasks displayed on simulated HUDs at different positions. In a reading condition, text would appear on the HUD showing a typically female or male name. Participants would press a finger switch (either on their left or right hand) to indicate whether a male or female gendered name was present. Alternatively, in a detection task, participants pressed the finger switch simply when they saw that text appeared on the HUD. The HUD imagery was simulated through an acrylic sheet reflecting LCD screens from the floor in front of the driving simulator cab. The authors found that HUD position had no impact on the detection task time, however reading response time increased with eccentricity. It was fastest at 0 degrees (1100 milliseconds) and longer at 10 degrees either side (1250 milliseconds). Driving performance varied little as a result of HUD location. This is most likely because the only locations which were investigated were all located around the drivers' forward view.

Also looking at response times to displays, the previously reviewed study by Liu (2003) used a HUD and found that participants responded faster when attending to the HUD rather than the road signs within the environment. The HUD was positioned centrally, about 6 to 12 degrees below the driver's horizontal visual line, further corroborating the consensus that imagery close to the drivers' view is ideal for fast communication of information to the driver.

Research looking specifically at a driver's ability to detect on road events, typically also show HUDs to be most advantageous at lower eccentricities. Flannagan and Harrison (1994) used projectors to simulate a road task and HUDs. The HUDs showed an overhead map image to which participants had to verbally respond either 'left' or 'right' depending on the direction of the final turn in order to reach their destination. Additionally, participants also had to verbally respond if a pedestrian was present in the driving environment. The authors found that vertically increasing eccentricity of the HUD imagery (at 4, 9 and 15 degrees) significantly increased the error rate in the detection of pedestrians at the side of the road. However, the error rate remained very low regardless, and driving performance was not conducted or measured. The authors also looked into the impact of age and found that older drivers

(60-74 years) made more errors than the younger drivers (18-25 years) on both the HUD and pedestrian detection tasks.

Overall, the work reviewed so far broadly indicates that placing display imagery close the driver's line of sight (at a low eccentricity) would be ideal. However, the research also indicates that ideal display positioning is more ambiguous than this (see below), since it is susceptible to the concerns which were discussed previously (section 2.3).

Previously reviewed within this chapter is the work of Horrey, Wickens and Alexander (2003), who also explored display eccentricity with two HUD positions (on the horizon and 7 degrees below the horizon) and a HDD at the centre console (38 degrees eccentricity). Overall, the authors concluded that driving performance (lane deviation) was not influenced by display position, but that HUDs resulted in faster hazard detection than the HDDs. The authors speculated that hazard detection requires more focal vision, and the drivers could have used this focal vision whilst engaging with the HUDs due to their windshield location. As a result, drivers were better at hazard detection when using the HUDs. However, the authors also found that the two HUD positions did not significantly diverge in their support of this behaviour. This may be because the two HUD positions were not sufficiently separate from one another to cause an observable effect. Plus, only minimal ambient or peripheral vision was required to maintain basic vehicle control, so display position was less impactful (Horrey & Wickens, 2004). Additionally, and importantly to the discussion of HUD positioning, the authors (Horrey, Wickens and Alexander, 2003) did find differences in crash occurrences. Whilst not prevalent enough for a statistical analysis, the authors found that when the HUD was positioned over the horizon, three collisions occurred (out of three opportunities). This is clear evidence that the concerns over obscuration and tunnelling, as discussed previously (section 2.3), are a prevalent danger and that a central, low eccentricity windshield display location may not always be ideal.

Also looking at HUD imagery positioning, Smith (2018) conducted a driving simulation study investigating the vertical eccentricity of HUDs by positioning an after-market HUD in three central areas down from the vehicle cab's ceiling. Participants were required to complete visual search tasks on the display whilst maintain safe vehicle control. Visual attention to the display (total glance duration) was highest during HUD-middle condition (which overlaid a lead vehicle and the horizon). However, this did not result in any improved visual search task performance on the display. During this condition participants also placed themselves further right within the lane compared to other display conditions, presumably to prevent the central image from fully obscuring their view of the road. The higher HUD position (over the sky) resulted in better longitudinal vehicle control though the effect was small. The lowest HUD position (over the road) resulted in the highest task accuracy without any detriment to task completion time, participant self-reported confidence, or glance duration. Thus, the lowest position was deemed the best suited for more accurate completion of the display task. Overall, this makes the precise impact of vertical eccentricity unclear, but indicates that highly centralised displays, over the drivers' view, are often inappropriate.

HUD positioning work from aviation also reveals that display positioning is more complex than a simple eccentricity effect (Carrasco et al., 1995). Foyle et al., (1993) investigated the positioning of altitude information on a HUD during a terrain tracking task for pilots. Three HUD locations were investigated: with one over the pilot's view of the terrain, and the other two at increasing eccentricity diagonally away from the terrain. The authors found that positioning the altitude information close to the terrain path information resulted in inefficient attentional switching between the two information sources. When the HUD was closest to the terrain following task, the following task performance was poorer. The authors concluded that this was due to the previously discussed tunnelling effects (section 2.3.1). These results contradict some previous work on location-based attention which suggests two sources of information may be processed if they are proximate (Foyle et al, 1993). Foyle, Dowell and Hooey (2001) concluded that placing HUD symbology at least 8 degrees away from the window scene information would be beneficial in the prevention of tunnelling. The authors also discussed that this finding may be due to the reduced clutter in the background of the 8 degree HUD since it overlayed the sky (Dowell, Foyle, Hooey, & Williams, 2002). This work on HUDs overlaying ground paths, could be equated to HUDs overlaying a driver's typical line of sight just below the horizon (Land & Horwood, 1995), so this 8 degree recommendation may be worth consideration within the automotive context too.

Häuslschmid, Osterwald, Lang and Butz (2015) conducted a driving simulation study where they placed widget boards (displaying non-driving related information e.g., weather, and social media) at an eccentricity of 15 to 30 degrees in order to better appreciate the result of placing HUD or WSD imagery in more peripheral locations and away from the typical 'ideal' locations. Whilst they did not directly compare different WSD imagery positioning (but rather display techniques), the authors did find that the participants maintained basic vehicle control with the peripheral WSD present but, were slower in performing lane changes when prompted by overhead gantries. Thus, supporting the work by Horrey and Wickens (2004); the participants appeared able to protect the driving task and maintain vehicle control with their ambient vison. More recently, responses to and the detection of text and imagery across windscreen locations was examined by Haeuslschmid, Forster, Vierheilig, Buschek and Butz (2017) in a simulator study with a simulated WSD. Participants were asked to press a button in response to target shape stimuli. Across 17 positions with a relatively wide eccentricity (35 degrees x 15 degrees). The authors found that the shape stimuli needed to be a greater size at the periphery, than in central locations, for effective detection and response (ideally, they needed to be larger than 0.8 degrees of the visual area). Slightly smaller sizes were possible in central areas. The authors did not provide a definitive recommendation on text size but considered that it should be larger than the value mentioned above. The authors' focus was largely on response times, not driving performance, but it was found that the HUD detection task resulted in no variance in optimal lane changing.

In summary, whilst much work emphasises the importance of low eccentricity with vehicle displays, drivers appear able to effectively interact with imagery when it is placed somewhat away from the drivers' forward view (though some adaptation in stimuli size may be needed). Furthermore, very low eccentricity imagery (very close to the driver's forward view) is liable to suffer from the obscuration, legibility issues and tunnelling concerns, as previously highlighted (section 2.3).

2.6.4 Driver Preference on Display Position

Drivers have been shown to prefer HUDs over other vehicle displays (HDDs)(e.g., Smith, Streeter, Burnett, & Gabbard, 2015) . However, others have investigated more specifically the exact preferred positions of HUD imagery. For example, Tsimhoni, Green and Wantanabe (2001) found that central locations within 5 degrees eccentricity were most likely to be preferred by participants.

Tretten, Gärling, Nilsson and Larsson (2011) conducted an unusual study where participants were able to use their own cars, on-road, to examine their preference for HUD locations in comparison to a HDD. Both displays showed vehicle speed. The majority of participants preferred the HUD to be positioned in front of them, just below the line of sight. A large portion (30%) preferred a position 5-6 degrees below line of sign and centrally. Their work demonstrates that, despite unfamiliarity, HUDs are considered easy to use by drivers, in addition to the potential attention benefits. Along a similar perspective, Johansson (2022) researched the design and aesthetics of AR HUDs with a focus on driver preference. The authors found that a lower positioning was preferable in order to reduce obscuration. Yet the authors also found that most of the responses were highly conflicting, and they concluded that many design elements would be liked by some and disliked by others regardless. Park, Cho, Baek and Park (2015) found that a HUD showing a scrolling list was preferred in the bottom/middle/left of the windscreen (nearest the driver). Olaverri-Monreal, Lehsing, Trubswetter, Schepp and Bengler (2013) questioned drivers on where to locate information within a vehicle with various displays as an option, including a HUD. They found drivers were inclined to locate information and features based on experiences, meaning where it currently resides within a vehicle. Drivers tended to locate important driving information close to the forward view whilst less-necessary information was positioned further away, such as where menus and settings are commonly located now (e.g., in the centre console).

Looking towards future automated vehicles, there has been work around where certain information could appear on a windshield display according to driver preference and expectations. Riegler, Riener and Holzmann (2022a) conducted a driving simulator study replicating a SAE level 3 automated vehicle (see SAE International, 2021). Within these vehicles drivers are ideally expected to retain some awareness of the driving environment, even when the vehicle is in control, because the automation is conditional. The vehicle may issue a take-over request (TOR), and the driver must safely regain control of the vehicle. During the study participants experienced two baseline arrangements of a windshield display. One where the content was contained within one window (one rectangular area) and a second where there were multiple windows. Most of the content was located around the centre of windshield (off-centre to the driver's forward view). For the other conditions participants were asked to personalise these windshield display arrangements by changing the window dimensions, position, transparency and tilt in 3D space. During the simulated drives the participants were prompted to complete a TOR and regain control of the vehicle. The authors found that participants performed the take-over task significantly faster when the content was arranged within one window and the participant had personalised how it was arranged (compared to the baseline multi-window arrangement). Therefore, the findings indicate that the participants had some basic understanding of how to position the display's content so that it did not detrimentally impact the take-over task. Thus, while automated vehicles are beyond the scope of this thesis, an alternative approach to windshield display positioning in autonomous vehicles may be to listen to driver preference and enable users to somewhat personalise content locations.

Similarly, Riegler (2022), and Riegler, Wintersberger, Riener and Holzmann (2019) used a 3D environment and let participants create content windows (rectangles) on the windshield, and then determine what content they should contain. When the vehicle's automation was specified as conditional (meaning the driver may need to take-over the vehicle controls, see SAE level 3, SAE International, 2021) the participants were less inclined to put content in their direct line of sight. They also rated warnings or dashboard information as highly important. In contrast, for higher automation (see SAE level 5, SAE International, 2021) participants expressed a greater preference for entertainment or social media related content and appeared less concern about obscuring their forward road view.

Overall, drivers appear at least somewhat aware of how displays and interfaces may impact their driving and as such prefer those which are less likely to impede their performance. Therefore, driver preference provides an interesting perspective on perceived display demand, and as such, is monitored within the work conducted here. Furthermore, the above studies highlight that although safety is paramount, cars are commercial items. As a result, there is design pressure from vehicle manufacturers and their customers which makes driver preference a highly valued factor within vehicle design.

2.6.5 HUD and WSD Focal Depth

Not directly applicable to the current work, but analogous, is the concept of image depth in the presentation of HUDs and WSDs. Typical HDDs require drivers to look at displays within the vehicle and then revert to looking outside the vehicle. When drivers look between visual elements at different focal depths (such as within or outside the vehicle) the lens within the eye needs to readjust to ensure the image is focused, this process is called accommodation (Toates, 1972). HDDs will generally require a large accommodation from drivers since the visual targets are commonly at very different focal depths and large eye-movements and head movements may be needed. A regular need to accommodate to different focal depths may lead to visual fatigue and discomfort (Gabbard et al., 2019), which are highly undesirable in a driving context. Thus, HUDs and WSDs, which are able to present imagery at different distances from the driver, may be advantageous.

Due to the technological methods of presenting information on current vehicle HUDs, images or text is typically presented to the driver at a focal depth of ~2-3 metres (Smith, Doutcheva, Gabbard, & Burnett, 2015; Bark, Tran, Fujimura, & Ng-Thow-Hing, 2014). Thus, the display imagery from the perspective of the driver will often appear to float at the forward end of the vehicle’s bonnet. However, there is the potential to present imagery at other depths (Tasaki, Moriya, Hotta, Sasaki, & Okumura, 2013; Lisle, Tanous, Kim, Gabbard, & Bowman, 2018).

Gish and Staplin (1995) discuss ideal focal depth within their early review. Based on their summation, they recommend that HUD imagery should be located approximately 2.5 to 4 metres away, from the driver’s perspective. The authors comment that optical infinity (around 6 metres) or distances shorter than 2.5 metres should not be used as they would not meet the needs of all drivers, particularly older drivers who may experience visual deterioration.

In contrast, Charissis and Naef (2007) used virtual reality (VR) equipment to investigate preference and comfort with HUD depth during motorway driving. They examined several simulated weather conditions to ascertain any difference due to varying visibility. Distances of 0.7 metres were considered uncomfortable by all, with many reporting difficulties focusing on the HUD or other vehicles on the road. Positioning it at 2.5 metres from the driver was considered a great improvement to all but one participant, and 5 metres was also well accepted. Overall, participants preferred the greater focal depths as it most consistently aligned with environmental stimuli and reduced eye strain. Although, this was less pronounced in the very low visibility conditions where participants had a greater reliance on the HUD. However, it is important to consider that if greater focal depths are used, stimuli may need to be presented larger in order to maintain legibility (Gabbard et al., 2019).

In more recent developments, depth is primarily discussed in relation to AR HUD or WSD imagery. Since AR imagery is intended to augment the real-world environment, the use of varying depths can further communicate information and prioritise it to the driver in relation to the real-world environment. Haeuslschmid and Shou (2015) discussed these concepts within a highly advanced concept vehicle. The authors concluded there should be 4 display zones which are visualised below (Figure 13). The authors propose, first a privacy display zone (70-95cm), where personal social messages may be displayed. Secondly a vehicular display zone (95-120cm) where vehicle identifying information is located, such as indicators and fuel tank levels. Next the social display zone (120-360 cm) where information regarding other people, such as the passengers, may be located. Finally, the public display zone (360cm-infinity) where information about the external environment should be located, such as navigation hints or headway to other vehicles. Thus, the authors argue that information displayed on a windshield display should vary its depth depending upon its task. For many of the HUDs which are currently within vehicles, the vehicular or public zones would be most prevalent. Similarly, Riegler, Riener and Holzmann (2022a) investigated WSDs by using VR and allowing participants to personalise where they located windshield display imagery. The authors found that participants often used the continuous depth available to them. Furthermore, they also used the depth available within the WSD to tilt content toward themselves. Whilst these forms of display are beyond the scope of this research, they do provide an alternate perspective on the location of displays within vehicles for the future, and these approaches may pose as a future benefit to HUDs and WSDs once more readily available.

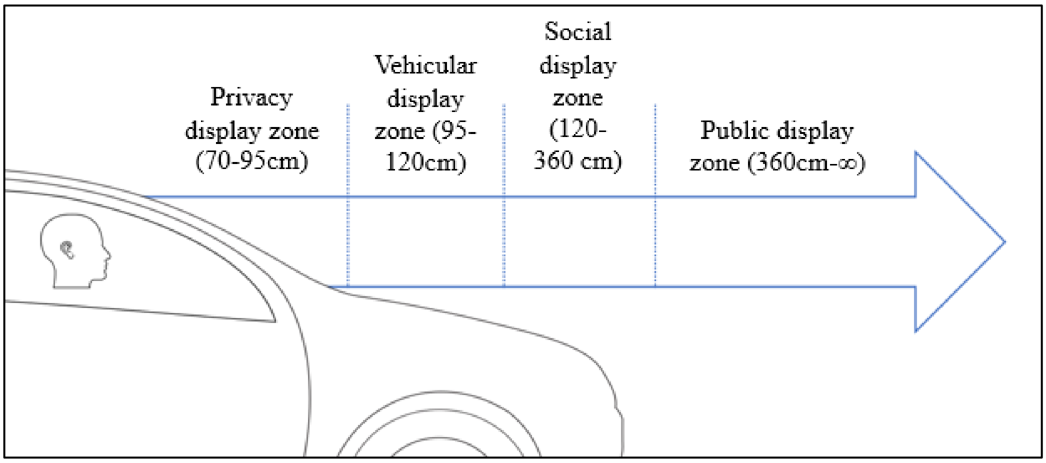

Figure 13. An estimated visualisation of display zones as conceptualised by Haeuslschmid and Shou (2015).

Overall, whilst discussions on HUD depth began as a simple question of where an ideal depth location is (similarly to overall display location), various display depths are likely to become usable with continuing technological development and so isolating one ideal depth may not be important to fixate on. As touched upon above, this opportunity may pose further benefits for HUDs and WSDs. As discussed by Haeuslschmid and Shou (2015), there is the added ability to prioritise information to the driver, and make information proximate to real-world relevant elements in 3D space. Additionally, variable depth may enable drivers to set their own preferences (Riegler, Riener, & Holzmann, 2022a) or set the depth to a range which is comfortable to their specific eye accommodation.

In summary, optimal HUD depth may require more research to clarify, but is likely to greatly depend on the driver's age (Gish & Staplin, 1995) due to eye accommodation. Currently, Gish and Staplin's (1995) approximation of 2.4-4 metres remains a commonly followed recommendation. Although, work indicates locating HUD imagery at a further distance may also be acceptable (Charissis & Naef, 2007). While focal depth is not a factor of the present thesis, it is a characteristic of HUDs and WSDs which needs to be appreciated and will likely benefit from further study in the future.

2.6.6 Conclusions

Overall, the ideal positioning of any vehicle display may vary slightly depending on the exact task the driver needs to complete with the display (Tsimhoni, Watanabe, Green & Friedman, 2000) the age of the driver (Flannagan & Harrison,

1994) or their experience (Summala, Neiminen & Punto, 1996). Lower eccentricities are more commonly praised for their benefits. However, locating HUD or WSD imagery directly over a driver's line of sight is not recommended, since it appears to amplify common issues with these displays (section 2.3). Some research indicates that a driver's lateral visual field may be more robust than the vertical, therefore, displaying information at a high lateral eccentricity on a WSD may be less problematic than if it were displayed at high vertical eccentricity (Wittmann et al., 2006).

2.7 Chapter Summary and Conclusions

The development of windshield displays has been motivated by their many potential benefits (see section 2.4). However, there are still several concerns around them which need to be addressed (see section 2.3), and as a result there are many questions which need answering to fully understand how to implement these displays in a way which consistently assists rather than detracts.

Assessing display demand is commonly conducted using several methods and approaches which are discussed above (section 2.2). In particular, glance behaviours and driving performance are considered indicative of display demand. As a result, visual behaviours are commonly used in assessment approaches to ascertain whether a display, or interface, is suitable for in-vehicle use (see review above in section 2.5). However, currently there is limited work on visual behaviour-based guidelines or assessments which are specifically appropriate for HUDs or WSDs; those which are current suggested are unsuitable mostly due to their development which focused on other displays such as HDDs (section 2.5.2.1). Hence this work aims to start filling this knowledge gap by developing approaches and assessing display demand, whilst specifically focusing on windshield displays.

Also reviewed here, in addition to the benefits and concerns of the displays, are the intertwined discussions on display locations. Broadly the research indicates that displays may measure as less distracting when they are close to the drivers forward view of the road, because it enables drivers to keep their eyes towards the road environment and better maintain vehicle control. Thus, windshield displays benefit because they can be positioned very close to the drivers' forward view. However, display stimuli close the drivers' view also increases the likelihood of issues such as obscuration, legibility, clutter and attentional tunnelling (section 2.3). Due to this precise balance, the exact location of HUD or WSD imagery also appears to be highly influential in the demand it imposes on a driver. According to the current literature, the ideal positioning of a HUD would likely be off-centre, but still close to a drivers' view of the road ahead in order to balance these concerns. However, the continuing development of display technology (see section 1.3.1) indicates that HUDs and WSDs are likely to get larger. With the expansion of these displays into full WSDs, a better understanding of display location across a whole windshield is needed rather than just a focusing on an 'ideal position'. Thus far, there has been minimal work actually looking into wide display locations and their resulting demand on the driver (see section 2.6.3). Therefore, to address this uncertainty within the literature, this work investigates how demand varies with location across the entire windshield.

The next chapter describes the first driving simulation study conducted to address the thesis research questions.

3 Study 1: Exploring Interactions with Near-Future HUD and WSD Tasks

3.1 Chapter Introduction

An explorative study was conducted which aimed to further elucidate the tasks which may be presented on near-future HUDs and how drivers interact with them. Current in-vehicle displays manage large amounts of visual vehicle information and controls which require menu navigation and text reading in order to operate (Parkhurst, Conner, Ferraro, Navarro, & Mouloua, 2019; Strayer et al., 2017). Moving these operations to a HUD could encourage beneficial glance patterns out of the vehicle, rather than within the vehicle (Ablaßmeier et al., 2007).

There has been some preliminary work on menu navigation and text reading using HUDs. For example, textual lists presented on HUDs have shown to score better on mental load and satisfaction ratings than an auditory presentation or HDDs, without the expense of task efficiency which auditory methods can cause (Weinberg, Harsham, & Medenica, 2011). Focusing on the demand of menus and text on HUDs, Milicic and Lindberg (2009) found simple interactions on a HUD such as scrolling through text and adjusting analogue bars, to result in better lateral driving performance, faster responses to a peripheral detection tasks and lower subjective workload, than the same tasks on a HDD. However, the authors also found no difference in longitudinal driving measures. Furthermore, glance times to the HUD tended to be longer than to the same task on a screen in the centre console. The authors speculated this was due to the attractive HUD design. Angelini et al., (2016) used a basic HUD menu to show feedback information (e.g., song selection) whilst participants interacted using gestures or speech within vehicles. However, the focus was on the interaction methods rather than the display, so no analysis was conducted on this topic.

Looking more closely at text reading tasks on HUDs: Karvonen, Kujala, & Saariluoma (2006) used a text-based tutoring system presented as a HUD in a driving simulator. The added task of reading the text guidance messages did not appear to add a significantly detrimental load to participants, since the authors found that the system resulted in them performing fewer driver errors. However, more detailed driving measures may be required to reveal the true impact this reading had upon the participants. Some impact would be expected, since research with pseudo-text search tasks have demonstrated both degradation in driving performance and task accuracy (Smith, Streeter, et al., 2015). In a similar pseudo-text study Smith, Gabbard, Burnett and Doutcheva (2017) investigated the role of complexity by manipulating the number of lines of text. The authors found that HUDs appeared to be less demanding than HDDs with increasing task complexity. More recently, Hensch et al., (2020) found reading scrolling text on a HUD positioned below the road environment horizon, encouraged longer and a greater total of glances than a reference task during partially automated driving. However, the use of scrolling text likely makes the study somewhat ecologically invalid (see section 2.5) to current or near-future vehicles, since scrolling text is specifically not recommended (e.g., NHTSA, 2010) and automated driving was used. In summary, an ecologically valid text reading task on a HUD, in an un-automated vehicle, is still largely unexplored.

Evidently, further work is required to explore the demand these near-future tasks incur when presented on HUDs. Equally, more research is needed which better emulates realistic tasks with varying complexity to comprehend their full impact on driving performance and visual behaviours. Consequently, the research presented here investigates the likely implementation of text reading and hierarchical menus on HUDs with varying task complexity, and different interaction forms.

This study aimed to address RQ1 (see section 1.5) by investigating driving interactions with near-future HUD tasks, such as text reading and menu interaction.

Objectives: Determine how the complexity of near-future tasks influences simulated driving performance and visual behaviour.

Determine how the nature of near-future tasks (a text reading task or a manual interaction and search task within a menu) influences simulated driving performance and visual behaviour.

3.2 Methods

3.2.1 Participants

Twenty-six participants were recruited: 11 females (42.3%) and 15 males (57.7%). All participants were 18 years or older, the average age was 23.73 years

(Standard Deviation, SD = 4.88). All participants self-reported that they held a full driving licence and drove regularly. On average participants self-reported driving 8389 miles (~13500km) a year (SD= 4692) with the minimum being 3000 miles (4828km). Participants were asked not to volunteer if they were susceptible to severe motion sickness, migraines, epilepsy, dizziness, blurred vision, or were pregnant, to reduce the opportunity for simulation sickness.

To better comprehend the participants' perspectives, a questionnaire examined their previous experiences with in-vehicle displays and driving simulators (for results see Table 1). Overall, they indicate that all participants were experienced with interacting with some form of in-vehicle navigation device, and many were familiar with touch-screen interfaces specifically. However, few had experience with HUDs or driving simulators.

Table 1. Previous participant experiences with in-vehicle interfaces and driving simulators.

Questions	Number of Participants		
	Yes	No	Unsure
Does the car you typically drive include a display in the centre console?	10	15	1
Do you ever use a navigation device when driving?	26 (1 built-in, 25 portable)	0	0
Have you previously used a touch-screen device in a car?	23	3	0
Does the car you typically drive include a touch-screen device?	12 (4 built-in, 8 portable)	14	0
Have you previously used a head-up display or "HUD" in a car?	4	18	4
Have you previously driven a driving simulator?	6	20	0

3.2.2 Design

The study used a 2x3 within-subjects design with six main task conditions within a driving simulator. Participants experienced two HUD tasks (a text and a menu task), each with three levels of complexity. Within each condition, the participant experienced six iterations of the task; during half of the iterations, a lead vehicle braked during the task, which added to the difficulty of longitudinal vehicle control. Participants also performed a baseline drive along the same section of the simulated road environment. Dependent measures included questionnaire responses, eye-tracking, and data on driving performance from the simulation. Task performance was not analysed as it was not the focus of the study. Ethical approval was granted by the University of Nottingham Faculty of Engineering Ethics Committee, and the Virginia Polytechnic Institute and State University Institutional Review Board.

3.2.3 Materials

The study was conducted in a medium fidelity driving simulator at the Cogent laboratory at Virginia Polytechnic Institute and State University in the USA, which was constructed from a Mini Cooper and was left-hand drive (Figure 14).

Figure 14. The Cogent Lab driving simulator.

The road environment was created using MiniSim v.2.2. The scenario followed rural highways, which were from the in-built ‘Springfield’ map (Figure 15). The highway contained both curved and straight sections. The simulator recorded data on driving performance at 20Hz.

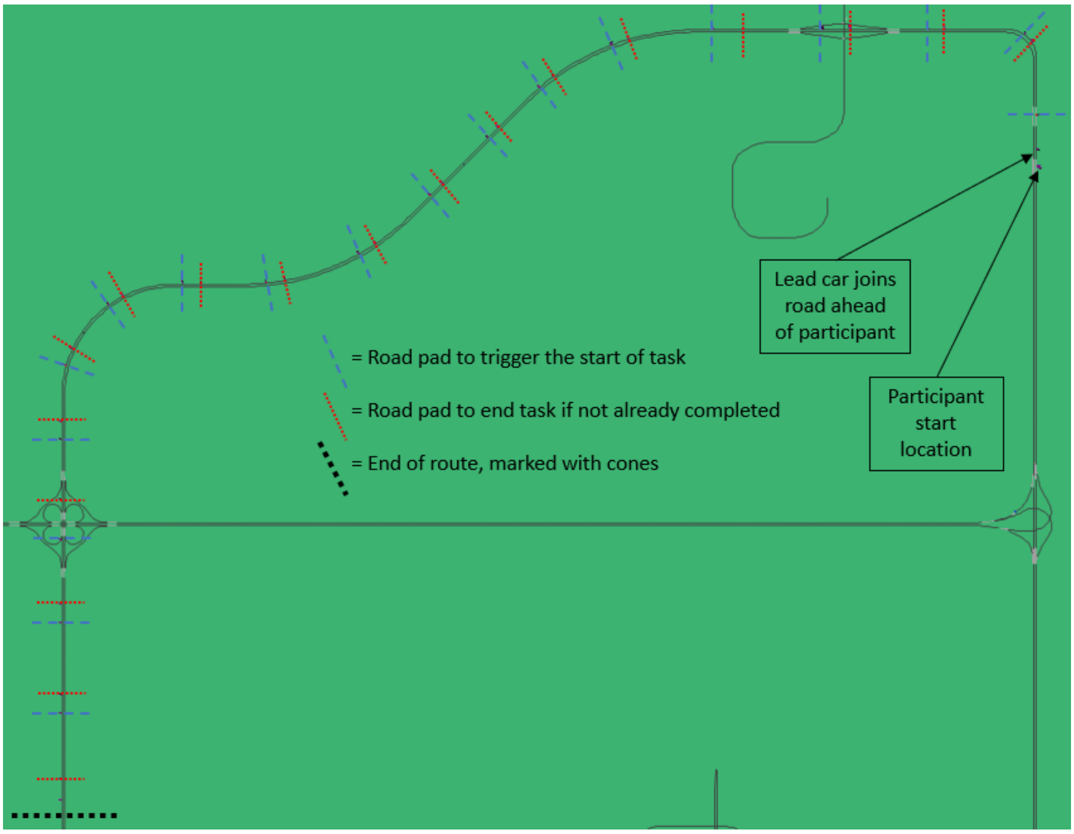

Figure 15. A map of the road environment used. The study used sections labelled as a 'interstate highway'. The route travelled by participants was approximately 13 miles long.

SMI eye-tracking glasses monitored the participants' eye behaviours (Figure 16). These also captured the driver's forward view of the simulation and the participants' verbal responses to the tasks.

Figure 16. The SMI eye-tracking glasses

A Pioneer Head- up Display was attached to the roof of the vehicle cab to display the HUD imagery. The combiner glass folded down in place of the drivers' sun visor. The HUD imagery lined up to a section of the simulated road environment just over the horizon (Figure 17).

Figure 17. (Left) The Pioneer HUD within the driving simulator, and (Right) the HUD's appearance from the drivers' seat perspective (displaying text).

The text stimuli which was used in all tasks (both text and menu tasks) was captured from real-world text conversations written by Enron employees on Blackberry devices around the year 2000 (Vertanen & Kristensson, 2011). Thus, the creators wrote on a QWERTY thumb keyboard without abbreviations. This ensured the tasks, particularly the text task, were ecologically valid.

Several pre-developed questionnaires were used during the procedure including: the Susceptibility to Driving Distraction Questionnaire (SDDQ) (Feng, Marulanda, & Donmez, 2014), a driving risk-attitude questionnaire (Iversen, 2004), and the Simulation Sickness Questionnaire (Kennedy et al., 1993). Participants completed the subsections two and three of the SDDQ, which covered attitudes and beliefs about voluntary distractions and susceptibility to involuntary distractions. Iversen's (2004) scale on risk attitude was included, but the scale on risk behaviour was not. Some scales were excluded due to time restraints and ethical concerns around asking participants about driving violations. Questionnaires were also created to ask participants about their driving background and how they felt about the HUD and tasks after the driving simulation. The consent form and recruitment adverts were produced on paper (Appendix B). All questionnaires were conducted using Qualtrics on a portable touch screen device (see Appendix B).

3.2.3.1 Tasks

The participants experienced two main drives. During one main drive, there would be a text task, during the other there would be a menu task. During each of these drives the HUD task was activated 18 times at specific points along the road, once the participants' vehicle, within the simulation, had reached certain points ('invisible road pads') along the route (see Figure 15). Out of these 18 tasks, 6 were low complexity, 6 were medium complexity, 6 were high complexity. During half of the tasks the lead car would brake, during the other half the lead car would stay at a constant speed. Half of the participants did the text task drive first; the other half completed the menu task first. The pattern of when the lead car braked, and which task complexity was shown, varied between drives according to two predetermined schedules which ensured equivalent patterns of vehicle behaviours. The participants were informed that the task had appeared on the HUD using an auditory cue which consisted of three quick beeps lasting roughly 1.5 seconds in total. Both of the tasks used text-based imagery and were created using java script, which was run by a separate PC. If a participant did not complete the task promptly, a road pad would trigger and close the task before the next one was prompted (see Figure 15).

3.2.3.1.1 Text task

During the text task, text messages from real world text conversations (Vertanen & Kristensson, 2011) would appear on the HUD. Participants had to read out loud the text messages as they appeared. The task finished when participants finished reading the message, and the experimenter pressed an external button (Figure 18). Thus, this task required cognitive and visual engagement from the participant but no manual interaction (see Figure 18).

Figure 18. (Left) The external button used by the experimenter to mark the end point of the text task. (Right) An example of a high complexity text task (18 words) on the Pioneer HUD over the simulated road environment.

There were 3 levels of complexity to the text task which was determined by the number of words which appeared and required reading. The low complexity task involved two words, the medium tasks contained ten words, and the highest complexity tasks were eighteen words long (Figure 18).

3.2.3.1.2 Menu task

The menu task was a visual-manual task which participants could interact with using either the left or right d-pad on the in-built Mini Copper steering wheel (see Figure 17). The up and down icon would allow the participants to move up and down between menu items, and the enter button would allow them to select an item and move further into the menu or make their final selection when they found their target.

Once the menu task triggered, the HUD displayed a target word for 2 seconds, which participants would have to remember and look for within the menu system. The target word then vanished, and the first level of the menu would appear (Figure 19). The menu was always 3 levels deep. The number of items at each level of the menu would vary between 3 and 5, depending on the complexity level (3– low, 4- medium, 5-high complexity). At the first menu level, the menu items contained grouped alphabetical segments (e.g., A – F, see Figure 19 and 20). Participants were required to select the menu item which would contain their target word according to alphabetical order. At the second menu level another array of items would again show grouped alphabetical segments but at a finer level, or individual letters (Figure 20). At the final menu level several words would appear (within the alphabetical range the participants had navigated to); participants had to select their target word from this list.

Figure 19. A mid-level complexity menu task displaying level 1 of the menu over the simulated road environment. The first item (A – F) is highlighted in blue to show the user's position in the menu.

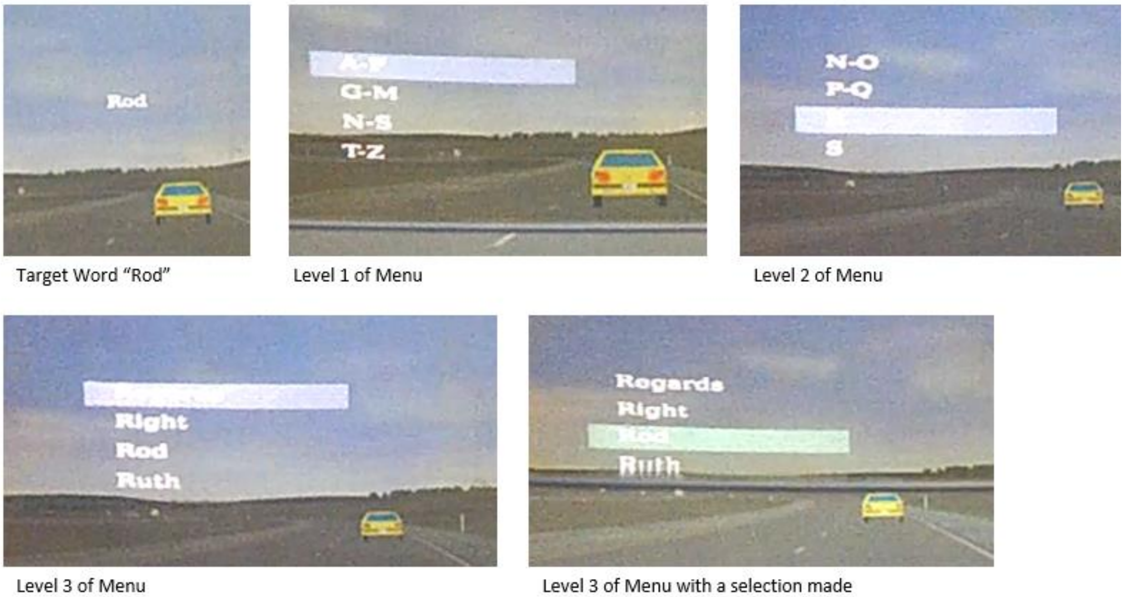

Figure 20. A full example of a menu interaction at mid-level complexity (each level has 4 items) taken from the forward-facing eye-tracking camera. The final selection is shown, with the selection highlighted in green.

As participants navigated the menu a blue highlighted aura over the text would indicate where they were in the menu. The highlighting aura would turn green when a selection was made (Figure 20). Once participants made a selection at the final level of the menu the end time was recorded, and the HUD imagery disappeared until the next task trigger point.

3.2.4 Procedure

After arriving at the Cogent Laboratory, participants were seated at a desk to read the information sheet and they were given the consent form to sign if they were happy to proceed. Next, participants completed several questionnaires on demographics, attitudes to driving risk (Iversen, 2004), susceptibility to distraction (Feng et al., 2014) and finally a Simulation Sickness Questionnaire (Kennedy et al., 1993) to monitor their well-being before entering the simulator.

Next, participants were asked to enter the driving simulator. Throughout the study participants were instructed to drive as they would on a real road. The Pioneer HUD was calibrated to them by displaying a rectangle both on the HUD and on the road environment projection area. Participants were asked to manually adjust the Pioneer HUD by tilting the combiner glass until the two rectangles lined up and the image was clear to them from a comfortable driving position. Participants then practiced driving the simualtor vehicle and each of the display tasks. Next, the eye-tracking glasses were fitted and calibrated to the participant. . Participants were asked to refrain from touching or moving the eye-tracking glasses after calibration to prevent tracking errors. Participants completed a short baseline drive, where the lead car was present and braked occasionally, which lasted around 5 mintues, in order to monitor each participants typical driving. Participants complete a Simulation Sickness Questionnaire after each drive (Kennedy et al., 1993) (Appendix A).

In all conditions the lead car travelled at roughly 60mph. If it was intended to brake, this behaviour was triggered by the same road pad trigger which also started the task (Figure 15). During braking, the lead car started at ~60mph (~96kmh) and slowed to ~25mph (40kmh) in approximately 6.5 seconds. While braking, the lead car's brake lights were simulated which illuminated in a red colour (see Figure 20).

Participants would then complete the two main task drives which each lasted about 15 minutes. During these drives participants completed the text tasks during one of them and the menu tasks during the other as described above (see section 3.2.3.1). Participants were encouraged to promptly complete the task once it appeared. If participants took too long, a road pad along the route would stop the task and remove it from the display. This occurred only during the menu task (13 instances across 5 participants).

After the drives in the simualtor, participants completed a post-trial questionnaire that assessed their perspective on the HUD tasks they completed. Finally, participants were asked to complete a post-trial consent form. This consent form ensured that any simulation sickness has subsided, that participants undertstood that they are asked not to drive for at least 30 mintutes after the study and that compensation for their time was received ($10). The full experimental procedure took around 1 hour and 30 minutes.

3.3 Results

3.3.1 Pre-developed Questionnaires

The results of the pre-developed questionnaires (Feng et al., 2014; Iversen, 2004) were evaluated to gain a better understanding of the participants' beliefs around driving risk and driving distraction. The median and mode are reported as measures of central tendency as is typically recommended for Likert scales (Sullivan & Artino, 2013).

First the SDDQ was evaluated, each Likert value was assigned a number which was then averaged for each section as originally described (Feng et al., 2014). The *“Attitudes and Beliefs about Voluntary Distraction”* section resulted in a median and mode score of 4 which indicates that drivers were typically in agreement with statements on voluntary distractions such as *“You think, it is alright for you to drive and adjust the settings of in-vehicle technology (e.g., radio channel or song selection)”.* The *“Susceptibility to Involuntary Distraction”* section resulted in a median score of 2, thereby indicating that the participants were generally in disagreement with involuntary distraction statements such as *“When driving, you find it distracting when you are listening to music”.* Further details on these questionnaires are in Appendix B. Overall, the participants generally believed that conducting activities such as chatting with passengers and interacting with in-vehicle systems is acceptable and that they were resilient to distractions such as passengers, music, and phone alerts.

Secondly, a 16 question scale on risk attitudes towards traffic safety (Iversen, 2004) was examined. The 5-point Likert scale was also numbered, and the average found (Table 2). A score of 3 indicated a response of ‘Neutral’, thus any lower indicates averaged disagreement and higher indicates averaged agreement.

Table 2. Average responses to risk attitudes towards traffic safety (Iversen, 2004)

Scale Item	Median	Mode	Corresponding Descriptions
1. “Many traffic rules must be ignored to ensure traffic flow”	2	2	“Disagree”
2. “It makes sense to exceed speed limits to get ahead of slow drivers”	4	4	“Agree”
3. “Traffic rules must be respected regardless of road and weather conditions”	3.5	4	“Agree”
4.”Speed limits are exceeded because they are too restrictive”	3	2	“Neutral” to “Disagree”
5. “It is acceptable to drive when traffic lights change from yellow to red”	2	2	“Disagree”
6. “Taking chances and breaking a few rules does not necessarily make bad drivers”	3	4	“Neutral” to “Agree”
7. “It is acceptable to take chances when no other people are involved”	3	2	“Neutral” to “Disagree”
8. “Traffic rules are often too complicated to be carried out”	2	2	“Disagree”
9. “If you are a good driver, it is acceptable to drive a little faster”	3	2	“Neutral” to “Disagree”
10. “When road conditions are good, and nobody is around, driving at 100mph is OK”	2	2	“Disagree”
11. “Punishments for speeding should be more restrictive”	3	2	“Neutral” to “Disagree”
12. “It's OK to ride with someone who speeds if that's the only way to get home at night”	3	3	“Neutral”
13. “It's OK to ride with someone who speeds if others do”	3	3	“Neutral”
14. “I don't want to risk my life and health by riding with an irresponsible driver“	4	4	“Agree”
15. “I would never drive after drinking alcohol”	5	5	“Strongly Agree”
16. “I would never ride with someone I knew has been drinking alcohol”	5	5	“Strongly Agree”

These results indicate that participants were averse to traffic violations and generally reported being risk-avoidant.

3.3.2 Participant Perception Questionnaire

After all the simulation drives participants were asked about their experiences with the HUD tasks.

The results, presented below (Table 3), suggest that the tasks which were used, were perceived to be ecologically valid as intended, since participants on average agreed that they were tasks they would typically perform in a car. Furthermore, participants generally considered the HUD to be safe to use whilst driving.

The question on HUD usage demonstrated that participants were middling in their response, indicating that they would “sometimes” use such a system. The questions on environment perception revealed that participants were confident in their awareness of the lead car braking, but more uncertain on their awareness of their general surroundings and the level of control they had (Table 3).

Table 3. Participant perception questionnaire description and results.

Question	Number of Points on Likert Scale	Description of Points Range	Median	Mode	Corresponding Description
Would you consider the Head-up Display (HUD) you experienced is "safe to use" whilst driving?	7	“Strongly Disagree” to “Strongly Agree”	5	5	“Somewhat Agree”
Do you agree that the tasks you completed are like the tasks you typically perform whilst in a car?	7	“Strongly Disagree” to “Strongly Agree”	5	5	“Somewhat Agree”
Would you commonly use the HUD you experience?	5	“Not at all” to “All the time”	3	3	“Sometimes”
Did you feel in control whilst using the HUD?	5	“Not at all” to “All the time”	3	3	“Sometimes”
Did you feel aware of your surroundings?	5	“Not at all” to “All the time”	3	3	“Sometimes”
To what degree did you feel aware of the lead car when it braked?	5	“Not at all” to “All the time”	4	4	“Often”

3.3.3 Driving Performance Analysis

Throughout this thesis before statistical tests were used, the assumptions were checked, and changes were made to the analysis approach where required. Details on the specific approaches are detailed where necessary. Where a Bonferroni correction is used, the p-value is adjusted when it is reported unless stated otherwise.

To analyse the driving simulation data for this study, the data was annotated with when the tasks on the HUD were active: from the line after the road pad was activated and the task was triggered, to when the task was marked as complete by the experimenter (in the text task) or when the final selection was made by the participant and the menu disappeared (in the menu task). During the main task drives 18 task events occurred during each drive. For the baseline drives, the average length of the tasks was found (13 seconds) and a sample of data was taken at the same road locations (from the trigger road pads) for the average length of a task. In total, six baseline samples from the baseline drive (in half the lead car braked) were selected to be visually compared to the experimental conditions.

At some points the driving simulator malfunctioned and stopped detecting the lead vehicle without any outward indication, and therefore, dependent measures which were reliant on this information, could not be calculated. These periods only lasted for a couple of seconds (e.g., participant 24, fourth menu task: 1.55 seconds of missing data; participant 8, fifteenth menu task: 2.65 seconds of missing data). This predominantly impacted the menu task at the second level of complexity (participants: 8, 9, 11, 13, 14, 23 and 25) and the menu task at the lowest complexity (participant 24). However, this only impacted one task event out of the eighteen. The short duration and multiple iterations of the tasks should prevent this error from influencing the results. The simulation data from participant 15 during the text conditions were corrupted. Participant 22 did not complete the text tasks and part of the menu tasks as the procedure was stopped due to simulation sickness.

3.3.3.1 Standard Deviation of Lane Position (SDLP)

The data during each task type (text or menu) and complexity condition was sampled, and the SDLP was calculated for each participant across iterations.

A Shapiro-wilk test indicated that the data was normally distributed across conditions (p>0.05) and a visual inspection of the plots confirmed. An inspection of the studentised residuals indicated there were no outliers (>±3). A two-way repeated measures ANOVA compared task type, task complexity and any interaction between them. Mauchly's test indicated that sphericity was not violated (χ^2 (2)=3.648, p=0.161) for the interaction. However, the interaction was not significant (F(2, 46)=0.779, p=0.465). The main effect of task type was also not significant (F(1,23)=1.567, p=0.223).

The main effect of complexity was examined, sphericity was not violated ($\chi 2$(2)=3.286, p=0.193), and it was significant (F(1,23)=8.301, p=0.001). A pairwise comparison with a Bonferroni correction showed significant differences between complexity levels low and mid (p=0.017) and between complexity levels mid and high (p=0.006). Therefore, task type had no impact on SDLP, but task complexity resulted in varying SDLP, with the highest values seen in the mid-level complexity (see Figure 21).

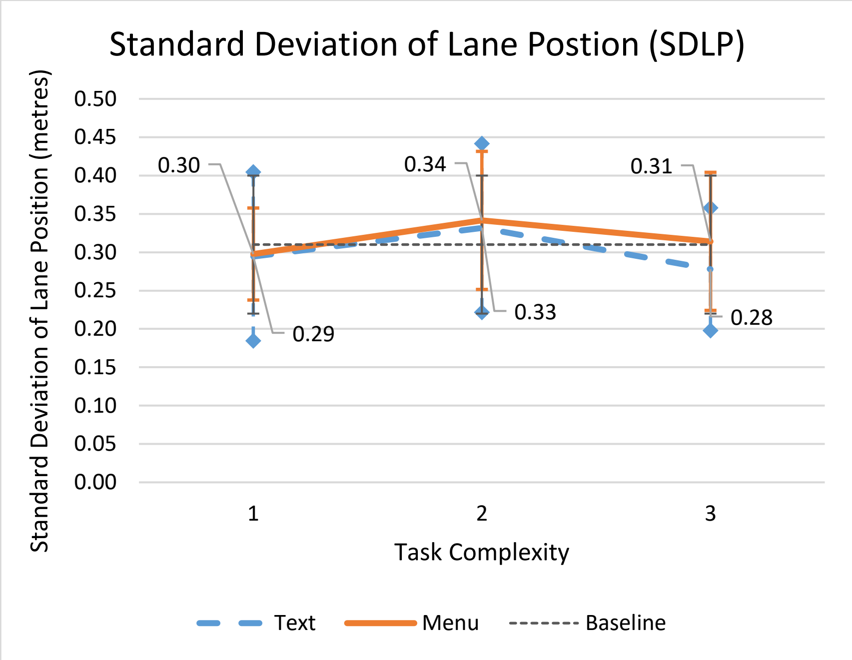

Figure 21. Standard Deviation of Lane Position (SDLP) across task type and complexity. Displaying mean and standard deviation (SD) error bars.

To summarise, complexity significantly influenced SDLP, with mid-level complexity resulting in significantly higher values than the lowest and highest complexity tasks (Figure 21).

3.3.3.2 *Sum of Steering Reversals*

For the purpose of this analysis a steering reversal was calculated as a change in steering angle from clockwise to anticlockwise (or anticlockwise to clockwise) of larger than 3 degrees per second (De Groot, De Winter, García, Mulder, & Wieringa, 2011; Theeuwes, Alferdinck, & Perel, 2002).

The sum of the steering reversals was calculated for each condition meaning the measure was non-parametric frequency data. Thus, a Friedman test was conducted to compare the 6 conditions, which was found to be significant ($\chi^2(5)=96.201$, $p<0.001$). A pairwise comparison with a Bonferroni correction was used to make 15 comparisons. It located several significant differences between both task type and complexity, some of which are presented in Table 4 and in Figure 22.

Table 4. Significant pairwise comparisons of sum of steering reversals. A '-' denotes a non-significant result.

Condition 1		Condition 2		Result
Task Type	Complexity Level	Task Type	Complexity Level	Adjusted P Value
Comparisons of task type at same complexity level				
Menu	1	Text	1	<0.001
Menu	2	Text	2	<0.001
Menu	3	Text	3	<0.001
Comparisons of complexity within Text Tasks				
Text	1	Text	2	-
Text	1	Text	3	=0.027
Text	2	Text	3	-
Comparisons of complexity within Menu Tasks				
Menu	1	Menu	2	-
Menu	1	Menu	3	=0.001
Menu	2	Menu	3	-

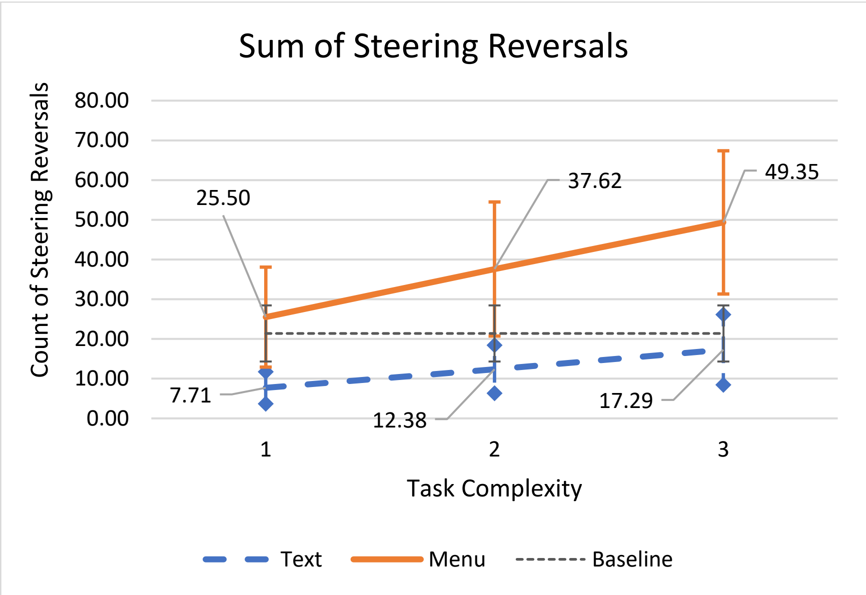

Figure 22. Mean Steering Reversal (SR) counts for each condition. Displaying mean and standard deviation (SD) error bars.

In summary, the menu task resulted in SR sums significantly higher than the than the text task across all levels of task complexity (Figure 22, Table 4). Furthermore, higher complexity tasks resulted in significantly higher counts of steering reversals compared to the lower complexity in both the text and menu tasks.

3.3.3.3 *Average Speed of the Participants' Vehicle*

For each task type and complexity, the data was inspected collectively, and the average speed of the participants' vehicle was found for each participant during each condition. An inspection of the studentised residuals indicated there were no outliers (>±3).

The data was found to be normally distributed through Shapiro-Wilk testing on all but the text high complexity condition (p=0.007). Considering this is not a particularly large sample, it is unusual that it failed a test of normality (Ghasemi & Zahediasl, 2012). The data was log-transformed, but further normality tests still showed the condition was not normally distributed (p=0.014). Similarly, a square root transformation did not result in normal distribution; this result is fairly common and transforming often doesn't solve the issue of normality (Feng et al., 2014). Therefore, a non-parametric Friedman test was used to compare the menu and text conditions at all levels of complexity, which was found to be significant ($\chi^2(5)=78.071$, $p<0.001$). Further pairwise comparisons with a Bonferroni correction found several significant differences, some of which are presented in the table below (Table 5, Figure 23).

Table 5. Significant differences found in a pairwise comparison of average participant speed. A '-' denotes a non-significant result.

Condition 1		Condition 2		Result
Task Type	Complexity Level	Task Type	Complexity Level	Adjusted P Value
Comparisons of Task type				
Menu	1	Text	1	<0.001
Menu	2	Text	2	=0.018
Menu	3	Text	3	-
Comparisons of complexity within Text Tasks				
Text	1	Text	2	-
Text	1	Text	3	<0.001
Text	2	Text	3	=0.001
Comparisons of complexity within Menu Tasks				
Menu	1	Menu	2	-
Menu	1	Menu	3	=0.023
Menu	2	Menu	3	-

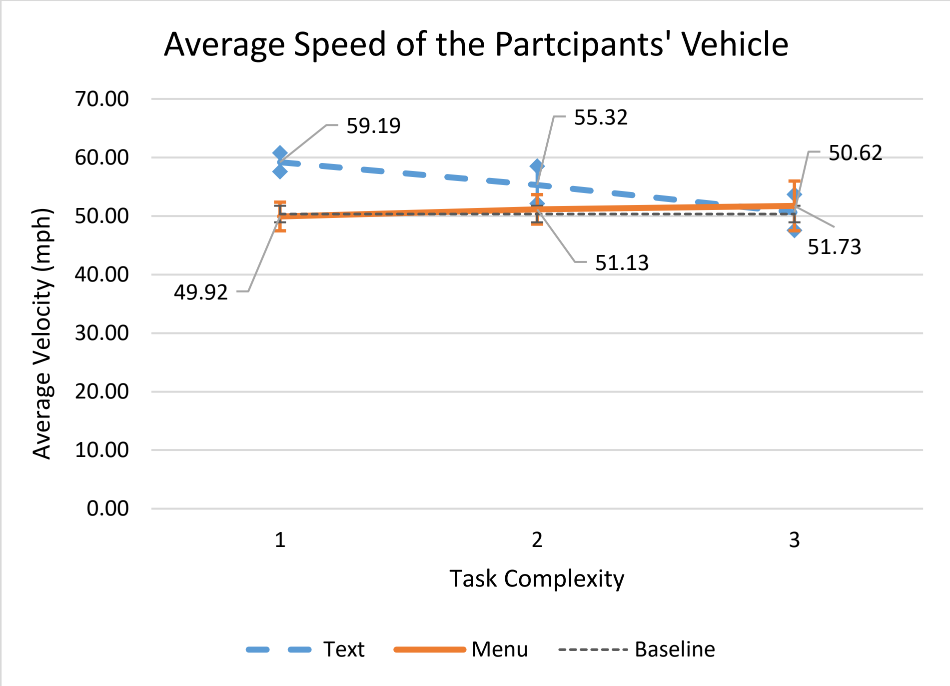

Figure 23. Mean velocity (mph) across conditions. Displaying mean and standard deviation (SD) error bars.

In summary, the results indicate that the task types result in significant differences in average speed at the low and mid-levels of complexity. Furthermore, significant differences in complexity were also demonstrated in both the text and menu conditions between specific levels (Table 5). A visual inspection of the data (Figure 23) demonstrates that the average participant's speed decreased across complexity in the text condition, whilst it increased slightly in the menu condition.

3.3.3.4 Average Distance to Lead Vehicle

The average gap (front bumper of the participants' virtual vehicle to the rear bumper of the virtual lead car) was calculated in metres whilst the tasks were active. Shapiro-Wilk tests of normality were met across conditions and the visual plots appeared normally distributed. No outliers were identified (studentised residuals >±3). Mauchly's test of sphericity was not violated for the interaction ($\chi^2(2)=2.150$, $p=0.341$).

A two-way repeated measures ANOVA was conducted and a significant interaction was found ($F(2,46)=10.132$, $p<0.001$). As a result, the simple main effects were examined with a Bonferroni correction. Use of the Bonferroni correction at this level, should prevent any Type 1 errors, though the correction is conservative and subsequently Type II errors will be more common (Jaccard & Guilamo-Ramos, 2002).

First looking at task type: no significant effect was found at the lowest level of complexity ($F(1,23)=<0.000$, $p=0.989$), however, significant differences were found between the menu and text task at the mid-level complexity ($F(1,23)=12.161$, $p=0.010$) and at the highest complexity ($F(1,23)=21.582$, $p<0.001$).

Next looking at the simple main effects of complexity: for the text task sphericity was violated ($\chi^2(2)=6.370$, $p=0.041$) so a Greenhouse-Geisser correction was used, and no significant difference was found ($F(1.598, 36.759)=4.013$, $p=0.175$) with the Bonferroni correction. Examining the impact of complexity in the menu tasks showed sphericity was again violated ($\chi^2(2)=36.812$, $p<0.001$), and with a Greenhouse-Geisser correction no significant difference was found ($F(1.121,28,022)=2.585$, $p=0.580$). The visual data demonstrates these findings (Figure 24).

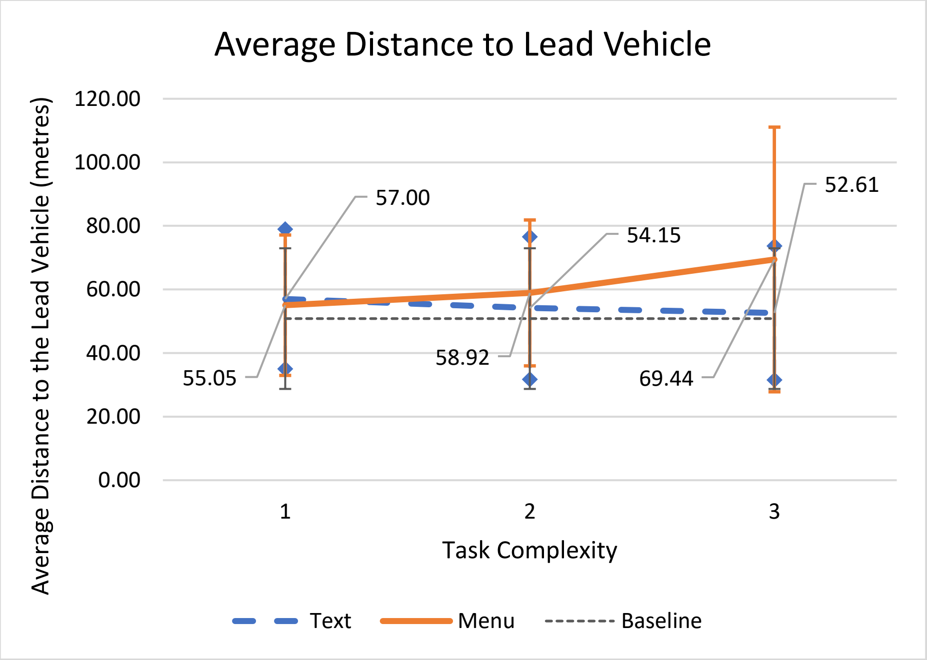

Figure 24. Average distance to the lead vehicle in metres during the tasks. Displaying mean and standard deviation (SD) error bars.

Overall, the interaction results indicate that gap distance was dependent on task type and task complexity. The simple main effects identified significant differences between task type, though further examination found no significant differences between the various complexity levels. This may be a result of the

Bonferroni correction. The data visualisation (Figure 24) demonstrates that as complexity increased, distance slightly decreased on average during a text task but increased during the menu task. The high SD (see Figure 24) indicates high variability between participants.

3.3.3.5 Minimum Time to Collision (Min TTC)

Time to collision (TTC) within this thesis uses velocity to calculate the duration in seconds until the participants' vehicle would make contact with the lead vehicle. See SAE J2944 for definitions and calculations (SAE International, 2015). For this measure, the data for each task type and complexity condition was inspected, and the minimum TTC for each participant in each condition was analysed.

An outlier was identified, in the menu task at the highest complexity, which had a studentized residual value of 3.26. Once removed, a Shapiro Wilk test of normality showed all conditions to be normally distributed ($p>0.05$). Sphericity was not violated for the interaction ($\chi^2(2)=0.922$, $p=0.631$) or the main effect of complexity ($\chi^2(2)=5.657$, $p=0.059$). The interaction was not significant ($F(2,44)=1.455$, $p=0.244$), nor was the main effect of task type ($F(1,22)=1.940$, $p=0.178$).

However, the main effect of complexity did display a significance ($F(2,44)=3.471$, $p=0.040$). A pairwise comparison with a Bonferroni correction, found a significant difference between the lowest and mid-level of complexity ($p=0.048$). See Figure 25.

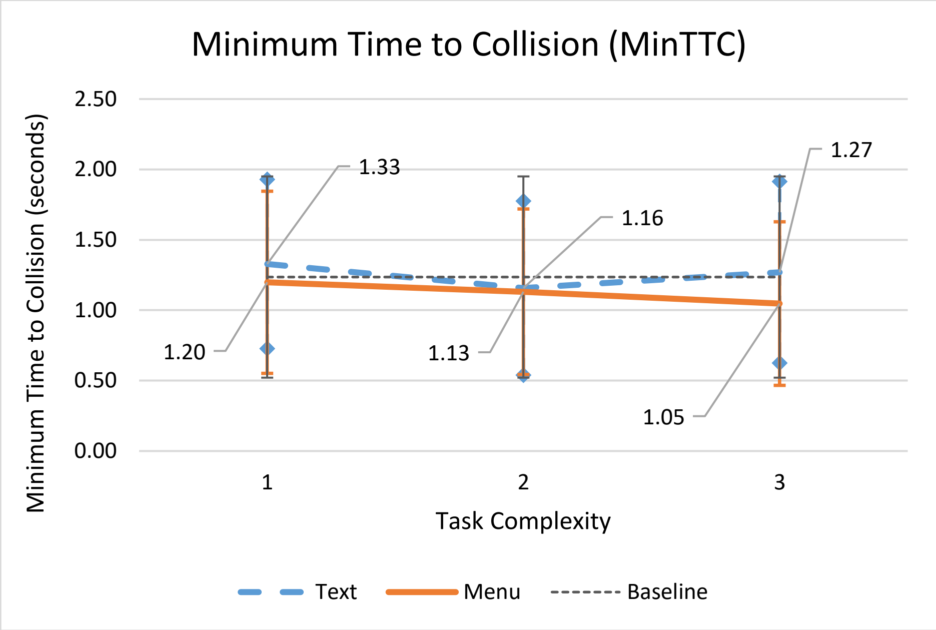

Figure 25. Minimum Time to Collision across task type and complexity. Displaying mean and standard deviation (SD) error bars.

Overall, these results suggest complexity, and not task type, influenced Min TTC (Figure 25).

3.3.4 Eye-Tracking Analysis

The analysis was conducted using the SMI eye-tracking software, Begaze. The SMI glasses recorded, saccades, blinks and fixations displayed over a forward video of the participants' view. If the fixation circle overlayed an area of interest (such as the HUD), it was assigned a name by the coder for analysis. To convert these eye behaviours into glances, the duration of saccades before and after the fixations were summed. A glance could contain multiple fixations and saccades if they were consecutively in the same area of interest. Blinks ended the current glance and a new glance started with the subsequent saccade or fixation. If no glances towards the area of interest were detected, that iteration was excluded from analysis. If the fixation was included within the task time but the glance went beyond, one saccade from beyond the task boundaries was included. This criteria is the same as that used by others (e.g., Smith, Gabbard, & Conley, 2016).

This analysis focused on HUD imagery as the area of interest. As the combiner glass commonly covered some part of the participants' visual view of the road (see Figure 19), this was defined as when participants appeared to look towards the text which was being displayed by HUD, as decided by the experimenter. The times of each task was manually annotated within the eye-tracking software. Data was excluded from the analysis at the experimenter's discretion as a result of eye-tracking difficulties (e.g., no eye movement was detected); fifteen participants were analysed for the menu task data and fourteen for text reading task. If an interaction was found, the simple main effects were analysed using a Bonferroni correction.

3.3.4.1 Average Glance Length Towards HUD Imagery

The first analysis inspected the average glance length to the HUD Imagery across the two task types (menu and text) and the three levels of task complexity. A visual inspection of the data and Shapiro-Wilk test found the data to be normally distributed (p>0.05). Studentised residuals did not indicate any outliers and Sphericity was not violated for the interaction (χ^2 (2)=3.346, p=0.188), so a two-way repeated measures ANOVA was conducted.

A significant interaction (Figure 26) was found between task type and complexity (F(2,22)=15.153, p<0.001) so the simple main effects were examined with a Bonferroni correction.

First, comparing task type found no differences at the lowest (F(1,11)=5.729, p=0.180) and mid-levels (F(1,11)=5.829, p=0.170) of complexity with a Bonferroni correction. However, a significant difference between task types was found at the highest level of complexity (F(1,11)=12.966, p=0.020).

Secondly looking at the simple main effects of complexity, within the text task, sphericity was violated (χ^2 (2)=12.909, p=0.002) so the Greenhouse-Geisser correction was used. A significant effect was found (F(1.206, 15.672)=21.674, p<0.001). A pairwise comparison with a Bonferroni correction found significant differences between the levels of complexity: low to high (p=0.001), low to mid (p=0.005), mid to high (p=0.002). Within the menu task, Sphericity was not violated but no significant effect was found (F(2,28)=0.879, p=0.426).

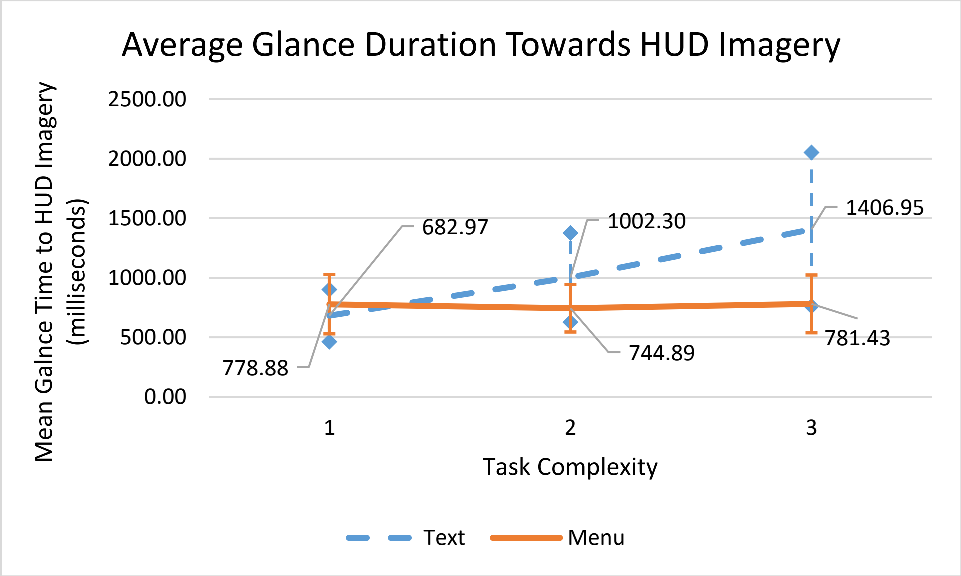

Figure 26. Average Glance Durations Towards HUD Imagery during the display tasks. Displaying mean and standard deviation (SD) error bars.

In summary, average glance duration was dependent on a combination of task type and task complexity, as a significant interaction was found. During the menu task, average glance duration remained consistent across the task complexity levels, whereas during the text task, average glance duration significantly increased with increasing task complexity (Figure 26).

3.3.4.2 Total Glance Time Towards HUD Imagery

The next analysis investigated the sum of glances towards the HUD imagery during the tasks. This is sometimes referred to as total eyes-off road time (TEORT). A visual inspection of the data and Shapiro-Wilk testing found the data to be normally distributed (p>0.05). No outliers were identified with studentised residuals of >±3 and Mauchly's test of sphericity was met ($\chi^2(2)$=4.848, p=0.089). A two-way repeated measures ANOVA was conducted and a significant interaction was found (F(2,22)=12.118, p<0.001) (Figure 27), therefore the simple main effects were examined with a Bonferroni correction.

Task type was first examined and significant differences were found between the text and menu task at the lowest complexity (F(1,11)=61.301,p<0.001), mid complexity (F(1,11) = 25.439, p<0.001) and on the significance threshold at the highest complexity (F(1,11)=9.504, p=0.050).

Next, task complexity was examined. For the text task, sphericity was violated (χ^2 (2)=7.963, p=0.190), so a Greenhouse-Geisser correction was implemented and a significant effect was identified (F(1.347, 17.508)=186.681, p<0.001). A further pairwise comparison with a Bonferroni correction found significant differences between all levels of complexity (low to mid p<0.001, low to high p<0.001, mid to high p<0.001). For the menu task, sphericity was also violated (χ^2(2)=10.021, p=0.007), and a Greenhouse-Geisser correction was used, but no significant effect was identified (F(1.301,18.213)=5.615, p=0.110) with the Bonferroni correction (see Figure 27).

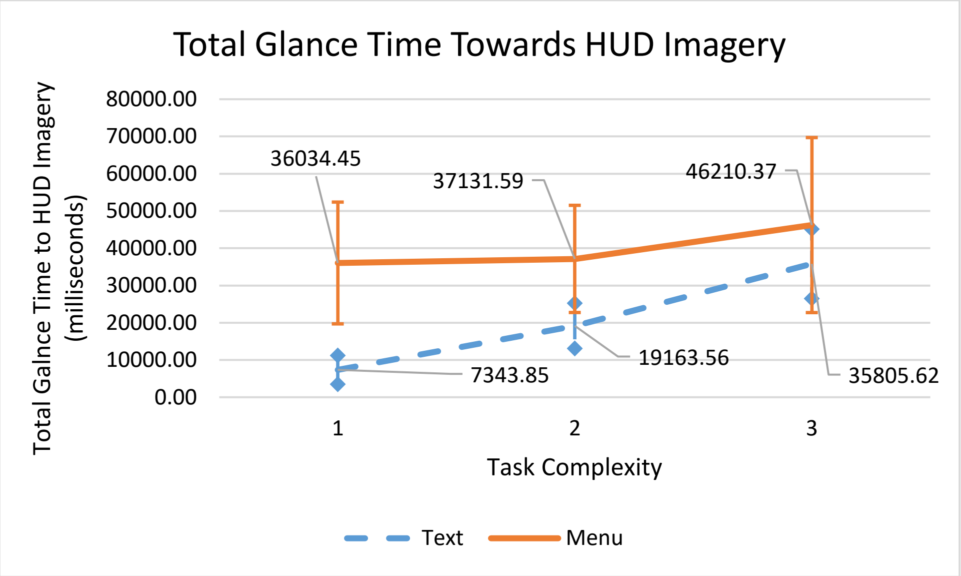

Figure 27. Average total glance time during the tasks. Displaying mean and standard deviation (SD) error bars. Each data point is the sum of six task iterations (e.g., each participant completed six iterations of the menu task at low complexity).

Overall, a significant interaction was found, meaning total glance time (or TEORT) was dependent on both task type and complexity. There were significant differences in task type across all levels of complexity. The menu task resulted in similar total glance times across complexity, whilst the text resulted in a significantly higher total glance time with each increase of complexity. These data points are the sum of six tasks. So, on average, each of the high-complexity menu tasks took around 7701.72ms of total glances and each of the high complexity text task took around 5967.60ms of total glances.

3.4 Discussion

The tasks used in this study were intended to imitate tasks which could appear as elements in HUDs in the near future. Participants questioned on this, (*"Do you agree that the tasks you completed are like the tasks you typically perform whilst in a car?"*) on average responded that they "Somewhat agree" that the tasks are typical in-vehicle tasks (Table 3). Participants equally "Somewhat agreed" that the display was safe to use, thereby indicating that participants should be accepting of HUD features which are currently common on HDDs. Potentially, a stronger agreement was not reported due to the disconnected nature of the tasks; they were not motivated by the participants themselves. Furthermore, the menu task required participants to artificially look for a target word amongst alphabetised lists. However, it is presumed this process does effectively imitate the process of searching a multiple levelled menu. In contrast, the text task required participants to read real-world texts (Vertanen & Kristensson, 2011), thereby adding to the perceived validity. Participants were on average confident that they would detect the lead vehicle braking (Table 3) but were less certain about their general surroundings, perhaps because of the relatively monotonous highway environment. Moreover, participants reported that they "Sometimes" felt in control whilst using the HUD (Table 3). Uncertainty around this may be due to the display's limitations. While functional, the interface created for the study was entirely text based, with occasionally slow responsiveness. Participants could have perceived it as in-elegant, thereby reducing how 'in control' they felt whilst using the display. Finally, the HUD imagery for the menu task was slightly aligned to the left of the display area (Figure 19 and 20). As a result, it rarely obscured the forward road view of the lead vehicle, but equally this positioning may have been off-putting to some participants.

Two measures of lateral driving performance were analysed: SDLP and a sum of SRs. SDLP was not influenced by task type, however, significant differences were found for complexity. Curiously, SDLP was highest for the mid-level complexity tasks, whilst for the highest level of complexity there was significantly lower SDLP (Figure 21). This decrease in lateral variation in high-complexity tasks has been observed previously in on-road driving studies (Reimer, 2009). It is generally considered to be compensatory behaviour that occurs when the driver's attention is shifted more to the secondary task due to the secondary task's high demand of attentional resources. Drivers begin to neglect their lateral performance so less deviation occurs. Thus, the high complexity display tasks used here may be highly demanding of attentional resources. SDLP is also highly influenced by variation in time between samples, since longer times allow for more variation in lane position. However, if this effect was present here, the highest complexity tasks would be expected to show the highest SDLP (Young, Seaman, & Hsieh, 2016).

The sum of SRs throughout the study showed that the menu task resulted in a significantly greater average number of SRs compared to the text task across all complexity levels (Figure 22). This increase generally indicates that the menu caused greater demand (Macdonald & Hoffmann, 1980); the number of reversals increases because drivers attend less to small steering corrections and instead make more large corrections (SAE International, 2015). Equally, there was a greater number of SRs for higher complexity tasks, indicating demand increased with task complexity. However, the distinctive difference in SRs between the task types may be a result of different task lengths. The text tasks required participants to read a maximum of 18 words, resulting in short tasks where the opportunity for SRs occurring is limited. As a result, the SRs recorded for the text task were on average below the baseline sample (Figure 22). As this is likely due to the very short task length, and is not detrimental, this should not be considered an indication of distraction. In contrast, the menu tasks often resulted in SRs well above the baseline (Figure 22). The menu task required participants to read a target word and navigate 3 levels of a menu, resulting in a longer task, so the potential for more SRs occurring is greater. Furthermore, the menu task required manual interaction with push buttons on the steering wheel; previous work has demonstrated that visual-manual tasks such as this can be more disruptive than vocal tasks, such as the text task used here (Young, 2014).

Differences found between task types may also be due to the interaction approaches they encourage. The menu task had clear opportunities for breaks in it (as the imagery changed between menu levels) meaning participants could do part of the task (e.g., navigate the first level of the menu), stop interacting, and respond to the road environment before resuming the HUD task. This is commonly referred to as resumability or ‘interruptibility’ and naturally it can increase the duration of a task; this may mean more opportunity for poor driving performance. Or conversely, the gaps in the task can improve driving performance by allowing the driver to regain situational awareness (Burns, Harbluk, Foley, & Angell, 2010). With the tasks used here, the menu task had clear resumability. Technically, the text reading task could be interrupted, but there were less obviously breaks in the design of the task since the text was all one sentence.

Longitudinal driving performance was also assessed with several measures. Over the text tasks, average speed decreased as the task complexity increased. This response is likely a compensatory behaviour in order to best complete the task when there was higher demand. Thus, participants were driving slower in order to reduce the level of demand (from the combination of the HUD task and the primary task of driving) to maintain performance as well as perceived risk (Lansdown, Brook-Carter, & Kersloot, 2004; Oviedo-Trespalacios, Haque, King, & Washington, 2017). In contrast, participants were significantly faster during the high-complexity menu task compared to the menu task at the lowest complexity (Table 5). Previously, Oviedo-Trespalacios, Haque, King, and Demmel (2018) found that drivers tended to maintain a higher speed when completing longer visual-manual tasks, specifically when the driver could self-regulate their interaction with the secondary task, potentially because they only engaged with the task when they felt they could maintain their speed. While drivers could not fully control when they did the task in the present study, the menu task did enable easy resumability, as discussed above, which may have encouraged a similar behaviour here.

Compensatory and adaptive behaviours were also evident within other longitudinal measures. For example, in the distance to lead vehicle measure, a significant interaction was found, indicating that the distance was dependent on both the task type and complexity. The visualisation of the data (Figure 24) indicates that participants were leaving a larger gap between the vehicles during the higher complexity menu tasks, yet the high SD (see Figure 24) further suggests this behaviour was performed by some participants but not others. Increased headway has commonly been demonstrated with phone usage while driving; drivers attempt to mitigate the increased demand by leaving a larger gap between vehicles (Collet, Guillot, & Petit, 2010), but it should be noted that these compensatory behaviours do not necessarily result in good driving performance (Strayer, Drews, Crouch, & Johnston, 2005; Collet et al., 2010), since the variations in headway do not fully account for the impact of the secondary task. The Min TTC values were generally lower than seen during the baseline drives, thereby indicating that the tasks may have led to more dangerous following behaviours in participants. However, the visualisation of the results (Figure 25) also demonstrates that the Min TTC values fluctuated across complexity and task type. The impact of individual differences on TTC, such as driver age and gender, are more prominent at higher speeds (Kusano, Chen, Montgomery, & Gabler, 2015), so these elements may be somewhat obscuring the impact of task type and complexity.

The eye-tracking analysis inspected how participants visually attended to the HUD imagery while the tasks were present. Glance duration was on average below three seconds which lines up with previous work on head-down displays (Wikman, Nieminen, & Summala, 1998; Hensch et al., 2020). The average glance duration showed a significant interaction, with the text task at high complexity resulting in the longest average glance times, thereby indicating it was more demanding (Figure 26). These differences are likely a result of the task type variations, as discussed above. The menu task was interruptible, participants could freely glance away and easily resume the task. In contrast, participants may be tempted to look longer at the text task as it is not so easily stopped, since participants were required to read a full sentence. Moreover, this effect may have been amplified in the high complexity conditions which contained more words. Equally, previous work in this area has shown that list-style menus, as used here, enable more efficient searching and are therefore are recommended over grid-style menus (Kujala & Saariluoma, 2011).Thus, the menu used here may have encouraged particularly efficient visual behaviours.

Although average duration is a commonly used measure, drivers rarely exceed average durations of 1.6 seconds (Kujala, 2009); this was also observed here. As a result, some recommend analysing the variance of glance duration measures (Kujala, 2009) or analysing durations at the tail end of the distribution (Horrey & Wickens, 2007) since averaging durations may not show an effect (e.g., Kujala & Saariluoma, 2011). Therefore, the significant differences between average durations found here indicates that individual glances to the text tasks were generally longer per-glance, and the high complexity text task was not simply leading to occasional longer glances as is commonly seen (Horrey & Wickens, 2007).

A secondary analysis of the eye-tracking data examined the total glance time directed to the HUD imagery during all the tasks. The results found a significant interaction between task type and task complexity (Figure 27). Overall, the results for the menu task remained consistent across complexity, whilst the text task increased significantly with every stage of increasing task complexity. These findings may have been the result of how complexity was implemented. Text reading tasks on HUDs have previously resulted in longer total eye-on-display times, than more interruptible tasks (e.g., Hensch et al., 2020). Within this study, the significantly increasing times within the text task, was likely due to the increasing length of the sentence participants were required to read. This made the task increasingly less easy to resume, as complexity increased. However, the greatest total glance times were all a result of the menu task (Figure 27), which is indicative of even higher demand (Ablaßmeier et al., 2007).

Comparing these glance values to assessment criteria (section 2.5.2) provides some context to them. First looking at the total glance times. Within the graphical presentation (Figure 27) each data point is the sum of six task iterations. Therefore, the average total glance times, for both the menu task and the text task, are all under 8 seconds per task, which falls below the current assessment criteria (e.g., NHTSA, 2016; AAM, 2003; JAMA, 2004). Equally, the average glance times (Figure 26) for all the tasks are under 2 seconds which is also within the assessment guidelines. Thus, the average participant completing these tasks might have met the display assessment criteria (see section 2.5.2). The current study was not set-up according to the assessment guidelines and this is not the correct analysis approach. Nonetheless, comparing the glances times observed here to the assessment glance times provides a good reference for how these tasks are performing. Generally, they suggest the tasks are not too demanding. However, this conflicts with some of the driving performance measures, since they indicate that some distraction did occur (see 7.4.1 for further discussion).

Beyond the considerations previously discussed, there are a few additional constraints on the findings presented here. First, unintended variation may have occurred because of low-frequency words being randomly selected from the sample. Words that are common in typical English are more efficiently processed than uncommon or low-frequency words (Brysbaert, Mandera, & Keuleers, 2018). Work on this effect within the driving field has shown it can be present with words visible on road signs (Tejero, Insa, & Roca, 2019). Since the words and phrases used in the text and menu tasks here were randomly selected from real-world text conversations (Vertanen & Kristensson, 2011) and low-frequency words (e.g., *"almanac"*) were not controlled for, there is a possibility that low-frequency words confounded some tasks as they applied unintended cognitive load. Additionally, the road environment was relatively simple, a more visually complex environment may vary the results. Particularly meaningful may have been the simulated traffic which was only present on the opposite side of the highway, and not in the same direction of travel as the participant. The presence of no other vehicles directly around them may have made participants somewhat disregard their lateral driving performance. Previous work on the impact of traffic density has highlighted its potential to increase workload (Teh, Jamson, Carsten, & Jamson, 2014), but this common element of the road environment was not present for participants within this study. Finally, the lowest complexity level of the text task was unusually simple, requiring the participant to read only two words. While realistic, its quick nature may have meant its impact could not be clearly captured in the same measurement approaches as with the other task variations.

3.5 Conclusions

The results here indicate that task type (menu or text task) and complexity (low, mid and high) impact driving performance and glance behaviour, thereby indicating that task type and complexity variably influence demand.

Considering the two factors in isolation, complexity commonly influenced measures of SRs, SDLP, average speed and Min TTC, average glance time and total glance time. Equally, considering task type in isolation, significant differences between task types were seen in SRs, average speed, average distance to the lead vehicle, average glance duration and total glance time to HUD imagery. However, the impact on driving performance and eye-behaviour was also mediated by the interaction of task type and complexity. For SRs and average speed, the interactions between the factors were not examined due to not meeting the assumptions for the statistical test. However, significant interactions were found in the measures: distance to the lead vehicle, average glance duration and total glance time. It appeared that the resumability of the task, and drivers' self-management of their interactions, were likely to be involved in how the display demand influenced the dependent measures.

As a result, how driver's respond to near-future HUD tasks often depends on the exact nature of the task and in some instances a combination of a specific task type at a specific complexity. Taking a broader view, the results suggest that some drivers were able to self-regulate their interactions with the HUD in specific circumstances. Firstly because, many tasks resulted in driving performance measures which were visually close to baseline (Figure 21-25). Secondly because, the eye-tracking times were generally within vehicle display assessment guidelines (see section 2.5). However, see section 7.4.1 for further discussion on this.

The subjective questionnaires explored opinions on near-future HUDs, and generally found participants to respond positively towards the display, indicating that moving information and tasks currently found on a HDD to a HUD should be accepted by drivers. However, the occasionally indifferent response from the participants shows the importance of self-motivation, positive experience, and well-executed interfaces in determining how they are perceived.

3.6 Chapter Summary

Regarding the research question (RQ1), the results showed how driver respond to the attentional demand from these tasks and displays depends on the nature of the specific task. There was varying influence from the different tasks, and different task complexities, on driving performance and visual behaviour. Overall, the eye-tracking measures generally indicate that these tasks were not too demanding (the glance times were within the current assessment criteria, see section 2.5.2). However, the driving performance results indicate that some near-future tasks might result in instances of distraction, according to the definitions previously outlined (see section 1.3).

For the simple text tasks, the eye-tracking measurements did not reach thresholds which would be considered concerning in display assessments (see section 2.5) and driving performance was often visually close to the baseline level (Figure 21-25). Thus, it might be considered that the demand which was imposed by some near-future tasks would be considered acceptable whilst driving. However, this point is further discussed, and the implications are reviewed in section 7.4.1.

The next chapter continues to evaluate demand incurred by HUDs, specifically focusing on visual demand and how this can vary with display location.

4 Study 2: Investigating Display Imagery Across Windshield Locations

4.1 Chapter Introduction

Throughout the previous literature presented within this thesis (Chapter 1 and 2) it is evident that further research is required in order to appreciate the demanding impact of imagery displayed across a whole windshield. Previous research generally recommends locating display imagery proximate to the driver's forward view to optimise the beneficial characteristics of HUDs and WSDs. Overall, the importance of eccentricity from the forward view is a prominent feature, with displays close to the drivers' forward view generally resulting in preferable driving results, whilst displays at greater angles away from the forward view result in less desirable results (see section 2.6).

However, there are also reasons to explore how display imagery in non-ideal locations impacts drivers, since there are increasing reasons for multiple windshield display locations to be employed. These include reducing issues of obscuration, tunnelling, and clutter (section 2.3). Furthermore, lower priority information may be better placed not on a HDD, but on a HUD which is somewhat offset from the driver's forward view. Finally, thinking towards the future development of displays, AR displays benefit from positioning imagery close to the real-world elements which they intend to augment. Thus, the possibility of presenting information anywhere across a windshield becomes a necessary aspect which requires investigation. This study aims to investigate how the demand imposed by WSDs varies by imagery location according to specific driving performance markers.

In order to study this topic, a somewhat unusual approach was employed in order to manipulate the visual attention of participants whilst driving and interacting with the displays.

Generally, drivers appear able to adapt their behaviour in order to protect the driving task (Horrey, Alexander, & Wickens, 2003) when interacting with various display positions. As a result, variations in driving performance are not always clearly evident (Wittmann et al., 2006). However, display positioning has been previously investigated in a manner which counteracted this (e.g., Summala et al., 1996;

Summala, 1998). In order to achieve this, the authors used a highly visual demanding task which required participants to attend to a display showing rapidly alternating digits. For example, Summala et al., (1998) required participants to verbally identify when any “4”s or “7”s appeared on the display. As a result, participants were unable to share their visual attention time between the display and the road as they may do when normally driving. Instead, they had to look continuously to the display in order to complete the task. Therefore, drivers were unable to easily adapt their behaviours and the effects of the display locations would be visible in the driving data without individual behaviours confounding the results. Thus, this approach investigates a potential worst case scenario where, whether due to individual differences (e.g., Chiang, Brooks, & Weir, 2004; Yang, Kuo, & Lenné, 2020) or display and task design (e.g., Tivesten & Dozza, 2014), a display encourages a long glances away from the road environment. It does not allow the driver to effectively or adaptively employ their visual attention as desired in order to maintain their driving (Metz, Schömig, & Krüger, 2011; Underwood et al., 2003). Therefore, the intrinsic demand of the display position is examined.

A similar visual detection task (to those described above) was developed here to investigate HUD and WSD positioning which is described in detail below (see sections 4.2.3.1 and 4.3.3). In addition to these tasks, the results were also partially analysed using an atypical approach. ‘Unacceptable’ or ‘error’ criteria (see section 4.3.3) were created to explore whether drivers could be considered to have reached a threshold of poor driving performance.

Therefore, within this study, RQ2 and RQ3 (section 1.5) were examined by studying intrinsic display demand. Specifically, it investigated to what extent drivers are able to maintain driving performance when artificially encouraged to continuously look to WSD or HUD locations across the windshield.

Objectives: Identify how HUD location, across a full windshield, intrinsically influences driving performance during a demanding visual-detection task.

Explore alternative approaches to investigating demand.

4.2 Methods

4.2.1 Participants

Twenty-six participants were recruited, with 16 male (44.44%), 9 female (34.62%) and 1 other (3.85%). The participants reported that they held their driving licence for an average of 15.9 years and drove on average 7563 miles (~12171km) per year. The average participant age was 36.5 years old (SD=13.04 years).

4.2.2 Design

A within-subject design was implemented. The study was conducted within a medium fidelity static car simulator at the University of Nottingham. Participants experienced ten drives during which they completed a visual-detection task on each of the ten different display positions (Figure 28). Driving performance measures were collected by the driving simulation software.

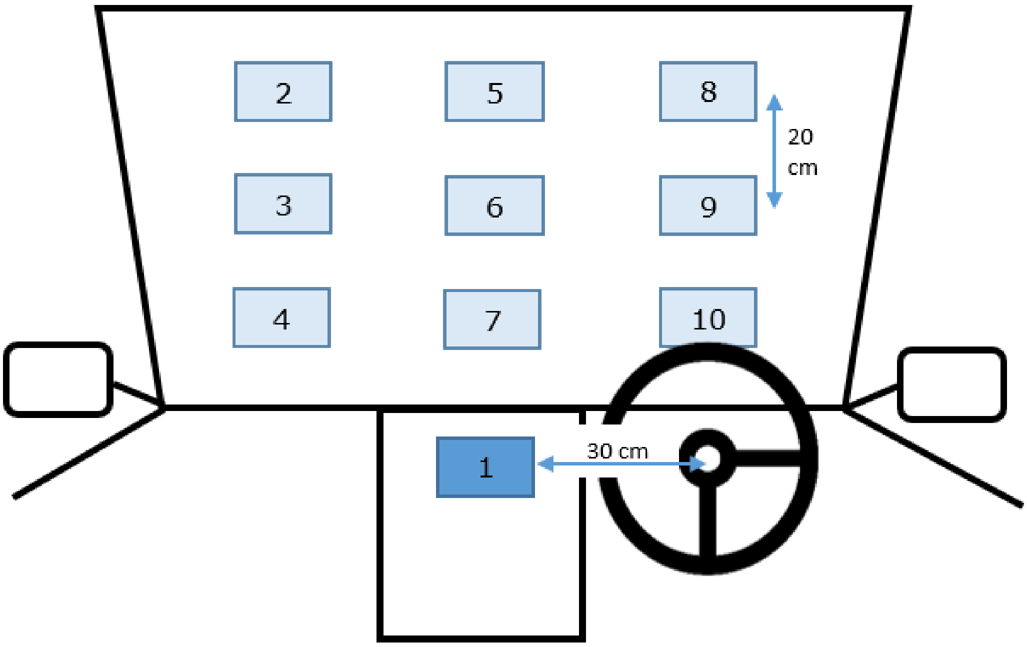

Figure 28. The 10 display locations (9 across the windshield and 1 HDD).

4.2.3 Materials

The study was conducted within medium-fidelity static car simulator (see Figure 29). The car simulator was composed of the front half of a 2001 Honda Civic (right-hand drive). Carnet Soft simulation software (https://cs-driving-simulator.com) was used to create the visual road environment. Three projectors and three projector screens were arranged around the car to display the simulated road environment. Each projector screen created a projection area of 244 by 183cm. These were positioned

200-230cm away from the windscreen of the car cab and approximately 50cm up from the floor. The rear-view mirror, side mirrors and speedometer were not present within the simulation. This simulator configuration was used as it enabled the display of real HUD imagery using real aftermarket HUDs (Pioneer HUDs) at a realistic focal distance.

Figure 29. The driving simulator using a Honda Civic vehicle cab.

Within the simulated environment participants followed a curved slip road and joined a dual carriageway behind a leading yellow car. At the start of the drive, the road was curved to the participants' right but towards the end of the drive it became straight (see Figure 30). Participants were instructed to follow the yellow car in the left-hand (outside) lane throughout the study procedure. During half of the tasks the lead car braked so that the participants was required to respond to a longitudinal driving demand.

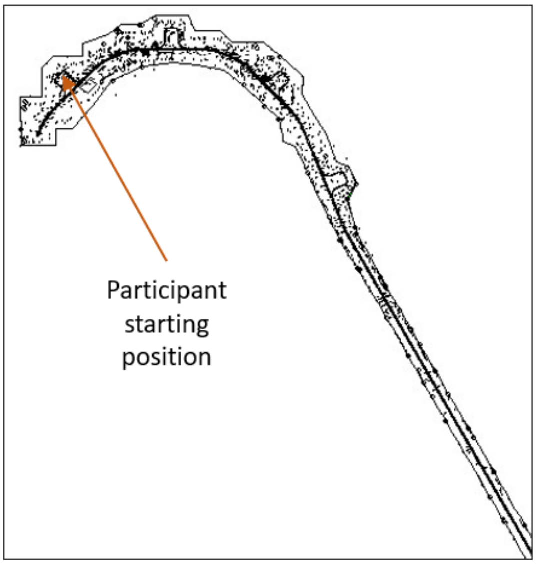

Figure 30. The road map which participant followed during the study.

A total of ten driving display locations were investigated (see Figure 28). The HDD was comprised of a small 7-inch LCD, which was attached to the simulator vehicle's interior on the centre console, approximately level with the centre of the steering wheel. The windshield display positions were created using two Pioneer HUDs which were suspended from the vehicle's ceiling in the place of the sun visors. The two displays were mounted on extendable arms which meant the location of the display imagery could be manipulated (Figure 31). An example of the HUD moved to Position 4 is shown below (Figure 32).

Questionnaires were constructed to ask about the participants' experiences with the displays. All paper materials used in conducting the procedure are in Appendix C.

SMI eye-tracking glasses were used during the study just to monitor whether participants were able to maintain their visual focus towards the tasks as instructed (see section 4.2.3.1).

Figure 31. One of the Pioneer HUDs on an extendable arm within the driving simulator

Figure 32.The letter "G" presented in position 4 on the second Pioneer HUD captured by the forward eye-tracking glasses camera. The body of the projection system obscures the driver's view of the slip lane.

4.2.3.1 Tasks

During each drive the participants completed a secondary task using the display positioned in one of the pre-defined display positions (Figure 28).

Primarily the tasks were inspired by the work of Summala (1998), Summala et al., (1996) and Lamble et al., (1999), where highly demanding visual detection tasks were employed to investigate opaque displays and their positions within road vehicles. The tasks ensured the participants were not permitted to freely share their visual attention between the road and the task, as they may do naturally. Instead, they were instructed to attend only to the display task whilst it was active. Thus, these tasks reduce a driver’s ability to protect their driving performance (Horrey, Alexander, & Wickens, 2003) and enable the investigation of display position in a worst-case scenario where the drivers’ attention is directed to the display for the duration of the task. Therefore, the intrinsic demand of the display position is examined.

The tasks developed here, were adjusted from those used by others previously (e.g., Summala et al., 1998). First, alternating letters were used as the primary display elements, rather than digits, and also faster speeds of alternating characters were employed. It was anticipated that this would create more uncertainty and better maintain the participants’ focus on the displays, whilst still only using a single character for easy flexibility in study construction. Secondly, the primary aim of the tasks was changed; participants didn’t need to identify a specific character (e.g., “4” s) instead participants were required to identify when a perceptual change occurred (when a character appeared on the display for a longer time period than the others) and then verbally state the delayed character.

Within this study, the participants were made aware that the task was starting through three quick audible beeps which lasted a total of 1.3 seconds. The task was created within Windows PowerPoint. During the task, letters would rapidly alternate in the centre of the display. There was a total of 60 letters, each of them remained on screen for 0.2 seconds. Three times during each task, a letter would remain on the display for a slightly longer time period (0.5 seconds). Participants were instructed to verbally report when this occurred by saying the slower letter out loud; this was then noted by the experimenter. Participants were instructed to look continuously to the task whilst it was active. Overall, the task lasted 15 seconds. Although, the tasks were identical between participants, the overall sequence of letters and the position of the slowed letter was randomly generated. This meant that the same letter, one after the other, could occur.

The HDD task was in a consistent position for all participants (Figure 28). In order to position the imagery consistently using the HUDs, an ‘X’ was displayed on the relevant HUD device before the drive, and participants were asked to manipulate the device on the movement arm until the ‘X’ overlaid a pen mark present on the windshield when viewed from a comfortable driving position. Position 8 (see Figure 28) was the position closest to the recommended positioning for the Pioneer HUD.

For each drive, participants completed the tasks on one display position. During each drive the task was completed twice. During one instance the lead car braked and during the other it did not. During braking, the lead car slowed from approximately 22.35m/s (~80.5kmh) to 12m/s (~43kmh) in approximately 10 seconds (or ~50mph to ~28mph). If the participant’s vehicle ever came within 2 metres of the lead car, the lead car would quickly accelerate away in an attempt to prevent a collision (in about 1 second it would return to ~50mph/ 22.35m/s /80.5kmh). Each drive took around 4 minutes to complete.

4.2.4 Procedure

Ethical approval was received from the University of Nottingham Faculty of Engineering Ethics Committee. During the main experimental procedure, participants were first asked to read the information sheet about the study. Once the participant had asked any questions and signed the consent form, the procedure continued. Each participant then completed questionnaires on their demographics and driving (Appendix C).

Next the participants completed a practice drive to ensure they were familiar with the simulator vehicle, and the driving route which was expected of them. Participants were also given the opportunity to complete a practice task using one of the display positions. Participants were instructed to maintain their visual focus towards the display tasks when they were active, rather than look back to the road. The SMI eye-tracking glasses were then fitted (which were used during the study to monitor to what extent participants were able to follow this instruction). Participants were asked to refrain from touching or moving the eye-tracking glasses after calibration to prevent tracking errors.

Participants experienced ten primary drives, one for each display/task position. During each drive, participants drove around a corner, along a slip way and on to a motorway behind a yellow car. Participants were asked to follow this lead yellow car throughout all the conditions, the experimenter would verbally prompt participants to catch-up to the yellow car if it was moving out of view. Within each drive participants experienced the task twice. During one instance the lead car braked whilst the task was active, during the other it maintained its speed. The lead car also braked at one point when a task was not active. The start of the tasks was controlled by the experimenter, meaning the exact co-occurrence of the lead car braking and the task starting varied somewhat between drives and participants.

The order of display positions was varied between participants to limit order effects. The HDD remained in a fixed position for all participants on the centre console (see Figure 28). Throughout the procedure participants were monitored for indicators of simulation sickness and between drives participants completed the Simulation Sickness Questionnaire (Kennedy et al., 1993) (Appendix A). After completing all the simulated drives participants completed a final questionnaire on their preferences for the display positions (Appendix C). Overall, the procedure took approximately an hour to complete.

4.3 Results

The tasks were cued by the experimenter in the room, so the sections of data which were analysed were manually identified according to noted times. Each analysis period was approximately 15 seconds (the length of the task) which occurred twice per display position.

4.3.1 Driving Performance

In order to assess the impact of display position, various driving performance measures were monitored. These included, average speed, average gap to lead vehicle, steering reversal rate (SRR), minimum time to collision (MinTTC) and standard deviation of lane position (SDLP). Using repeated measures ANOVAs, display position was only found to be significantly influential to SRR and SDLP.

Thus, only measures of lateral driving performance were significantly influenced by display positioning (see Table 6) and these are reported here.

4.3.1.1 Steering Reversal Rate (SRR)

Steering reversals (SR) were calculated as previously described (section 3.3.3.2). However, rather than counting the number of steering reversals which occurred during the task, a steering reversal rate was calculated continuously throughout the data (per minute) so that a parametric statistical analysis could be justified as conducted by others in the area (Markkula & Engstrom, 2006).

No outliers were found according to studentised residuals, though sphericity was violated ($\chi^2(44)=65.994$, $p=0.021$), and consequently a Greenhouse-Geisser correction was used and significance found ($F(5.748, 126.450)=2.4$, $p<0.033$). A following pairwise comparisons with a Bonferroni correction showed no significant differences, although it was approaching significance between positions 1 and 7 ($p=0.055$).

4.3.1.2 Standard Deviation of Lane Position (SDLP)

SDLP was calculated over each task, and the average was taken for each participant. Sphericity was violated ($\chi^2(44)=173.994$, $p<0.001$), so a Greenhouse-Giesser correction was used and a significant result was found ($F(3.373, 74.207)=10.589$, $p<0.001$). A visualisation of these results is present below (Figure 33). Pairwise comparisons between all of the display positions with a Bonferroni correction found several (14) significant differences between the display conditions. More specifically significant differences in SDLP were found between the following display positions: 1 and 4 ($p=0.055$) (approaching significance), 1 and 6 ($p=0.019$), 1 and 7 ($p=0.005$), 1 and 8 ($p=0.001$), 1 and 9 ($p=0.002$), 1 and 10 ($p=0.003$), 2 and 6 ($p<0.001$), 2 and 7 ($p=0.017$), 2 and 8 ($p<0.001$), 2 and 9 ($p<0.001$), 2 and 10 ($p=0.017$), 3 and 8 ($p=0.045$), 4 and 8 ($p=0.024$), 8 and 10 ($p=0.029$).

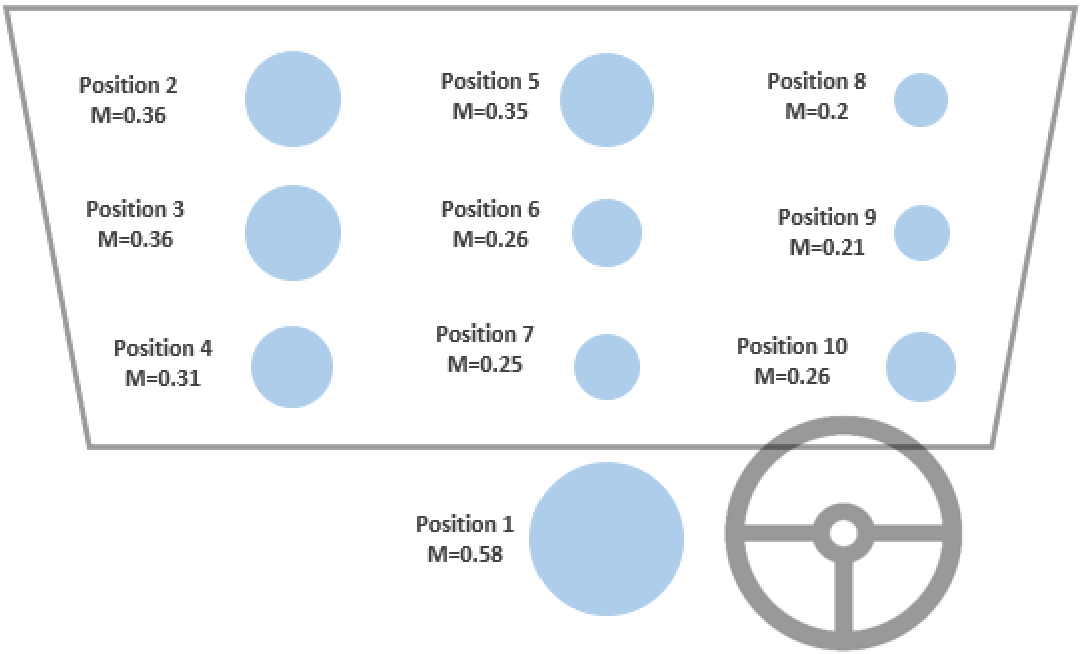

Figure 33. A visual representation of SDLP means across display positions. Each circle position indicates each display position (see Figure 28). The width of each circle reflects the average SDLP for each position. "M" = mean in metres.

A summary of the lateral driving performance results is also presented in the table below (Table 6).

Table 6. Descriptive statistic results found in lateral driving performance measures.

Display Location	SRR (per minute)		SDLP (metres)	
	Mean	SD	Mean	SD
1	28.30	8.63	0.58	0.36
2	29.73	8.66	0.36	0.11
3	30.65	8.47	0.36	0.22
4	29.72	9.95	0.31	0.12
5	31.00	10.98	0.35	0.26
6	31.20	10.46	0.26	0.09
7	33.64	10.29	0.25	0.09
8	30.45	8.96	0.20	0.07
9	29.41	10.23	0.21	0.07
10	27.49	8.58	0.26	0.11

4.3.2 Preference Analysis

After experiencing all the display positions participants were asked to rank them (1 to 10), with low scores indicating the highest preference. One participant did not fully follow these instructions as they did not fully complete the questionnaire but, their data was included as their scoring still reflected their perspective. A Friedman test was conducted in order to analyse the results and a significant result was found ($\chi^2(9) = 138.41$, $p<0.001$). The descriptive statistics for each display position are available in Table 7.

Table 7. Descriptive statistics results of the preference analysis

Display Position	Median	Mode	Minimum	Maximum
1	10	10	3	10
2	8	7	3	10
3	7	7	2	9
4	9	9	7	10
5	3.5	2	1	6
6	3.5	4	1	7
7	6	6	2	9
8	2	1	1	6
9	2	1	1	6
10	5	5	2	10

Subsequent pairwise comparisons were conducted with a Bonferroni correction found multiple significant differences (24) were evident between various display positions. Of particular note, are the significant differences between position 8 (the recommended Pioneer HUD position) and the others which were investigated. Significant differences (Bonferroni adjusted p-values displayed) were found between: position 8 and 7 (p=0.041), 8 and 10 (p=0.021), 8 and 3 (p<0.001), 8 and 2 (p<0.001), 8 and 1 (p<0.001) and 8 and 4 (p<0.001). Thus, participants appeared to prefer the recommended Pioneer HUD position over the HDD. Furthermore, they ranked display positions closer to their forward view more preferentially. This is more apparent in the visualisation below (Figure 34).

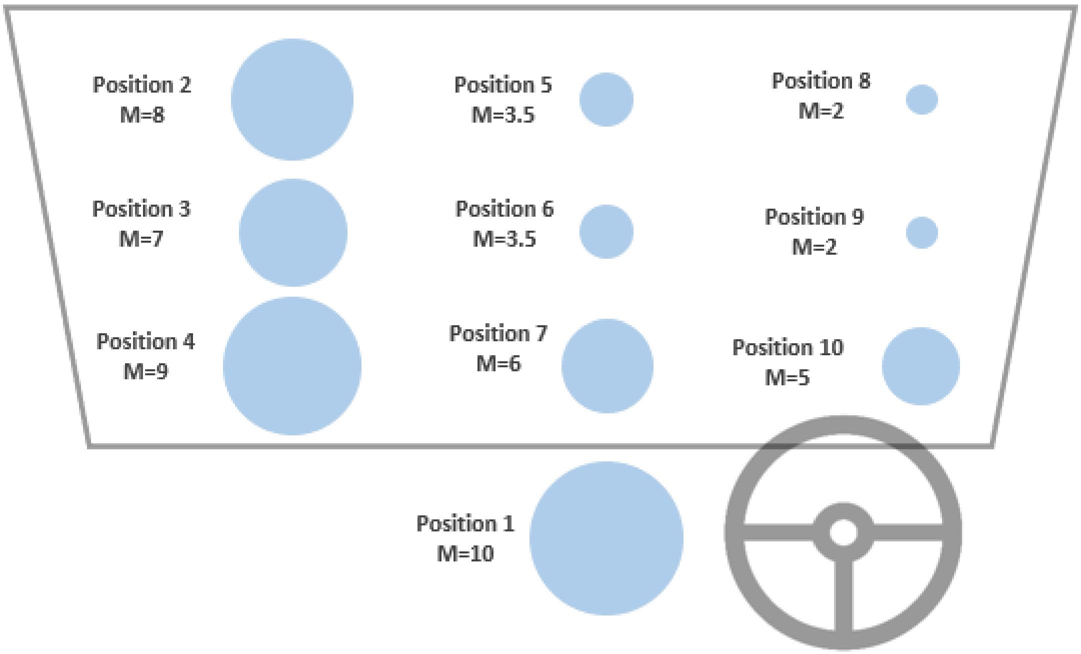

Figure 34. *A visual representation of the median preference for each display position. Each circle position indicates each display position (see Figure 28). The width of each circle reflects the median preference for each position, with lower numbers indicating higher preference. "M" = median in metres.*

4.3.3 Count Analysis of Driving Errors

In order to begin addressing RQ3 (section 1.5) and explore alternative approaches to assessing demand, the number of driving errors was counted and used to monitor the impact of HUD display position.

Whilst task errors are relatively commonly examined as an assessment of displays within vehicles (e.g. Smith, Streeter, Burnett, & Gabbard, 2015), driving performance is more typically assessed continuously (as above) rather than through instances of error. However, driving errors have been used as a measure to validate driving simulators (e.g., Shechtman, Classen, Awadzi, & Mann, 2009; Meuleners & Fraser, 2015). Furthermore, the number of driving errors have been shown to be significantly higher during instances of visual distraction (Young, Salmon, & Cornelissen, 2013). Thus, they pose as an attractive quick and simple approach to assessing the demand that may be imposed by displays during driving.

Expanding on this, this work classified errors as unacceptable instances of driving performance, specifically when:

- The participants' vehicle collided with another simulated vehicle.

- Part of the participants' vehicle left the lane (the lanes were 3.5m wide).
- The participants' vehicle moved within 2 metres of the lead vehicle (when this occurred the lead vehicle would accelerate in order to prevent a collision where possible).
- The time to collision (TTC) between the participants' vehicle and the lead vehicle was less than 2.5 seconds. This threshold was selected as it is an accepted threshold within collision warning systems, and should therefore be perceptibly unsafe (Botzer & Musicant, 2016).

These criteria were selected and were considered to be indicative of unsafe behaviour. Each task (two per participant, per display position) was inspected and a count was created to total the number of tasks where the criteria was reached. The results are presented below (Table 8).

Table 8. The nature and number of driving errors occurring during the display tasks.

Display Location	Count Data				
	Collision	Out of Lane	Distance to Lead Vehicle	Time to Collision	TOTAL
1	2	17	11	17	47
2	1	6	9	16	32
3	2	3	3	16	24
4	1	3	7	15	26
5	3	3	13	17	36
6	0	0	3	11	14
7	0	0	8	18	26
8	0	0	3	8	11
9	1	0	6	10	17
10	0	0	8	17	25
TOTAL	10	32	71	145	258

A Friedman analysis was conducted to compare the total error counts between the display locations, which was significant ($\chi^2(9) = 44.744$, $p<0.001$). Further pairwise comparisons using a Bonferroni correction showed significant differences between positions 8 and 1 ($p<0.001$), 8 and 5 ($p=0.022$) and, 6 and 1 ($p=0.011$). Thus, the HDD (position 1) resulted in significantly higher counts than two of the HUD positions (8 and 6). Also, the middle-high HUD position (position 5) resulted in significantly higher counts than the recommended position (position 8) ($p=0.022$). These results are presented in the Figure below (Figure 35).

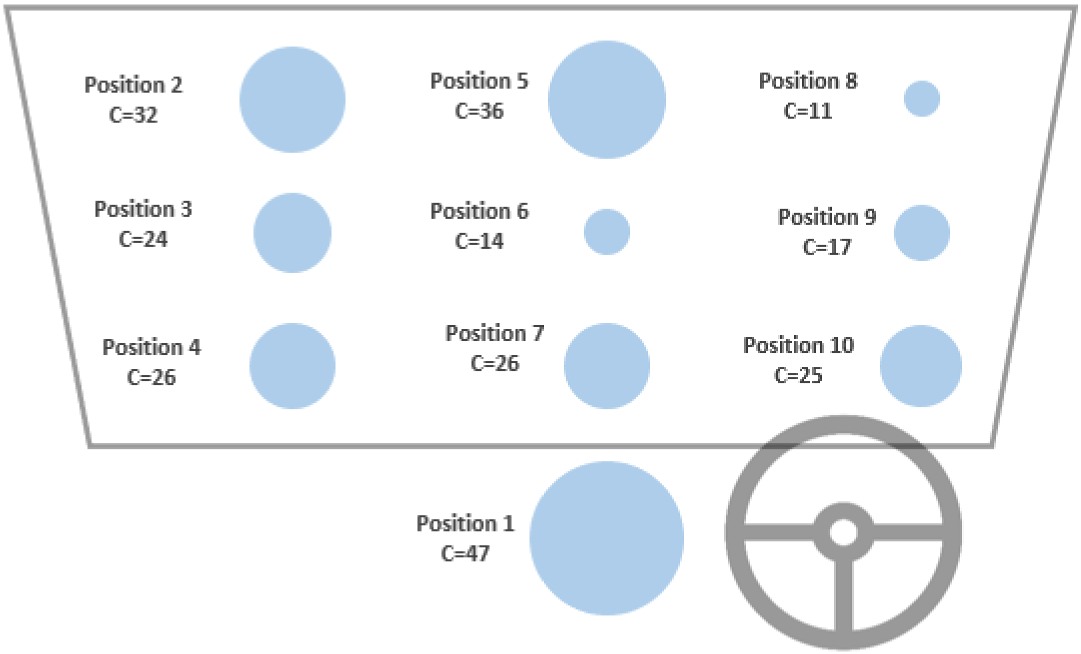

Figure 35. A visual representation of the error count for each display position. Each circle position indicates each display position (see Figure 28). The width of each circle reflects the error count for each position. Significant differences were found between positions 8 and 1 (p<0.001), 8 and 5 (p=0.022) and 6 and 1 (p=0.011). C= count.

4.4 Discussion

First, looking at the driving performance measures, it is evident that display position was significantly influential to lateral driving performance. This supports previous work in the area which has shown that engagement with different display positions may influence lane-keeping performance (Wittmann et al., 2006). In contrast, measures of longitudinal driving performance were not significantly influenced by display position. Previous work has also shown display positioning has a minimal impact on longitudinal measures. For example, (Smith, 2018) found varying vertical HUD position had no impact on driver speed, though there was some minor influence on headway time and distance which interacted with driver gender and task type.

However, within this study, the differences in findings between longitudinal and lateral measures may have been the result of the precise experimental set-up.

First, many of the displays (positions 1, 2, 3, 4, 5, 6 and 7) were offset laterally from the driver's forward view of the road. Possibly, forcing the participants' visual attention to areas which are highly laterally offset, and using HUDs which were not designed for that (Figure 31 and Figure 32), made maintaining their lateral driving performance more demanding than maintaining their longitudinal. (This issue is further reflected upon later within this discussion.)

Secondly, participants may have actually been better able to maintain their longitudinal performance because the lead vehicle was present. Previous research has shown that drivers can use their peripheral vison to detect a lead car braking (Lamble, Laakso, & Summala, 1999; Summala, Lamble, & Laakso, 1998, see section 2.2.2.1). Therefore, lead cars can provide salient positional information during driving tasks (they might help drivers understand where they were in the road environment even when they were not directly looking at it). Moreover, the distinct appearance of the lead vehicle may have amplified this effect. It was a large yellow object within the road environment, so the looming (optical expansion) of the lead vehicle within the participants' peripheral vision would likely be readily detectable and alarming (Regan & Vincent, 1995; Kiefer, Flannagan, & Jerome, 2006). If this did occur within the studies of this thesis, potentially the absence of a lead vehicle would have made maintaining longitudinal driving performance more difficult. Moreover, a lead vehicle's consistent presence may also give drivers a false sense of security rather than risk (Tivesten & Dozza, 2014) which could then lead to degraded vehicle control. However, the presence of the lead car was maintained throughout these studies in order to impose a consistent need for effective longitudinal vehicle control, provide a sensitive measure of longitudinal driving performance and as an indication of SA (see section 2.2.1.3 for the introduction of this and section 7.6 for further discussion on the use of lead vehicles within this thesis).

Overall, the longitudinal performance findings support the concept that drivers employ their non-focal vision to maintain basic vehicle control (as seen in previous work, Wolfe et al., 2017; Summala, 1998). However, the lateral control measures also demonstrate that this has limits and where exactly displays encourage drivers to focus their visual attention is important to driving performance.

Regarding the result of the driving errors assessment and RQ3 (section 1.5), it is evident within previous work (e.g. Young, Salmon, & Cornelissen, 2013 ; Papantoniou, Yannis, & Christofa, 2019), that drivers may perform unacceptable behaviours or driving errors regardless of whether a distraction (or a clearly evident distraction) is present. Since the errors regarded here were not compared to non-task driving, it is worth cautioning that a baseline of driving errors would have likely occurred regardless of the display task. However, display position did have a significant effect on the error count, with the HDD resulting in significantly higher counts than two HUD positions. Thus, driving error counts were broadly reflective of the other measures of driving performance which were inspected. Therefore, this assessment indicates that error counts can be successfully used as a quick approach to determining demand. Further criteria could be added or changed in order to better detect particular driving concerns.

The driver preference findings reflected previous work, with participants generally expressing a preference for lower eccentricity positions (e.g., Tsimhoni, Green and Wantanabe, 2001). The results for display position preference showed that participants preferred the positions close to the forward view of the road (8 and 9) which were also closest to the intended Pioneer HUD position. The HDD was significantly not-preferred compared to other HUD positions, which is somewhat surprising considering participants are likely to be familiar with HDDs and mere exposure typically results in a positive attitude towards a familiar object (Zajonc, 1968). Within this study, this result may be due to the positioning of the HDD within the vehicle cab, which was somewhat low on the centre console, which may have made it more awkward for participants to look at.

Reflecting on the full pattern of findings, position 8 (which was on the driver's side of the vehicle, at the top) would be considered to have the highest preference and least negative impact on driving performance. However, this may be due to the specific construction of the aftermarket devices used within the study. Position 8 was the closest to the recommended HUD position for the HUD devices being used. The Pioneer HUD is a real aftermarket HUD; it was considered that this added realism and would be beneficial for assessing true participant preference and responses. However, in order to investigate multiple positions, the HUD had to be manipulated in ways which were not intended by the manufactures (Figure 31 and 32). Some of these positions were difficult to obtain without the device otherwise obscuring the drivers' vision. Whilst the arms made it possible for the equipment to be moved across the drivers' field of view (see Figure 32), the process was cumbersome and often left the projector portion of the HUD obscuring part of the participants' view. This may go some way to explain why position 10 (low within the drivers' line of sight) did not show significantly positive results, despite being commonly employed in current real-world displays (see discussion from Lamble et al., 1999). Thus, participants may have been particularly averse to the display positions for which the equipment was not designed. Position 6 also resulted in significantly fewer driving errors than the HDD (position 1), potentially because the required positioning of the HUD device for that location (in the centre of the windshield) was less obstructive to the drivers' view than other similar positions. In order to clearly view the displayed imagery, participants also needed to view the combiner glass at a precise angle. Although they were asked to set the position themselves, so it was clearly visible from a comfortable driving position, some moved enough whilst driving to lose sight of the display task and found it difficult to relocate it whilst driving.

The HUD positioning also led to some issues when monitoring task completion. Eye-tracking was used concurrently in an attempt to monitor whether or not participants were following the instructions (to look towards the display continuously during the task), but this was not always possible due to the following issues. For some participants, the offset camera on the front of the eye-tracking glasses meant that, whilst the participant could see the display stimuli, it was not visible to the eye-tracking camera. Furthermore, although they were encouraged to adjust its positioning from a comfortable driving position, the unusual positioning of the HUD (particularly at high eccentricity locations) often encouraged dramatic head movements which then misaligned the eye-tracking, preventing further monitoring of eye-movement for many of the participants. This also led to participants adopting unusual postures which blocked the eye-tracking glasses from monitoring the participants eyes. Task performance was also deemed to not effectively reflect whether a participant maintained continuous visual attention on the display. As only three data points were collected (participants only had three target letters). Participants were capable of performing the task fully but still occasionally glancing away from the display. Thus, whilst the study design was intended to investigate a worst-case scenario of high visual demand and long glances to the displays, this could not be guaranteed. However, the significant impact on lateral driving performance measures does indicate that display position in combination with the task was disruptive enough to prevent participants from fully protecting their driving performance (Horrey, Alexander & Wickens, 2003) as was intended.

The construction of the simulator cab also meant the HDD had to be positioned somewhat low within the vehicle, approximately level with the centre of the steering wheel. Within modern vehicles, a HDD may be positioned higher in order to reduce the impact of looking down within the vehicle. Thus, the positioning of this particular display could have artificially amplified the contrasting findings between the HDD and HUD positions found within these results.

Notably, several participants found maintaining continual visual attention towards the displays difficult to achieve, with some finding the procedure uncomfortable. It appeared that drivers feel an ingrained need to regularly check the forward road environment, even within a simulation environment, and several struggled to overcome the inclination to do so even when under instruction by the experimenter.

4.5 Conclusions

The findings indicate that increasing the eccentricity of HUD imagery across a windshield increases demand and may have a significant detrimental impact particularly on lateral driving performance. It confirms that this occurs not only with opaque displays but those overlaying the driving environment (windshield displays). The findings indicate that the extent to which a driver may maintain their driving performance with their peripheral vision is dependent not only on the time that they are looking away from the forward road environment, but also by where exactly they are looking to. Drivers significantly preferred the intended HUD positioning, at a low eccentricity (position 8) over other HUD positions and the HDD.

Furthermore, driving errors or unacceptable driving behaviours were counted as an alternative approach to assessing the demand which was imposed by varying display position. Overall, the results indicated that lower eccentricity HUD positions resulted in a lower driving error count compared to the HDD, which is in line with the findings from the driving performance measures (section 4.3.1). These results indicate that, counting instances of driving errors could be used as a quick summary approach to monitoring demand.

4.6 Chapter Summary

Overall, in response to RQ2, the study demonstrates that when displaying a highly visually demanding task, display position will significantly influence driving performance measures, driving error counts and driver preference. Thereby indicating that the positioning of HUD or WSD imagery will significantly influence visual demand.

Regarding RQ3, the combination of a highly visually demanding task and the use of error criteria (see section 4.3.3) produced results which reflected more commonly used driving performance measures, thereby affirming this approach.

The next chapter further addresses how location can influence demand by developing an analysis method to quantify the time a driver can visually attend to a display before driving performances drops to an unacceptable level.

5 Study 3: Establishing the Visual Demand of Displays Across Windshield Locations

5.1 Chapter Introduction

Assessing and quantifying the visual demand of displays is generally conducted using time thresholds. For example, several publications recommend that a vehicle display should encourage a glance of no more than two seconds (see section 2.5). The NHTSA guidelines indicate that this glance duration should also not be exceeded for other aftermarket devices, such as HUDs (NHTSA, 2016).

However, research has shown that this criterion is unlikely to be applicable to HUDs and WSDs. Smith, Gabbard and Conley (2016) examined participants within a driving simulator completing tasks on a HUD and a HDD. The authors found that, although the HUD resulted in longer glances towards the task, it also resulted in better driving performance than the HDD, instead of the deterioration in driving performance which would be expected if long glances were performed to a HDD.

Other work has also investigated the impact of time looking towards HUD imagery by varying task time. As with the previous study reported here (Study 2, Chapter 4) a highly visually demanding task may be used to manipulate a driver’s visual attention. For example, Smith, Bagalkotkar, Gabbard, Large and Burnett, (2021) employed visual detection tasks of various lengths (1, 2, 5, 10 and 20 seconds) which displayed an alternating letters task which required continuous visual attention from the participants. The authors established that the HDD resulted in driving performance issues more quickly (it was evident in the shorter tasks) compared to the HUD. However, the findings of this work may be somewhat limited due using grouped time conditions.

Overall, looking over this work indicates that the length of time a driver may safely look to a HDD is not applicable to a HUD or WSD. The reasons for this phenomenon are likely to be multifaceted. First, the recommendations on glance times (e.g., NHTSA) were based on interactions with HDDs and tasks such as radio tuning, where the driver is required to fully look away from the road environment and within the vehicle. In contrast, HUDs and WSDs position information closer to the road environment and over the road environment using translucent display surfaces. This reduced separation of information means that drivers are not required to look as expansively in order to scan their visual environment to receive information (He, 2013). Thus, the time required by drivers to visually gather information may be lessened by this positioning. Furthermore, the length of time a driver looks towards these displays may be less disruptive to their driving, again because of their positioning close to the typical forward view. This may enable a driver to look towards the display yet simultaneously use their vision to detect hazards or changes within the environment (e.g., Summala, 1998). Finally, though not investigated within the current thesis, HUDs and WSDs can be presented at depths closer to the focal depth of the road environment (compared to HDDs). As a result, less eye-accommodation is required, and it may reduce driver eye-fatigue (Ablaßmeier et al., 2007; Gabbard et al., 2019) (see section 2.6.5).

With the likely expansion of HUDs and WSDs it is important to better quantify the visual demand of HUDs and establish how long a driver can look towards HUDs compared to HDDs. Equally, since many of the benefits of HUDs and WSDs appear to be due to positioning, it is important to establish how these factors vary when display imagery appears anywhere across the windshield.

In order to address RQ2 and RQ3, this study develops a novel analysis approach to continuously quantify how visual demand may vary when displays are positioned across a windshield, by establishing how long a driver may look towards a display before their driving performance becomes unacceptable or unsafe.

Objectives: Establish how long a driver can look to a visually demanding task across windshield locations before drivers consider it unacceptable or unacceptable driving performance criteria are met.

Develop and use innovative approaches to investigate intrinsic windshield display demand.

5.2 Methods

5.2.1 Participants

A total of sixty participants volunteered to participate in the study with 43 male (72%) and 17 female (28%) all recruited through emails or posters at the University of Nottingham. All participants held a driving licence for a mean of 10.02

years (SD=8.97 years) and on average each participant self-reported driving 6720 miles (~10815km) each year. All participants were above 18 years old, and the mean age was 28.18 years (SD= 8.62 years). Twenty-two of the participants (37%) self-reported that they had previously driven a driving simulator. Forty-six reported that they had used a touchscreen device within a road vehicle, and finally, 14 (23%) reported that they had previously used a HUD within a vehicle.

5.2.2 Design

A mixed design was implemented. The independent variable was the display locations that participants encountered (see Figure 36 and Figure 38). A total of 51 locations were investigated (48 windshield display locations and 3 HDD locations).

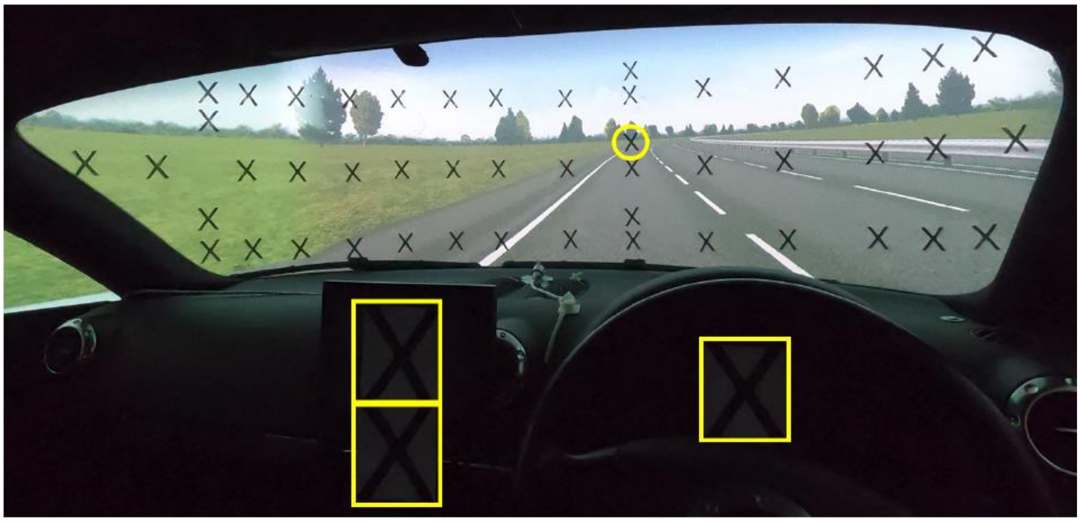

Figure 36. All the positions which were examined are represented by an 'X'. The yellow circle indicates the most central display position at 0° eccentricity. The yellow boxes are used to highlight the HDD positions as they are difficult to discern within the image. Two are located on the centre console and one is at the instrument cluster.

The approximate visual eccentricity for each location, was calculated in a similar manner to other driving display research (Recarte & Nunes, 2003; Wittmann et al., 2006) using trigonometry and distance measurements within the study setup (see Figure 37 and Figure 38). The 0° point was considered to be the middle of the road ahead at the horizon, as it would be the expected target location for a driver's vision.

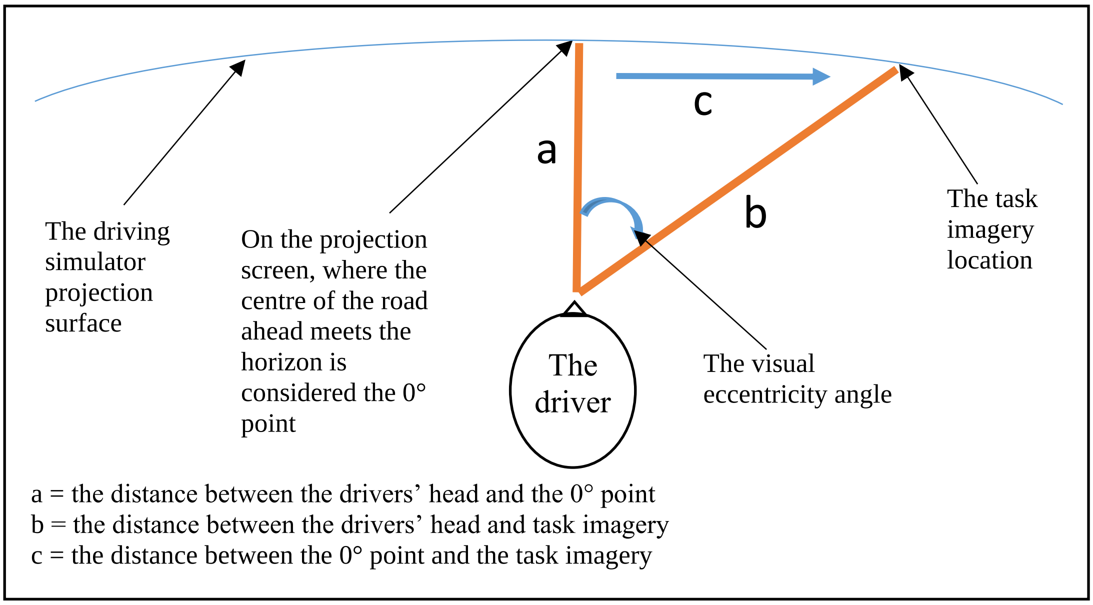

Figure 37. A top-down diagram demonstrating the measurements required for calculating the visual eccentricity angle.

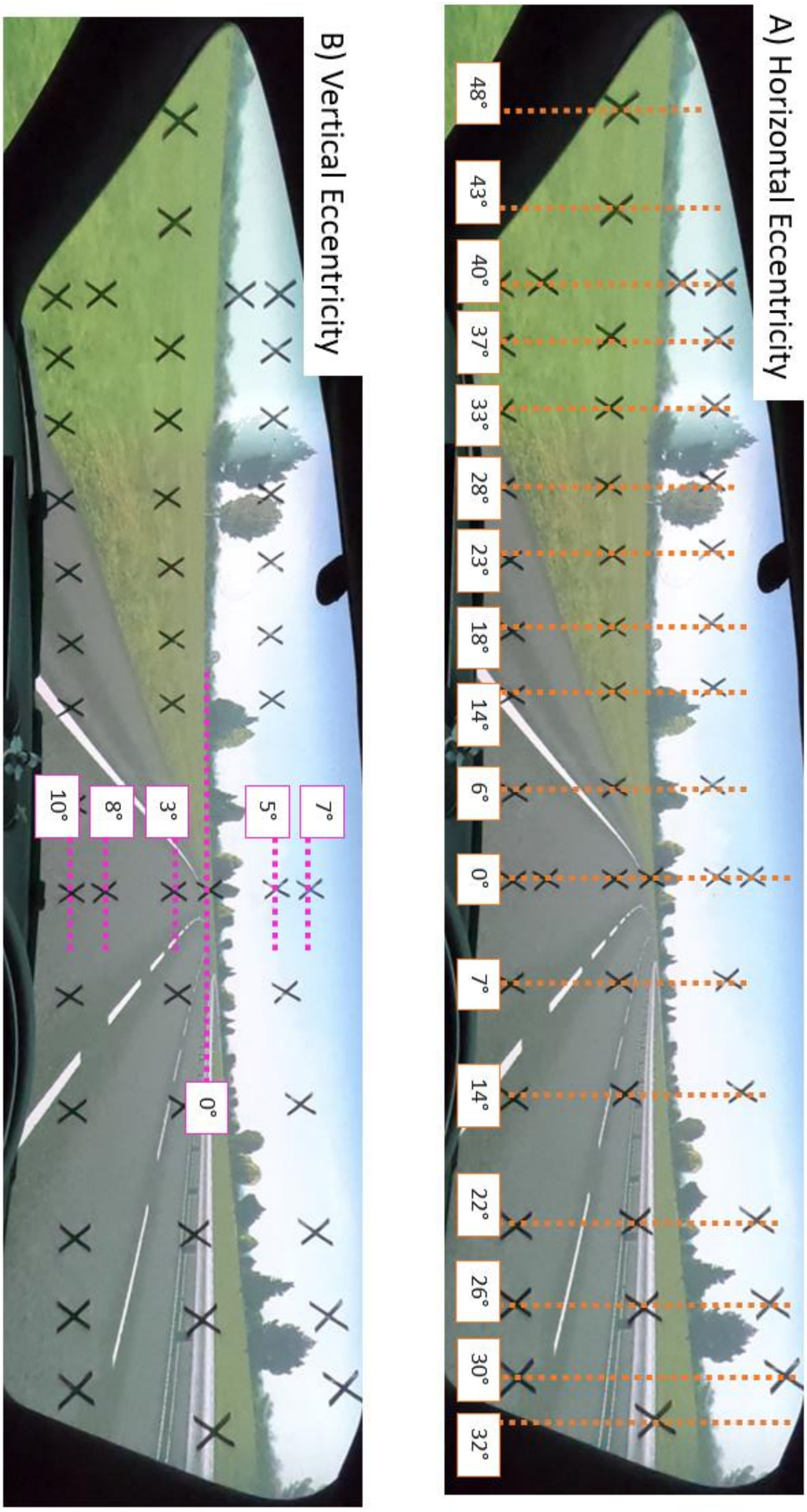

Figure 38. A visualisation of the eccentricity angles of the windshield display positions which were examined. Each 'X' represents a display position which was examined.

Due to the many display positions (51), participants only interacted with a selection of the potential positions; these were selected from across the potential display positions and always encompassed some from the far left, middle and centre of the windshield (13 in total, 12 being on the windshield and one HDD). At least 13 participants completed each of the individual display locations. The study was conducted using this approach in order to maintain participant well-being and reduce the impact of fatigue. Hence, a mixed design was used. The order in which participants encountered each location was rotated in order to further reduce any fatigue effects.

Several driving performance measures, and their timings, were recorded as dependent measures. The criteria for whether a participant’s driving became ‘unacceptable’ was split into two categories: lateral driving performance and longitudinal driving performance. The precise criteria are detailed in the sections below (sections 5.3.2 and 5.3.3). Participants were also asked how long they believed it would be acceptable to look towards each display position.

5.2.3 Materials

The study was conducted in a driving simulator at the University of Nottingham (see Figure 5 and Figure 39). The vehicle cab was constructed from a complete Audi TT (right-hand drive) whilst the simulated environment was projected onto a 270° screen. STISIM3 was used as the software to simulate the visual road environment. Video cameras were mounted to the interior of the vehicle to monitor participant behaviour throughout.

Rather than using an aftermarket HUD device to create a WSD effect (which had some limitations, see section 4.4), the display was simulated by projecting display imagery over the already projected environment from the roof of the vehicle cab (Figure 39). This enabled the simulated imagery to be easily and quickly moved between conditions.

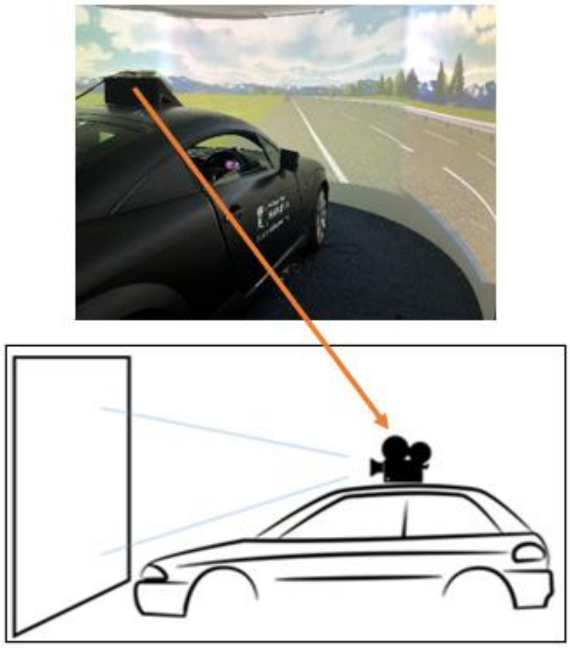

Figure 39. A photo and diagram of how a projector was mounted to the top of the simulator vehicle. It projected over the simulated environment in order to simulate a WSD.

The HDD positions were created using a small LCD either fitted to the instrument cluster or the centre console of the simulator vehicle cab (see Figure 36).

SMI eye-tracking glasses were used during the study to monitor whether participants were able to maintain their visual focus towards the tasks as instructed.

Participants were asked to complete questionnaires throughout the procedure to attain their opinions and monitor their well-being (see Appendix A and D).

5.2.3.1 Tasks

During each drive participants experienced three visual-detection tasks presented at one of the display locations (see Figure 36 and 38). The tasks were visually demanding and were designed to capture and control the participants' visual attention, as previously discussed (see section 4.2.3.1), rather than allow participants to regulate their own visual behaviours. This was done with the intention of deliberately taking their visual attention away from the road environment and towards the display location. Thus, the study could examine how long drivers are able to look to these display locations (and away from the road) before their driving performance became unacceptable. Before each drive participants were shown by the experimenter where the task would appear.

At the start of each task the driver would be prompted with an audio signal (3 beeps totalling 1 second in duration) to inform them that they should look towards the display location for the task to begin. During the task, random letters appeared and disappeared rapidly at the display location, each remaining in view for 0.1 seconds, thereby making them difficult to differentiate. Occasionally, a target letter would remain on screen for a longer time period (0.3 seconds). The participant was required to speak aloud any letters which they believe stayed on the display for the longer time period. As a result, to successfully complete the task participants had to look away from the road environment and towards the display location for the duration of the task. Participants were also instructed to look to the display for the duration of the task. Task performance was not under evaluation since the purpose of the task was to capture visual behaviours away from the road environment (4.2.3.1). The tasks were created using PsychoPy3 (Peirce et al., 2019).

The length of the tasks was determined iteratively according to its exact positioning throughout the study. As discussed previously (see section 4.4) participants found continuously maintaining their visual attention away from the forward view of the road to be difficult and in some instances uncomfortable. As a result, the task length was edited whilst the study was conducted with the aim of still capturing the time thresholds, but also not forcing participants to maintain visual attention unnecessarily in a manner which could become uncomfortable. The task lengths used for the analysis are presented in Figure 40. It was assumed that an unacceptable driving occurrence would occur before reaching these task time lengths for the majority of participants. The number of target letters varied with the length of the task, with a target appearing around every 5 to 10 seconds (approximately 4 target letters per 20 seconds).

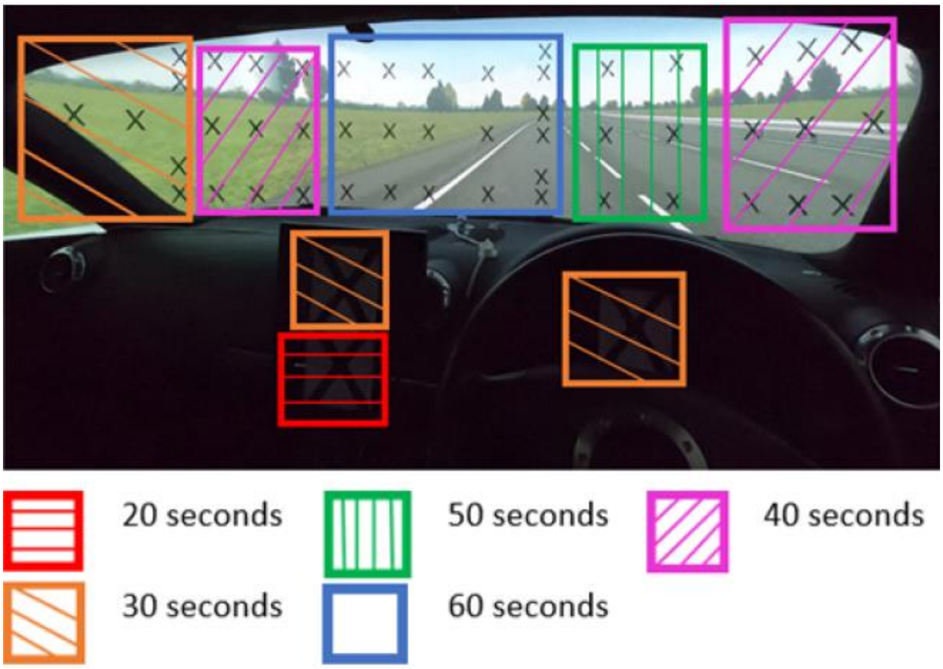

Figure 40. The length of the tasks analysed for each display position.

5.2.4 Procedure

Ethical approval was granted by The University of Nottingham Faculty of Engineering Ethics Committee prior to commencement of the study.

Once arriving at the simulator, participants were provided with an information sheet describing the study intentions and procedure. Once participants had the opportunity to ask any questions, they signed a consent form before continuing. Next they completed questionnaires including a demographic questionnaire and a simulator sickness questionnaire (Kennedy et al., 1993) (see Appendix A and D). Participants were introduced to the driving simulator and completed a practice drive to familiarise themselves with the driving controls. Before each drive, participants were shown where the task would appear. Participants were then fitted with the SMI eye-tracking glasses. These were used during the study only to monitor whether participants were able to maintain their visual focus towards the tasks as they were instructed. Within the information sheet (Appendix D) participants were instructed to try and maintain a consistent distance behind the yellow car and to not fall too far behind it. During a drive if a participant fell more than 150m (492ft) behind the lead car, an audio message played in the simulator which encouraged them to catch up: *"You are falling too far behind the lead vehicle. Please try to catch-up and match the lead vehicle's* *speed"*. Participants were asked to refrain from touching or moving the eye-tracking glasses after calibration to prevent tracking errors.

For each display condition, participants completed a short, simulated drive along a 3-lane motorway as would be typical within the UK. The roadway contained regular curves which created some visual roadway demand and meant participants were required to provide lateral inputs in order to maintain lateral driving performance (Tsimhoni & Green, 1999). A curve occurred every 2000ft, was 1700ft long with a radius of 2000ft (a curve every 610 metres, which was ~510 metres long with a radius of ~610 metres). Participants were asked to remain within the outside, left lane following the lead yellow car, which appeared once they were 1000ft (~305 metres) into the drive. The leading yellow car varied its speed in a sine-wave pattern between 55mph and 75mph over approximately 60 seconds (or between ~88.5kmh and ~120kmh over about 60 seconds). As within the previous studies (Chapter 3 and 4), the lead car was included in order to better assess longitudinal driving measures (see section 2.2.1.3).

During each drive, the task would appear three times at the designated display location. Participants were asked to complete the task as described above (section 5.2.3.1). SMI eye-tracking glasses were used to monitor the participants' gaze; the live video feed was transmitted to the experimenter in the controller room. If a participant was looking away from the task to glance to the road, they were verbally reminded of the instructions by the experimenter (e.g., *"Please remember to look at the task and not the road when the tasks are active"*).

Participants were asked to complete a questionnaire asking about their opinion on the position they had just experienced after each drive (Appendix D). Part way through the study, participants were also asked to complete a Simulation Sickness Questionnaire (SSQ) (Kennedy et al., 1993) to monitor their well-being within the simulator (Appendix A).

After completing the drives, participants were provided with a debrief sheet and an amazon voucher (with a value of £10) as compensation for their participation. Participants were also asked to sign a post-trial form which confirmed that they were feeling well after using the simulator and had received their voucher. Overall, the procedure took around 2 hours for each participant.

5.3 Results

5.3.1 Time Threshold Approach

In order to investigate this area, a novel approach was developed from the work conducted previously (Chapter 4) on driving errors and manipulating visual attention with visually demanding tasks.

For this approach, criteria were created, which once achieved, were assumed to indicate an 'unacceptable' level of driving performance. This criterion is detailed below for each measure (section 5.3.2 and section 5.3.3). The study intended to examine how long a driver may be able to glance continuously towards a display location (and not look back to the forward road environment) before their driving performance unacceptably degrades. Thus, for each measure the data was inspected for whether this criterion was met. If it was met, the time at which it occurred (how long into the task) was recorded. Thus, for each measure and task completed, a time value was created which quantified how demanding the display was.

Data from specific tasks were excluded if the participant clearly glanced away from the task before reaching any unacceptable criteria according to cameras within the vehicle. The length of the tasks varied between the display positions (see Figure 40), so caution should be exercised during comparisons. The contour plots were created using linear interpolation.

5.3.2 Lateral Driving Performance

Lateral driving performance was considered unacceptable if any part of the participants' simulated vehicle exceeded the lane boundary. The participants' vehicle was 6ft (~1.83m) wide whilst the lane was 12ft (~3.66m) wide. For this analysis it was noted when this occurred during the task and how long into performing the task it occurred.

It should be noted that participants did not commonly start the task in an ideal position in the centre of their lane. The mean starting point was 1.52ft to the left of the central position (SD=1.38). The potential reasons and consequences of this are discussed below (section 5.4).

5.3.2.1 Occurrence Percentages for Lateral Driving Performance

The first analysis recorded whether participants met the unacceptable lateral driving performance criteria during the task (Figure 41).

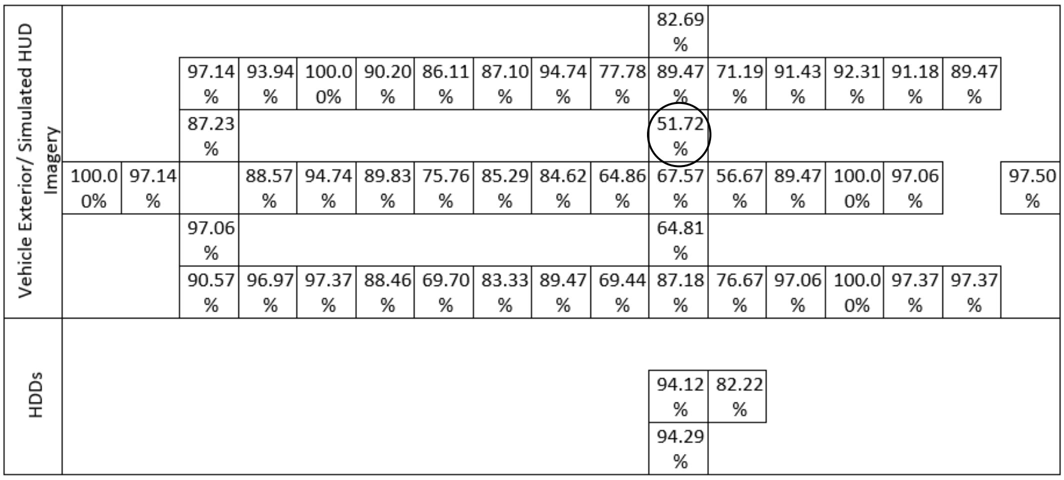

Figure 41. The percentage of tasks where some part the participants' vehicle exceeded the lane boundary. The percentage values are positioned in a manner reflective of the task positions as seen in Figure 36. The circle indicates the 0° position.

Overall, these results indicate that the majority of participants exceeded the lane boundaries at some point whilst completing the visually demanding task regardless of display position. However, the number was lower when the display task was located centrally, near where the lead vehicle would be located within the drivers' field of view.

5.3.2.2 Time Thresholds for Lateral Driving Performance

These results used the time threshold approach (see section 5.3.1). They reveal how long the participant could continue the task (in one continuous glance) before leaving the lane. The average time in seconds is presented as a contour map below (Figure 42).

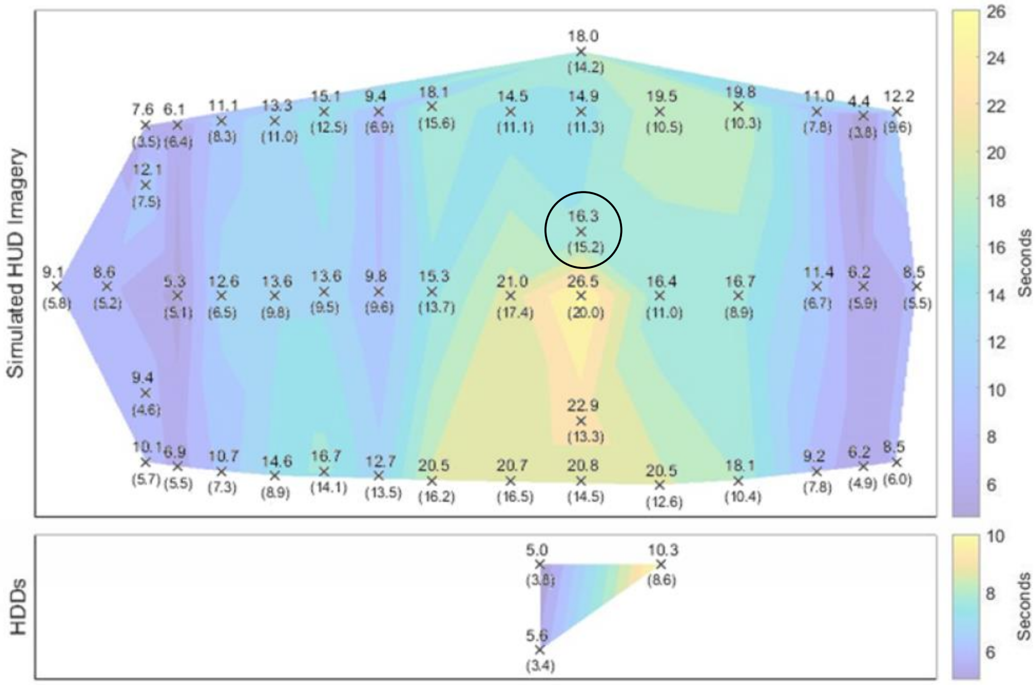

Figure 42. A contour map of the mean time (in seconds) into the task where the participant's vehicle first exceeds the lane boundary. Standard deviation (SD) is presented in brackets. Each 'X' indicates a display position as mapped in Figure 36. The circle indicates the 0° position.

Tasks which were located closest to the drivers' forward view of the road (at the lowest eccentricity) generally resulted in longer times before a lane departure occurred. There also appeared to be some influence of verticality, with displays positioned centrally and low resulting in longer times than those also central but high. Finally, there is also a high standard deviation across many of the positions (see Figure 42).

5.3.3 Longitudinal Driving Performance

In order to examine longitudinal driving performance continual time-to-collision (TTC) to the lead vehicle was calculated and examined (see SAE International, 2015). When TTC reached a value lower than 1.5 seconds then longitudinal driving performance was considered to reach an unacceptable level. This value is more conservative than the one used within the previous study (Chapter 4). This was done to ensure it could be undisputedly considered as unacceptable driving. TTC values under this criteria are regularly considered safety critical in the literature (Chen, Shen, & Wang, 2013; SAE International, 2015; Van Der Horst & Hogema, 1994).

At the beginning of the tasks the bumper-to-bumper time gap between the participants' vehicle and the lead car was, on average, 1.04 seconds (SD=0.09). This indicates that many participants started the task somewhat close to the lead vehicle, since drivers are typically accepting of times between 1 to 2 seconds (Ayres, Li, Schleuning, & Young, 2001). The reasons and implications of this are considered in the discussion section below (section 5.4).

5.3.3.1 Occurrence Percentages for Longitudinal Driving Performance

First looking at the proportion of tasks where this unacceptable criterion (TTC of < 1.5 seconds) was met. The results are presented in Figure 43.

Vehicle Exterior/ Simulated HUD Imagery											100.00%						
			91.67%	85.29%	94.59%	92.31%	97.37%	97.30%	100.00%	100.00%	100.00%	100.00%	100.00%	97.30%	91.18%	95.00%	
			86.00%								100.00%						
	98.36%	85.71%		88.89%	89.47%	98.21%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	97.22%	100.00%		97.37%
			93.94%								100.00%						
			91.53%	96.67%	92.11%	94.55%	100.00%	96.55%	97.30%	100.00%	100.00%	98.33%	100.00%	91.89%	89.47%	90.24%	
HDDs											75.00%	82.21%					
											96.10%						

Figure 43. The percentage of tasks where the TTC criteria was met. The percentage values are positioned in a manner reflective of the task positions as seen in Figure 36. The circle indicates the 0° position.

The results show that the unacceptable criteria were reached across most of the display conditions. In several of the central display positions all of the tasks (100%) reached the unacceptable longitudinal driving criteria. This indicates that a greater percentage of unsafe driving occurred when the task was positioned at a low eccentricity, which is contrary to the results found for lateral driving performance.

5.3.3.2 Time Thresholds for Longitudinal Driving Performance

Again, this analysis used the time threshold approach described above (section 5.3.1) in order to establish how long a participant could look towards a display position before their longitudinal driving performance became unacceptable. The results of this analysis are presented in a contour map (Figure 44).

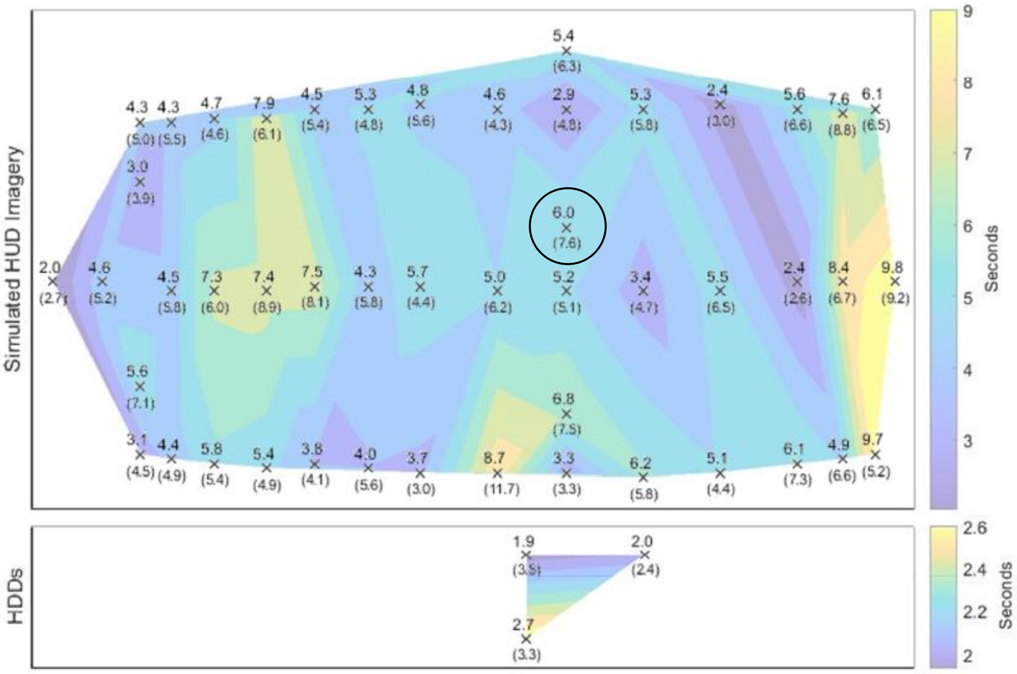

Figure 44. A contour map of the mean time (in seconds) into the task where the participant's vehicle reached a TTC of <1.5 second. Standard deviation (SD) is presented in brackets. Each 'X' indicates a display position as mapped in Figure 36. The circle indicates the 0° position.

The results show no clear pattern of how windshield display position influenced longitudinal driving performance time. The standard deviation was high for many of the positions (see Figure 44). It is evident that HDDs typically reached the unacceptable criteria before the WSD positions. However, the mean times were fairly consistent across the other display positions. On average, participants reached the unsafe TTC criteria 5.11 seconds after starting the task.

5.3.4 Participant Perspective

After completing a task position, participants were asked: *"How long do you think is an acceptable time to look away from the road, and towards that location?"* (Appendix D). The results for each of the positions were averaged and are presented in the contour map (Figure 45).

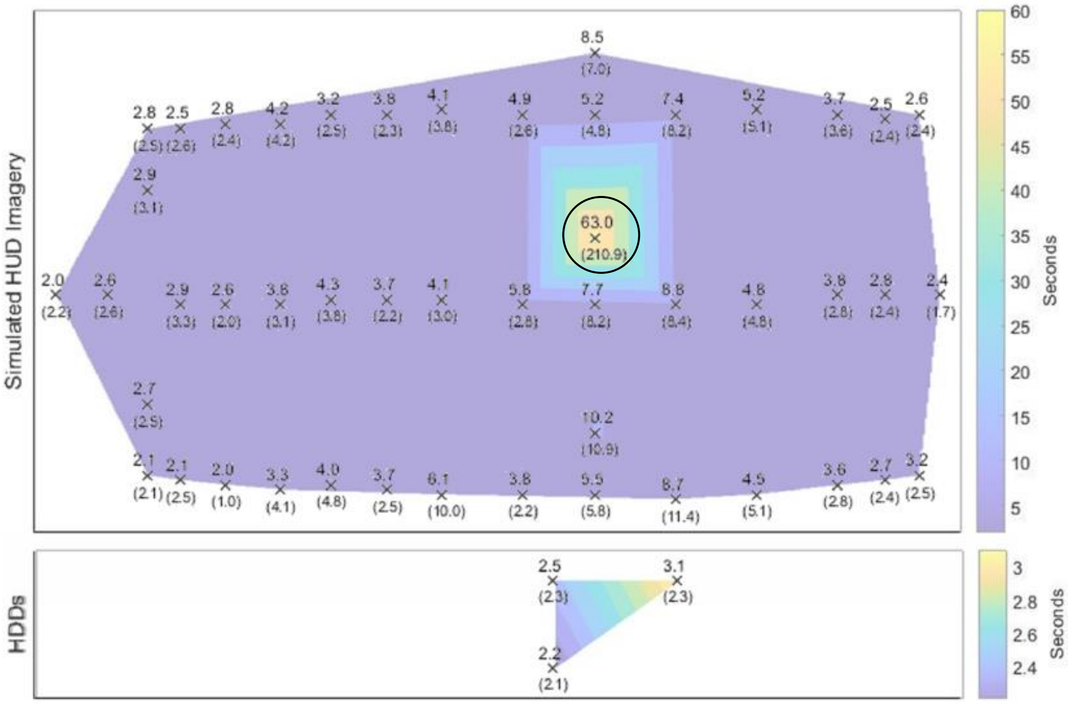

Figure 45. The mean participant perspective on how long (in seconds) it would be acceptable to look towards each display position Standard deviation (SD) is presented in brackets. Each 'X' indicates a display position as mapped in Figure 36. The circle indicates the 0° position.

Participants, on average considered it acceptable to look to the 0° position for over 60 seconds (Figure 45). However, the standard deviation for this was very high (210.9 seconds).

5.4 Discussion

Overall, the study aimed to outline how long it takes before unsafe driving occurs, when drivers make a continuous glance towards windshield display imagery. Looking across all the findings, the standard deviation values were very high, indicating that the times varied greatly between participants (see sections 5.3.2.2, 5.3.3.2 and 5.3.4).

The results for lane keeping ability (lateral driving performance) were broadly as expected based on the previous work conducted within this thesis (Chapter 4, Study 2). First, as display eccentricity increased, a higher proportion of tasks resulted in participants leaving the lane boundaries within the task time (Figure 41). Secondly, if the participant did leave the lane during the task, they were able to stay in lane for longer if the task was located at a low eccentricity (close to the forward road view) (Figure 42).

There also appeared to be some impact from vertical positioning, as central-low positions resulted in a longer maintenance of driving performance than those which were central and high. This is in line with previous research which commonly suggests an ideal HUD position would be 6 to 10 degree below the driver's line of sight (Gish & Staplin, 1995) (see section 2.6 for summary). However, the reason for this is most likely due to the visual information available to the driver beyond the display they were attending to. When engaging with low, central positions, participants were probably able to use their peripheral or ambient vision to detect the lane markings and maintain themselves between them. In contrast, when the display position was high, over the sky, there is little visual information surrounding the display which would help maintain driving performance.

It was noted that at the start of the tasks that participants tended to be positioned more to the left of their lane (section 5.3.2). There are two likely causes for this behaviour. First, when the participants' vehicle entered the simulated scenario, it was positioned slightly to the left of the lane, which may have influenced the participants' perception of the road environment. If they had started more centrally, longer lane-keeping times may have been recorded. Secondly, the simulated road contained an emergency stopping lane on the left (referred to as a 'hard shoulder' within the UK) whereas the right-hand lane contained passing traffic. As a result of this road environment, participants may have felt safer keeping further to the left as if they made a driving mistake it was less likely to result in a collision with another vehicle.

The average recorded times (Figure 42) demonstrated that many participants were able to exceed the recommended two second glance (AAM, 2003; NHTSA, 2012; NHTSA, 2016) before their lateral driving performance became clearly unacceptable. This was particularly true for the central positions, thereby indicating that the demand was lower, and drivers are able to maintain basic lateral driving performance even whilst fixating on one display location. However, as eccentricity increased, the times lowered greatly, indicating that more restrictive glance time criteria may be more applicable to displays in those locations.

The longitudinal driving performance results show that for many of the display positions (20 out of 51) all the tasks resulted in the unacceptable criteria being met (Figure 43). Furthermore, this was particularly prevalent in the low eccentricity locations. Thus, the low eccentricity positions appeared to result in more instances of unacceptable longitudinal driving performance.

The reason for these longitudinal findings may be partially due to the role of the lead vehicle. Participants may have remained close to the lead vehicle particularly when the task was nearby (at a low eccentricity) in an attempt to use it as a driving aid (see section 4.4). Low eccentricity positions would enable drivers to use their peripheral or ambient vision to detect changes in the lead vehicle's positioning or speed, which they could then imitate. This effect may have been less prevalent in the higher eccentricity positions because the lead car would not be clearly discernible whilst looking far away from the road ahead. This effect may have also been partially due to the study instructions. Participants were clearly instructed to follow the lead vehicle and an automated message sounded if they fell too far behind which reminded them to keep up. Thus, participants may have kept unusually close to the lead vehicle in order to best follow this direction. (The lead vehicle was implemented in these studies to serve several purposes, see section 2.2.1.3 for details). Since a lead vehicle was present within all of the studies conducted for this thesis, this discussion point is evaluated further in the final chapter (section 7.6).

As with the lateral measures, drivers were generally able to look to the display conditions for longer than two seconds before their longitudinal driving performance reached the unacceptable criteria. However, the times at which participants did reach the criteria varied greatly across the windshield with display positioning having no clear impact on the results. These results are likely due to the use of TTC as a measure. Notably, participants often started the task close to the lead vehicle with a time gap of 1.04 seconds on average. Yet this did not necessarily meet the unacceptable TTC criteria due to the nature of the calculation. TTC is considered infinite if the gap between vehicles is expanding, because no collision may ever occur. In contrast, time gap is simply the time interval between two surfaces (SAE International, 2015). Therefore, it may be said that the average participant started the task very close to the lead vehicle but whilst increasing their distance away from it. Therefore, despite being close to the lead vehicle, TTC would be measured as infinite.

Then at some point during the task they would gain on the leading vehicle and meet the unacceptable longitudinal criteria. Thus, the TTC measure, whilst commonly used, may not have fully captured the extent of how longitudinal performance was being affected.

Throughout the results presented here, the HDD positions often resulted in more instances of unacceptable driving faster than most of the WSD positions. Longitudinal driving performance became unacceptable for these display positions at around two seconds into the tasks which supports the current guidelines that tasks should encourage no more than two second glances to these types of displays (NHTSA 2012, AAM 2003). However, the lateral driving performance data showed that participants were able to stay within the lane for a much longer time period than these guidelines would indicate (Figure 42). This may be due to the clear road design and lane marking making lateral driving performance easier than may be typical.

Differences in the results between the windshield positions and the HDD positions are likely due to the eccentricity and location effects discussed throughout this thesis (e.g., see Chapter 2). HUDs and WSDs enable drivers to keep their eyes up and towards the road environment (so they can use their peripheral vision to maintain vehicle control), whereas HDDs force participants to look within the vehicle. This effect may also be amplified because of the focal depths of the tasks. Within this study the WSD tasks and the road environment were all presented on the same focal plane (on the projection surface, about 3 metres in front of the driver). However, the HDDs were within the vehicle, within 1 metre of the driver, thereby requiring greater eye accommodation (section 2.6.5).

After experiencing a display position, participants were asked for their own thoughts on how long they could look continuously to that location whilst driving. The results showed that, on average, participants believed they could look continuously to the central location for more than 60 seconds, which is a long time period. Although, the standard deviation results indicate that the responses to this question were highly variable (see Figure 45, section 5.3.4). One explanation for this is that when looking towards the central location participants believe they are looking to where they ‘should’ when they are driving: at the road environment ahead. However, this perspective is concerning for several reasons.

Firstly, it is important to highlight that, looking does not mean seeing (also discussed in 2.2.2.1). Although a driver may feel as though they are aware of the road ahead when they are attending to central WSD imagery, this will not necessarily be the case due to the attentional constraints imposed by attending to the display. As a result, drivers attending to the imagery may not detect a hazard or visual cue, even within the same area, due to inattentional blindness (Mancero et al., 2007). Furthermore, high perceptual load can exacerbate this effect (Murphy & Greene, 2016), so visually demanding displays are likely to be especially problematic. Secondly, to drive effectively and safely drivers need to regularly scan throughout the visual environment to detect any upcoming hazards; the road ahead is not the only place a driver should look (Victor, Engström, & Harbluk, 2008). Yet the results here indicate that several of the participants thought it would be appropriate to not do this, and instead look at only a central area for over a minute. Previous work has shown participants using HUDs can become overconfident and consider themselves to be fully aware of the road environment, even when they have missed elements (Kim & Gabbard, 2022). This has negative implications for the real-world use of windshield displays. These results indicate that some drivers might feel comfortable only looking to one display area for a concerning amount of time. The next study (Study 4, Chapter 6, section 6.4) further reflects on these self-reported findings by examining some of these concerns in greater detail and investigating how drivers naturalistically engage with windshield displays.

In contrast, the participant perspective results on HDDs showed that participants thought around 2 to 3 seconds would be acceptable for a continuous glance, which is remarkably close to the current assessment times for HDDs (e.g., NHTSA, 2012). This is likely due to participant familiarity and experience. Most will have interacted with some form of HDD previously and as a result are instinctually aware of how long they can safely look to it. If this interpretation is correct, increasing experience with HDD and WSD may enable drivers to better self-manage their visual attention when interacting with these displays in the future.

Finally, this study also encountered some limitations. Participants were given thirty seconds between tasks to drive normally. However, it was evident that participants did not always return to an ideal driving position before the start of the next task. As thirty seconds should have been long enough to return to an appropriate road position, it is unclear whether this reflects naturalistic driving. Potentially, this was due to the study construction which was encouraging unusual driving behaviours throughout. Furthermore, limited measures were used within this work to evaluate driving performance. While rigorous, they will not have fully captured the intricacies of driving performance and will not fully dictate whether or not an interaction with a display should be considered safe. However, for the purposes of this study they provide a succinct indication of how visual demand varies across windshield display positions and when driving performance degrades as a result.

5.5 Conclusions

Overall, the study suggests that drivers are generally able to maintain their basic driving performance when looking continuously to a HUD or WSD for longer than looking to a HDD. As a result, the current guidelines recommending continuous glances of no more than two seconds (NHTSA) are most likely not appropriate and are needlessly restrictive for these displays, as suggested by others (see Smith, Gabbard, & Conley, 2016). The time values presented here (Figure 42 and Figure 44) can function as initial maps for designers, highlighting the visual demand implications of display imagery across the windshield. They also pose as a first step in the potential development of new time criteria to help evaluate such displays. However, much further work is required to fully develop new criteria. For example, this data only looks at a simple driving environment and previously input from numerous sources (e.g., NHTSA, 2012) has been used to develop evaluation criteria. For further discussion on this potential future work direction, see section 7.7.

Importantly, the work here further demonstrates that a driver’s ability to maintain driving performance, whilst interacting with a display, is greatly dependent on imagery location. As display imagery was positioned at higher eccentricities, lateral driving performance was increasingly negatively impacted (Figure 42). Longitudinal performance did not show the same pattern of results due to display position (Figure 44). However, this may be due to the use of a lead vehicle within the road environment and TTC as a criterion.

The participant perspective results (Figure 45) indicate that some participants may be overly confident in their ability to control a vehicle whilst looking at a low eccentricity display for long time periods. This point is further explored within the final study (Study 4, Chapter 6).

5.6 Chapter Summary

Overall, this chapter addresses RQ2 and RQ3 by conducting an expansive study examining 51 display positions.

Regarding RQ2, the lateral driving performance results are generally reflective of previous work. As display eccentricity increases, driving performance degrades and degrades faster. The contour maps provide a more detailed insight into the nuances of how exact positioning may influence driving performance. Contrary to expectations this pattern of effect was not clearly evident within the longitudinal measures, likely due to the lead vehicle and the choice of measures. The participant perspective results indicated that participants were aware of how demanding high eccentricity displays or HDDs are likely to be, and participants generally did not believe that long glances to those locations would be acceptable. However, there is an indication that some participants are overly confident in their ability to look solely to central display positions (Figure 45).

Regarding RQ3, a novel analysis approach (see section 5.3.2) was used to establish how long a driver may look towards a display position before their driving became unacceptable. Overall, the analysis was successful in achieving this objective although, different ‘unacceptable’ criteria could be included to capture more nuance or investigate specific driving performance concerns.

The next chapter, and final study, combines several topics of this thesis to examine how drivers naturally respond to various task types across various display positions.

6 Study 4: Naturalistic Interactions Across Various Tasks and Windshield Locations

6.1 Chapter Introduction

The final study was conducted to combine two primary elements of the present work: the importance of display imagery location in combination with task nature. Thus, this study addressed RQ1 and RQ2 (see section 1.5). The previous work on display location within the present thesis has intentionally manipulated the driver's eye-movement in order to investigate visual demand (Chapter 4 and 5). Instead, this study investigates how drivers respond more naturalistically to displays on the windshield. As discussed previously (section 2.2.2) visual behaviours provide compelling insights into the cognitive processes which are guiding both the driver's driving behaviours and their interactions with vehicle displays (Rosner, Franke, Frederik, & Attig, 2016). Thus, it was not controlled here and was instead used as a primary dependent measure to investigate the drivers' unimpeded engagement with these displays.

Other investigations into how drivers behave naturalistically with technologies within vehicles demonstrate that how drivers respond is often dictated by the driving context. For example, the visual behaviours of drivers completing tasks on mobile devices has been influenced by factors such as whether there was an on-coming vehicle, whether they needed to turn or whether they were following another vehicle (Tivesten & Dozza, 2014). However, Gerber, Schroeter, Xiaomeng and Elhenawy (2020) found that drivers were more likely to self-interrupt their engagement with a HUD and look back to other areas of the environment, compared to when they were using a mobile device within an automated vehicle. This indicates that using a HUD or WSD may encourage drivers to stop their non-driving related task (NDRT) and attend to the road environment. Ablaßmeier et al., (2007) compared eye-tracking with a HUD and a HDD displays and found that HUDs had a lower gaze retention, indicating that HUDs may lead to beneficial visual behaviours. However, the previous study (Study 3, Chapter 5) found that some drivers considered it acceptable to use a centrally located windshield display continuously for over a minute (section 5.3.4), but it is unclear whether they would actually interact or engage with windshield displays in this manner.

Overall, research is needed on how this visual behaviour may vary with display imagery location on the windshield. Equally, research is needed to evaluate how this behaviour may vary with different display imagery and different tasks; this study initiates this required work.

In order to gain a fuller understanding of visual behaviours with displays across the windshield, two different tasks were used. First, a menu task was used. This was employed to address the concern of how a potentially near-future ecologically valid task would impact glance behaviour across windshield locations; thereby following up on the previous work conducting in Study 1 (Chapter 3). Secondly, a game task was used. Recommendations on in-vehicle displays (see section 2.5), typically advise that display interfaces or tasks should avoid certain characteristics. For example, NHTSA (2010) argues that visual information which involves continuous motion (such as video or automatic scrolling text) should not be visible to the driver during driving. Others recommend restricting the presentation of certain non-driving related information while the vehicle is in motion (JAMA, 2004). The game task used here deliberately contravened these recommendations and gave participants the opportunity to choose how much or whether they interacted with a game in order to gain a greater understanding of display location on driver visual performance and driver willingness to engage with these displays.

In summary, this thesis previously looked at more natural behaviours with ecologically valid HUD tasks (Study 1), now this study is looking at this across display locations in order to address RQ1 and RQ2. Furthermore, to better explore driver behaviour, an intentionally disruptive task was used across locations to monitor how drivers chose to engage.

Objectives: Examine more naturalistic visual behaviours; how they vary with display position and near-future windshield display tasks.

Establish how a task’s nature/type influences driver engagement with displays in various positions.

6.2 Methods

6.2.1 Participants

Eighteen participants, consisting of staff and students from the University of Nottingham, were voluntarily recruited. All participants were at least 19 years old

(Mean = 28.44 years, SD = 8.45) and included 7 females (38.89%) and 11 males (61.11%). All participants held a driving license (Mean = 8.60 years, SD = 7.34). On average the participants self-reported they drove 4920 miles (~7918km) per year (SD = 4907). Three participants reported that they had previously used a HUD in a car and 8 reported previously using a driving simulator.

6.2.2 Design

A within-subject 2x3 design was employed. The study was conducted in the medium fidelity driving simulator at the University of Nottingham, as used in the previous study (see Figure 5 and Figure 47). For each display position, participants experienced 2 different visual-manual tasks, a menu task and a snake-game task. A total of 3 display locations were investigated (Figure 46) two of which were simulated windshield display positions (HUD-A and HUD-B) and one of which was an LCD in the centre console (a HDD). HUD-A was off to one side roughly in-line with the rear-view mirror and over the hard-shoulder; HUD-B was over the participant's forward view of the road, just below the horizon (for eccentricity details please see the description for Figure 46). The three locations were selected to cover high and low eccentricity positions. No other display positions were investigated due to practical considerations. Thus, participants experienced 6 conditions in total (2 tasks x 3 display locations). The independent variables were the display location and the task presented. The dependent variables primarily included various eye-movement measures and interaction scores from the snake game task.

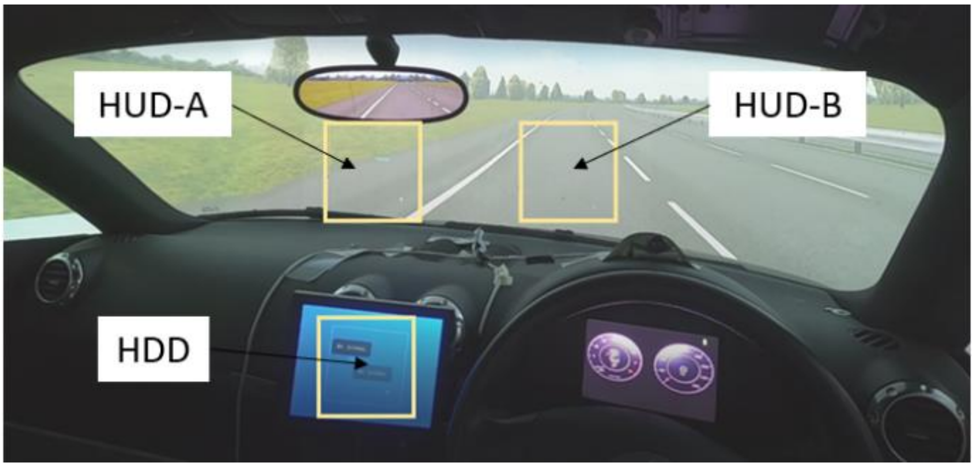

Figure 46. The display locations examined viewed from within the driving simulator vehicle. Vertically the HUDs were positioned between 3°s and 14°s down from the horizon (0 degrees). HUD-B was horizontally positioned between 5° to the left of the centre and 5°s to the right. The left far corner of HUD-A was at approximately 26°s eccentricity and the right corner was at 16.5° eccentricity. See Figure 36 for a comprehensive map of how eccentricity may be visualised across this driving simulator.

6.2.3 Materials

The University of Nottingham Audi driving simulator (right-hand drive) and STISIM3 were used to simulate the road environment. The HUD imagery used throughout the study was simulated by projecting it over the projection of the driving environment, these were in fixed positions, the same for each participant. Video cameras were mounted to the interior of the vehicle to monitor participant behavior and SMI eye-tracking glasses were used to monitor each participants' eye-gaze behavior (Figure 47). A 'KWmobile' Bluetooth button was attached to the steering wheel and used by participants to interact with the tasks (Figure 47). Participants could press up, down, left, right and enter.

Figure 47. The materials used within the study. The driving simulator and projection-based simulated HUD (A) the SMI eye-tracking glasses (B) and the KWmobile Bluetooth button which was attached to the right side of the steering wheel (C).

All the forms and questionnaires were completed remotely by participants on Windows Forms (see Appendix E).

6.2.4 Tasks

Participants experienced 3 display conditions: a Head-down display (HDD), and two Head-up displays: HUD-A and HUD-B (see Figure 46).

For each of these display positions participants encountered two tasks.

6.2.4.1 Menu Task

This task was constructed in C++ by the experimenter. The text-based menu first appeared 50 seconds after being activated by the experimenter at the start of the drive (see Figure 48). During the drive 3 beeps informed the participant that the menu task had appeared. Each beep was a tone of 800hz for 300ms. The top line of the menu indicated the target word or words the participants should search through the menu for (e.g., *"Find and select 'Bluetooth'"*). Participants could move the arrow cursor within the menu using the up and down buttons on the Bluetooth button attached to the right-hand side of the steering wheel (see Figure 47). The left button enabled participants to move back through the levels of the menu, the central enter button let participants go further into the menu or select the target word once they found it. The menu disappeared once a selection was made. Participants completed the menu task 4 times at each display location (4 iterations for each display position) with a 20 second gap between menu appearances. The menu was up to 3 levels deep depending on the menu options selected. The menu structure and content were consistent between appearances and display positions, but the target words were different for each iteration, with some requiring more button presses (maximum 9) and some less (minimum 3). However, all the menu tasks for each display position required a of total 24 button presses to reach all the correct target words. Overall, the menu tasks contained two searches to level 2 of the menu, and two searches to level 3 of the menu. The menu consisted of words and structures which may be expected in an in-vehicle menu system (e.g., System Settings > Connections > Bluetooth) (see Figure 48). Thus, the driver may have to search several areas of the menu to find where they think the target would likely be located within the menu. This task was selected to investigate how participants interacted with an ecologically valid task, which would be more expected by drivers.

Figure 48. Menu task in HUD-B position as it appears with target word (in this instance 'Bluetooth' present in top line). Image taken by the eye-tracking glasses' forward camera.

6.2.4.2 Snake Game Task

This task was constructed in HTML and Java by the experimenter. During this task, a simple version of the game 'snake' appeared in a square at the display location (see Figure 49). During this game, the user controls a simple line of pixels (or a snake) which is constantly moving (even without input from the user) towards other pixels (or apples) in order to score points. At the beginning of the task the 'snake' was 4 pixels long and was moving from left to right through the top half of the playable area. When the 'snake' 'eats' an 'apple' the player is awarded 10 points and the snake becomes one pixel longer. Also, the apple disappears and re-appears in another random location in the playable area. If the 'head' of the 'snake' ever touched its body, the round was over, and the game would restart. Thus, the game became harder the more the participants scored, and the 'snake' became longer. The playable area looped, so if the snake left the playable area on the right, it would re-enter from the left. For this study, the participants could direct the snake's movement using the up, down, left and right buttons on the Bluetooth button. When this condition was conducted, the snake task was present throughout the drive.

Participants were informed it was their choice whether and/or how much they wanted to interact with the game. This task was included as something which is most likely inappropriate for a vehicle display (Figure 49).

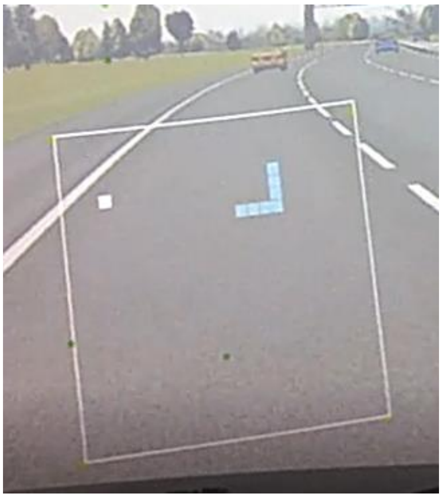

Figure 49. The snake game task in HUD-B position during a participant's drive. Image taken by the eye-tracking glasses' forward camera.

6.2.5 Procedure

Additional procedures were required due to this study being conducted during the Covid-19 pandemic. First, ethical approval was received from Nottingham University's Faculty of Engineering Ethics Committee. An additional risk assessment was also completed. Only university staff or students were recruited to be participants. All participants had to agree to the precautions set out, for the well-being of themselves and the experimenter, before being accepted for the study. Participants were remotely sent an information sheet, consent forms and introductory questionnaires to complete before the driving simulator portion of the procedure (Appendix E). Participants were also asked to bring a smart phone or similar device so that they could complete questionnaires online when at the driving simulator. Before arriving at the driving simulator, they had to complete a health declaration form confirming that they had not been exposed and did not currently experience any symptoms indicative of Covid-19.

Once arriving at the driving simulator, participants entered through a separate area from the experimenter and were asked to use the sanitization station. Participants and the experimenter were required to wear a mask throughout the procedure. Next, they completed a short practice drive to familiarize themselves with the vehicle controls; they also practiced interacting with each of the tasks using the Bluetooth button to ensure they understood what was expected of them. Following this, the eye-tracking glasses were calibrated and worn by participants for the 6 main experimental drives. Participants were asked to refrain from touching or moving the eye-tracking glasses after calibration to prevent tracking errors. Participants were instructed to drive during the study as they would in a real driving situation. The order of the conditions (2 tasks x 3 display locations) was varied for each participant to reduce the impact of order effects. The experimenter kept a two-meter distance from the participant at all times.

During each drive participants drove the simulation vehicle along a 3-lane motorway with an emergency lane on the outside, commonly called a ‘hard shoulder’ in the UK. The roadway contained curves so that the participant had to adjust the steering wheel to maintain lateral driving performance. A curve occurred every 2000ft, they were 1700ft long with a radius of 2000ft (a curve every ~610 metres, ~510 metres long, with a radius of ~610 metres). The participant was instructed to stay in the outside, far left lane. Other simulated vehicles passed them in the other two lanes. A yellow lead vehicle appeared ahead of the participants’ vehicle approximately 1000ft (~305 metres) into the drive. It varied its speed between 55mph and 75mph (~24.5m/s/ and ~33.5m/s, or ~88.5kmh and ~120kmh) according to a sine wave pattern (each wave lasted approximately 60 seconds) so that participants were required to manage their speed to maintain longitudinal driving performance. If they fell further than 150m (492ft) behind the car an audio message played to encourage them to catch up: *“You are falling too far behind the lead vehicle. Please try to catch-up and match the lead vehicle’s speed”.* Participants were monitored throughout for simulation sickness via the in-vehicle cameras. They also completed a Simulation Sickness Questionnaire (SSQ) (Kennedy et al., 1993) (Appendix A) part-way through. Participants also completed another questionnaire on their opinions of the tasks. All were completed using the smart device they brought to the driving simulator to maintain separation between the experimenter and the participant. The procedure within the driving simulator took approximately 1.5 hours.

Participants were emailed an Amazon voucher after the full procedure as compensation for their time.

After the main procedure the simulator was thoroughly cleaned. The eye-tracking glasses and Bluetooth button were also cleaned using a Cleanbox which uses UVC light (see Figure 50).

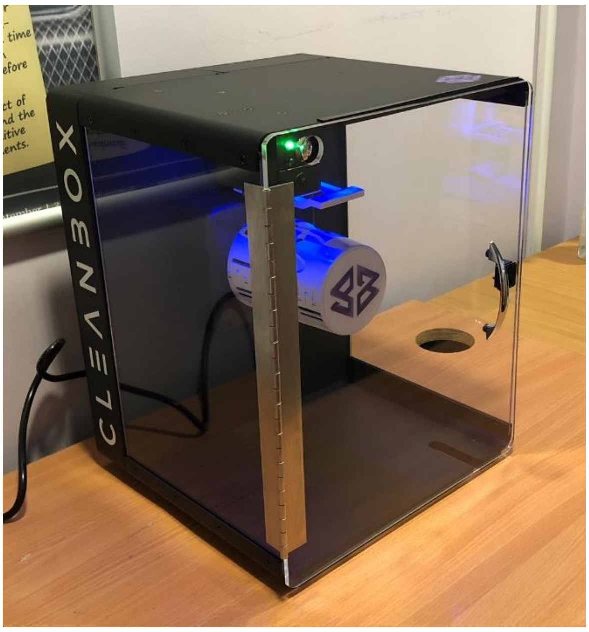

Figure 50. The Cleanbox used for UVC light cleaning.

6.3 Results

The menu task was analysed from when the menu visibly appeared on the eye-tracking video to when it disappeared (when the participant made a selection). The snake game task was present from the beginning of the drive, so the data was analysed during a selected period, which started a few seconds after the lead vehicle appeared ahead of the participant (approximately 1000 ft into the drive) and until 4 minutes later.

6.3.1 Collisions with the Lead Vehicle

The focus of this study was on visual behaviours and engagement with displays, so driving performance measures and safety were not a focus. However, collisions with the lead vehicle were noted by the experimenter and are reported here.

During the simulation if the participant’s simulated vehicle made contact with the lead vehicle it simply passed through the 3D representation and the simulation continued. This occurred twice within the present study, both during snake game tasks, once when the imagery was in the HUD-A display position and once when it was in HUD-B. This failure to detect the lead vehicle and take preventative measures indicates the snake game task was inappropriate to engage with whilst driving, as intended.

6.3.2 Eye- Tracking Results

A total of 17 drives were excluded from the eye-tracking analysis, out of a potential 108, due to issues with eye-tracking consistency (e.g., no eye movement was detected). For more information on how the eye-tracking was analysed, see section 3.3.4.

6.3.2.1 Average Glance Length

First, average glance length towards the active display was analysed. Studentized residuals (>±3) showed one outlier (with a value of 3.04). The outlier was removed, and a Shapiro Wilk test of normality showed all the conditions to be normally distributed. The sphericity assumption was violated for the interaction ($\chi^2(2)=6.875$, $p=0.032$), but was not for the main effect of display position ($\chi^2(2)=3.065$, $p=0.216$).

There was no interaction effect found between task type and display location with a Greenhouse-Geisser correction, and no significant main effect of task type. However, there was a significant main effect for display location ($F(2,20)=10.069$, $p=0.001$). A subsequent pairwise comparison, with a Bonferroni correction, found a significant difference between the HDD and HUD-B ($p<0.005$) (see Figure 51).

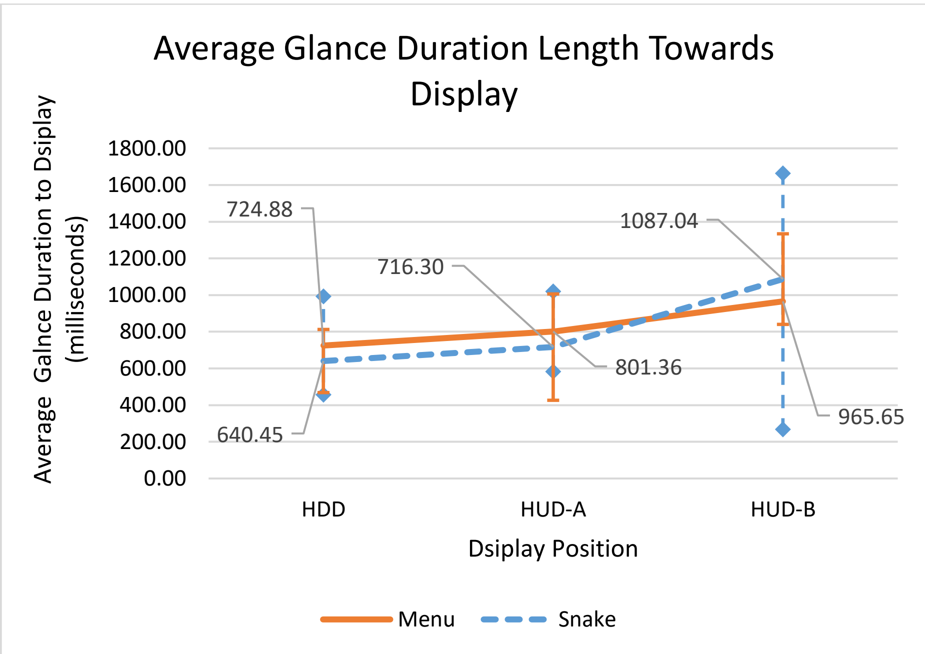

Figure 51. The mean glance durations across conditions. Displaying mean and standard deviation (SD) error bars.

Therefore, display position was found to influence average glance duration, with HUD-B resulting in a significantly longer average glances than the HDD. Notably (see Figure 51), there was also high variance evident. Specifically for the HUD-B display condition where the SD for the snake task was 697.83ms, and the SD for the menu task was 246.90ms.

6.3.2.2 Total Glance Time

Next, all the glance times towards the displays during all the analysis periods were totalled for this analysis. Studentised residuals showed no outliers beyond >±3. However, one data point was approaching this threshold (with a value of 2.25) and appeared to be skewing the data. Once this outlier was removed a Shapiro-Wilk test showed the data was normally distributed. Sphericity was not violated for the interaction ($\chi^2(2)=3.778$, $p=0.151$) and the interaction was significant ($F(2, 20)=4.977$, $p=0.018$) so the simple main effects were analysed with a Bonferroni correction to reduce the impact of multiple tests.

First looking at the simple main effects of display within the menu task. Mauchly's test of Sphericity was violated ($\chi^2(2)=12.116$, $p=0.002$) so a correction were employed. With the Greenhouse-Geisser correction, and the Bonferroni correction to the p-value, no effect was found ($F(1.223, 15.896)=6.319$, $p=0.095$). The simple main effects of the display were also inspected within the snake task. Sphericity was not violated ($\chi^2(2)=5.113$, $p=0.078$) and a significant effect was found ($F(2,22)=10.689$, $p=0.002$). Further pairwise comparisons, with a Bonferroni correction, showed significant differences between the HDD and HUD-B ($p=0.007$) and between HUD-A and HUD-B ($p=0.037$) during the snake game. The simple main effects of each task were also inspected but no significant differences were found between the tasks at any of the display locations. These results are evident within the graph (Figure 52).

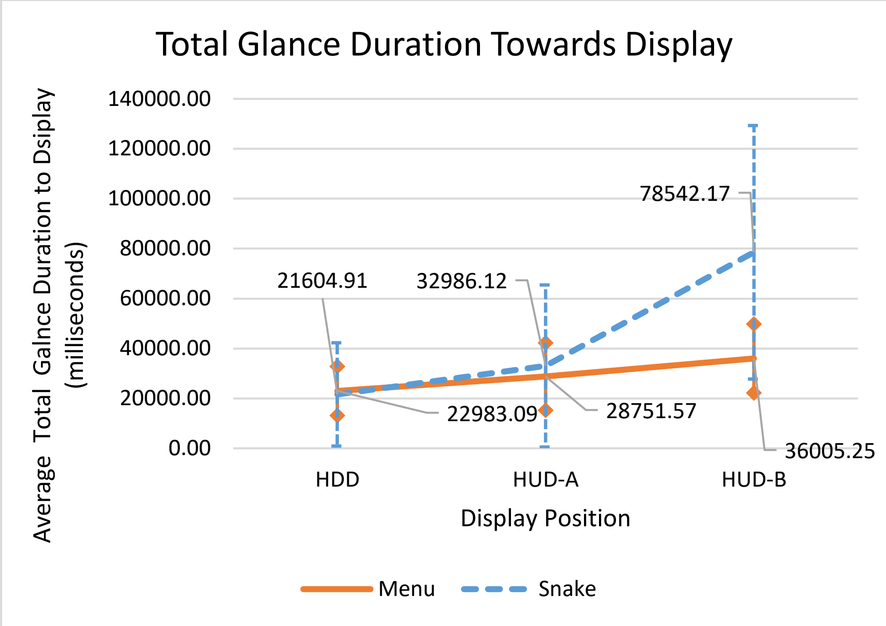

Figure 52. The means of total glance durations across conditions. Displaying mean and standard deviation (SD) error bars. Three Menu tasks occurred four times per drive and were summed. The snake game task was present continuously.

As shown by the analysis and within the graph (Figure 52) the impact of display position was significant during the snake game task, with the averaged total glance duration being significantly high in the HUD-B task, compared to the task in HDD and HUD-A. Each data point for the menu task combines all four menu tasks, per participant, performed on that display. Thus, on average the menu task took around 9001.31ms in total glances. Each data point for the snake task is the total over the 4-minute snake task for each display. Variance was high throughout as can be seen by the SD bars (Figure 52). This was particularly true for display position HUD-B, where the snake task had a SD of 50777.16ms and the menu task has an SD of 13791.60ms.

6.3.2.3 Maximum Glance Duration

For a final inspection of the visual behaviour, the maximum glance duration for each condition was analysed. Studentised residuals showed one outlier (with a value of 3.12) which was removed. However, even after removal a Shapiro-Wilk test indicated the menu HUD-A condition (p=0.005) and snake HUD-B condition (p=0.013) may not be normally distributed. A visual inspection of the QQ plots also indicated that the data was not normally distributed. As a result, a non-parametric Friedman test was employed to inspect the original data across all the conditions.

The Friedman test was significant ($\chi^2(5)=24.381$, $p<0.001$). Subsequent pairwise comparisons with a Bonferroni correction showed significant differences between HDD and HUD-B during the menu condition ($p=0.011$) and between HDD and HUD-B during the snake game condition ($p=0.007$). These results are evident below (Figure 53).

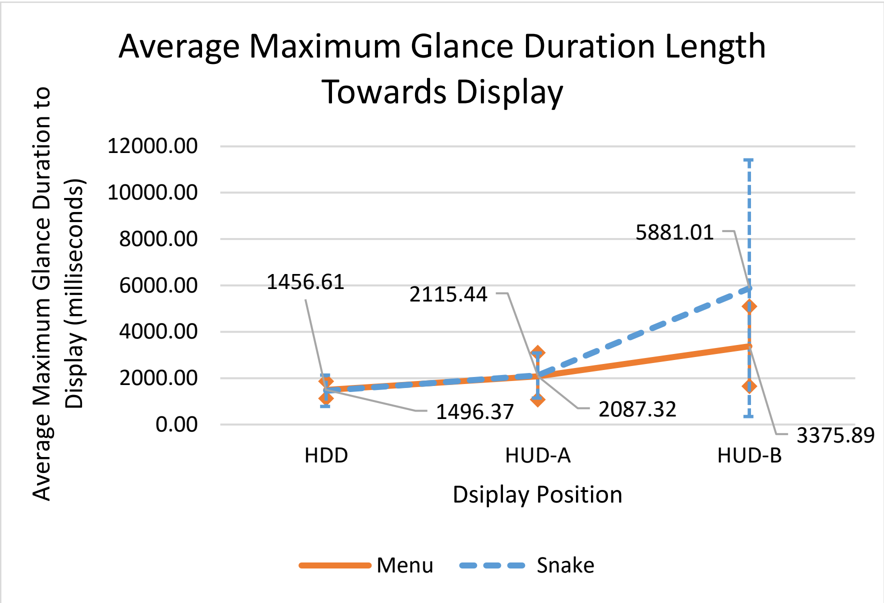

Figure 53. The means of the maximum glance durations across conditions. Displaying mean and standard deviation (SD) error bars.

As with the above measures, there is very high variance, particularly within the HUD-B condition. Within the menu task the SD was 1722.70ms while the SD in the snake game task was 5535.44ms (see Figure 53). The overall maximum glance in each condition is also reported in the table below (Table 9).

Table 9. The maximum glance towards the display in each condition.

	Task	Display Position		
		HDD	HUD-A	HUD-B
Maximum Glance Duration (milliseconds)	Menu	2195.1	4355.9	7457.2
	Snake game	2687.7	4223	24106.2

Overall, these results indicate that the longest glance durations occurred in the HUD-B condition when the snake task was active. Additionally, the maximum glance durations were significantly higher in the HUD-B condition compared to the HDD during both of the tasks. Finally, the high variance, particularly during HUD-B tasks, indicates that participant approaches to engaging with this display varied greatly.

6.3.3 Snake Game Scores and Interaction Count Results

A further analysis was conducted to more closely inspect the snake game task. The game itself was intentionally inappropriate to conduct whilst driving. Equally, participants were in full control of how much they wanted to interact with the game in each display position. Thus, it provides compelling information on how drivers may manage their behaviour with such displays and whether they choose to engage with them. Some missing data was excluded due to errors in the captures (two participants in each display condition).

6.3.3.1 Total Number of Interactions

The drivers interacted with the snake game using a temporary d-pad style button control attached to the steering wheel. The number of button presses during the 4 minute analysis period was totalled for this analysis.

As the data was count data, a Friedman test was used for the analysis and a significant result was found ($\chi^2(2) = 12.691$, p=0.002). Pairwise comparisons with a Bonferroni correction showed a significant difference between the snake game presented on the HDD compared to HUD-B (p=0.001). Therefore, based on the medians, presented below (Table 10), the HUD-B display resulted in significantly more interactions than the HDD.

6.3.3.2 Total Snake Game Scores

During the game white pixels appear, also referred to as ‘apples’, which the player, as the snake, has to touch with the front of the snake to ‘eat’ and thereby score. Each time the player touches the front of the snake to an apple the player is rewarded with 10 points and the apple disappears and re-appears in another random location in the playable area. The total of these scores during the 4-minute analysis period was summed for the analysis.

As the data was non-parametric, a Friedman test was conducted and again a significant result was found ($\chi^2(2) = 8.680$, p=0.013). A subsequent pairwise comparison with a Bonferroni correction revealed significantly greater scores from the HUD-B condition compared to the HUD-A condition (p=0.042) (Table 10).

Table 10. Descriptive statistics of the snake game scores, and interaction counts.

		HDD	HUD-A	HUD-B
Total Button Interactions with the Game	Median	29.5	40	86.5
	Min Value	0	1	6
	Max Value	116	151	162
Total Game Scores	Median	15	25	90
	Min Value	0	0	0
	Max Value	110	210	170

Overall, these results (see Table 10) suggest that the HUD conditions generally encouraged more manual interaction and resulted in higher scores than the HDD.

6.4 Discussion

Overall, the measures of visual behaviour and the interaction scores indicate that the participants tended to engage more with the windshield displays, particularly HUD-B which was located close to the forward view of the road.

First, focussing specifically on display position, the analysis found display position was a significant factor in determining the average length of glances, total glance duration, and maximum glance duration. All of these measures were highest for the HUD-B position and lowest for the HDD. Equally, manual button interaction counts (during the snake game task) were significantly higher when the HUD-B position was used, compared to the HDD, and snake game's scores were significantly higher with HUD-B than HUD-A. Thus, the results suggest that the HDD was the least captivating whilst HUD-B was the most captivating.

Previous work on visual behaviours towards displays has indicated that when comparing HUDs and HDDs the impact depends on the exact task. For example, HUDs may result in shorter gaze retention times if the task doesn't require interaction (Ablaßmeier et al., 2007) or longer glances if the display task does require interaction (Smith et al., 2016). The tasks used here did require interaction, and as may be expected, this resulted in longer glances to the HUDs compared to the HDD. Previous work has also shown that drivers may be able to perform these longer glances to HUDs without them causing the same detrimental effects on basic driving performance (Smith et al., 2016). However, they may impact other aspects of driving performance as discussed below.

When interacting with secondary tasks, drivers may adapt their behaviour or use compensatory behaviours (such as changing vehicle speed or choosing when to do a task) in order to protect the primary driving task from a performance deficit (Horrey, Alexander, et al., 2003; Young & Lenné, 2010). These behaviours are evident within the data collected here, since participants showed some understanding of which display locations were likely to be the most disruptive to basic driving control. They engaged least (in terms of task interaction and visual behaviour) with the HDD, which is most likely to quickly result in poor basic driving performance (see Chapter 5). Equally, participants engaged less with the HUD-A condition, compared to the HUD-B, potentially also due to some understanding of how these display positions would impact basic driving performance (see Chapter 5). However, since driving is a complicated task, which requires more than just basic driving control, these behaviour adaptations may go awry when within a real world setting. Horrey, Wickens and Alexander (2003) caution that the appropriate management or time-sharing of glances between displays and driving may fail during particular demands and hazard events. Drivers may feel as though they are appropriately attending to the road ahead (whilst using a HUD) and then miss critical visual cues (see section 2.3.1 on tunnelling).

Continuing this thought, this may be what occurred and resulted in the two collisions during the snake game task (see section 6.3.1). The snake game in the HUD-B position resulted in a significantly longer total glance times than the snake game in either of the other display positions (and this effect did not significantly occur during the menu task) (section 6.3.2.2). Therefore, the combination of the snake game and the HUD-B position made participants particularly willing to engage. This is likely due to the design of the tasks. The menu task was intended to be ecologically valid whereas, within the snake game task, the snake was constantly moving, and the driver could lose the game if they did not attend to it. Furthermore, these glance results suggest that not all drivers will successfully judge when a task is inappropriate, as the snake game task was deliberately inappropriate to engage with whilst driving (e.g., JAMA, 2004; NHTSA, 2010) yet several participants did so extensively. Thus, whilst many participants appeared to judge which display positions may detrimentally influence their basic driving, there was less consistency demonstrated in their understanding of which tasks would be suitable to engage with. The collisions indicate a severe lack of awareness and serve as a clear indication that the design recommendations for HDD interfaces (such as restricting imagery movement) may also apply to HUDs and WSDs.

Overall, the significant glance results around the HUD-B location suggest that some tunnelling or attentional capture may have occurred particularly for this display. This is where drivers become fixated upon one stimulus (e.g., the display) and neglect other visual information (Ward & Parkes, 1994); it is generally indicated by smaller gaze dispersion (Reimer, 2009). This is somewhat evident within the results on maximum glance duration since longer, uninterrupted glances to the display would indicate low dispersion and minimal visual scanning of the surrounding road environment. The road directly ahead is not the only place a driver should look to drive effectively (Victor et al., 2008). Effective visual scanning is associated with driving expertise (Underwood et al., 2003), thereby indicating that this static visual behaviour is undesirable, and may lead to drivers failing to detect hazards within the road environment. Tunnelling or capture may have been particularly prominent to the HUD-B due to two factors. First, HUD-B was close to the forward road environment and this likely exacerbated any tunnelling, since research has shown that information sources in close proximity (e.g., the display and the forward road view) can lead to issues switching between the two sources of information (Foyle et al, 1993). Secondly, the driving task being fairly low demand (the driving environment was fairly simplistic) may have had an impact. Previous research has shown that more complex driving tasks can make participants prioritise driving performance over the display tasks (see section 3.2.1, Liu, 2003).

It is worth noting that the results on maximum glance duration also broadly reflect the results found previously (Study 3, section 5.3.4), since in both cases the drivers appeared to think it was ‘acceptable' to look at central WSD locations for longer than higher eccentricity locations. However, the times shown here (Figure 53) are much lower than those self-reported previously (section 5.3.4) indicating that the self-reported values were not necessarily reflective of how drivers may actually behave.

Furthermore, throughout the results, there were high standard deviation values within the data (see Figure 51, 52 and 53, sections 6.3.2.1, 6.3.2.2 and 6.3.2.3).

Individual glance strategies when using in-vehicle interfaces can vary greatly and can significantly impact their evaluation (Broström, Ljung Aust, Wahlberg, & Källgren, 2013; Broström et al., 2016). However, the particularly high variation during the snake game task, may be due to participants taking different behavioural approaches; some participants may have played it continuously, whereas others may have chosen not to interact with it at all.

Comparing the results found here to the previous examination of naturalistic eye movement (Chapter 3), reveals similar total glance times during interactions with menus and similar average glance durations, thereby supporting the reliability of the present work. However, the present study does contain some limitations.

First, during the snake task the ‘apple’ was randomly placed; it could appear anywhere within the playable area. If it appeared more towards the bottom of the area (and further away from the drivers’ forward view) it may have made the task more difficult. Ideally, the random nature of the apple’s location should act as a control for this. However, if the starting location was particularly low this may have disproportionately dissuaded interaction and influenced the findings. Some of the longer glances captured in this work may have been caused by eye-tracking errors; issues were encountered during coding and some data was excluded from the analysis for this reason. Equally, this study aimed to investigate more naturalistic behaviours but was conducted within a driving simulator, so the extent of the conclusions is limited. Participants were aware they were not in a real moving vehicle and, as a result, may have engaged more with unsafe activities despite the instructions to drive as they normally would on a real road. Finally, only one driving context was investigated; more driving environments and situations would be needed to better understand the implications of these findings (Tivesten & Dozza, 2014). As discussed previously (section 3.2.1, Liu, 2003) if a highly complex driving environment was used, it may lead to drivers prioritising their driving over any secondary tasks, due to the demand from the driving task.

6.5 Conclusions

In summary, all of the primary dependent measures were significantly influenced by display position. The greatest visual engagement and manual engagement with the tasks was present when the imagery was in the HUD-B position closest to the drivers' forward view of the road. This behaviour indicates that drivers may be aware that they can better maintain their basic driving performance even whilst looking towards centrally located windshield displays such as this (as demonstrated in Study 2 and 3, Chapters 4 and 5). However, this finding may be concerning once applied to real-world driving, since it could indicate tunnelling and therefore the inability to notice important visual cues (see section 2.3). Drivers may feel like they are appropriately paying attention to the road (whilst looking towards the windshield display) and as a result could miss hazard detection opportunities. Potentially, participants would not engage with the display to this level within a real-world driving environment, because their perception of risk would be more accurate, but further work would be needed to confirm this.

In contrast, the only differences between the task types (the menu and the snake game) were found within the total glance time measure (section 6.3.2.2), where an interaction occurred. A significant difference was found between the display positions during the snake game task but not the menu task; this is most likely the result of the task designs (see discussion, section 6.4).

6.6 Chapter Summary

Overall, this chapter addressed RQ1 and RQ2 (section 1.5) and revealed the complex factors influential in the demand of WSDs.

Regarding RQ1 and RQ2, this study investigated tasks with both visual, biomechanical and cognitive demand elements across three display locations. Overall, it found how drivers respond to the demand imposed by near-future tasks is influenced by display location. The lowest eccentricity windshield display (HUD-B) resulted in greater visual engagement than the HDD or the other windshield display (HUD-A) when drivers were left to manage their own visual behaviours within a driving simulator. Furthermore, the deliberately inappropriate task on the windshield displays appeared to encourage high engagement particularly when the display is located centrally (HUD-B), suggesting that drivers may not be able to self-regulate their behaviour safely if inappropriate display tasks are located there.

The next chapter broadly reviews the work presented with this thesis, the research questions, the overall conclusions, the limitations and proposes future work which may be conducted.

7 Discussion and Conclusions

7.1 Chapter Introduction

This final chapter provides a discussion and the conclusions for the overall thesis. Each research question is restated from Chapter 1, and how these questions are answered, is addressed. This chapter also considers limitations relevant to the overall thesis or multiple studies which were conducted, and the impact these may have had on the overall findings. Additionally, this thesis is reviewed regarding the current literature and the direction of potential future research is considered.

7.2 Overall Aim and Research Questions

As stated within Chapter 1, this thesis aimed to investigate the demand imposed on drivers by Head-up Displays (HUDs) and Windshield Displays (WSDs) when used as near-future displays in road vehicles. More specifically, three research questions were addressed:

RQ1) How do drivers respond to the attentional demand imposed by near-future tasks on a windshield display?

RQ2) How does demand vary across windshield display locations?

RQ3) What approaches may be developed to help investigate windshield display demand?

7.3 Contribution

This thesis has investigated windshield displays within vehicles in order to gain a better understanding of the demand they impose on drivers. It highlights how task nature can influence the demand imposed, and how this demand (and the following impact on driving performance) varies when display imagery is positioned across the windshield. The tasks used within the present studies have generally used either verbal or manual interaction methods. The interfaces have been text-based or without complicated graphical imagery. Overall, they generally reflect potential near-future displays in their basic construction, as was intended.

However, the findings presented here are also likely to be applicable to displays beyond these interaction methods and visual constraints. Chapters 4 and 5 in particular address manipulated, continuous glances to areas of the windshield. Regardless of the exact interface, task, or the imagery in those locations, the work conducted here reveals the impact of a driver looking towards these locations. As such, displays which incorporate more advanced technology, such as AR imagery, may also benefit from understanding the results of continuous glances to these locations during driving. Furthermore, the analytical approaches initiated within this thesis (see RQ3, section 7.4.3) have the potential to aid vehicle display research regardless of specific display properties.

With automated driving becoming an increasingly prominent aspect of the driving landscape (Ayoub et al., 2019) it is also important to consider how this work contributes to the area. Automation levels are generally defined by what the features do and what the driver is responsible for. For a full definition of automation levels see J3016 SAE International (2021). The work conducted here is primarily applicable to instances where the driver is responsible for controlling the vehicle's behaviours. Thus, the results are highly relevant when early levels of automation are active (such as adaptive cruise control or others within SAE level 2) because the driver is still responsible for maintaining safety while driving (SAE International, 2021). Equally, up to and including SAE level 3 automated vehicles, full unaided driving may still be possible, and therefore this work is still highly applicable. In contrast, this work is much less applicable when higher automated features are active (present within SAE levels 3 to 5) since the driver does not retain the same control responsibilities. Though, the captivating nature of windshield displays, which was explored in Study 4 (Chapter 6), may still be thought-provoking when developing how windshield displays might be used in highly automated vehicles. For further discussion on future work and the role of windshield displays within developing automated vehicles, see section 7.7.2.

7.4 Summary of Findings

7.4.1 RQ1 How do drivers respond to the attentional demand imposed by near-future tasks on a windshield display?

Previously, there has been minimal research on near-future tasks, such as text and menu interaction on HUDs or WSDs (see section 3.1). The few that have been conducted were often not entirely ecologically valid, meaning they were not wholly applicable to current real-world vehicles or vehicles in the near future. The work conducted here focused on tasks and display stimuli which would be likely to appear imminently on HUDs or WSDs (e.g., text reading and menus), since they are already common within other vehicle displays. These tasks can demand visual, auditory, cognitive and biomechanical attention from drivers (see section 1.3). Within this thesis, two research studies were conducted which addressed this research question (Study 1 and 4, Chapter 3 and 6).

The findings of this work show that how drivers respond to near-future tasks on a windshield display is dependent on the exact nature of the task e.g., its form or complexity, and sometimes the exact combination of these features. For example, task complexity and task type were found to interact on measures of both longitudinal driving performance and visual behaviour (Study 1, Chapter 3). Furthermore, features such has how easily resumable a task is (how easily drivers can stop and then resume the task) appear to be influential in how drivers respond to the demand.

A closer inspection of the individual text and menu tasks reveals further details on how exactly they impose demand on drivers.

First, the text-reading task, incorporated into Study 1 (Chapter 3) demonstrated that as complexity was manipulated (increasing word number length) the participants' visual behaviour changed, with participant glance lengths becoming longer and the total glance time increasing. However, even within the highest complexity condition, the average glance length to the display remained below two seconds (1406.95ms) and on average totalled no more than six seconds (5967.60ms). No assessment procedures (see section 2.5.2) were directly followed within this study. However, these averaged eye-tracking results are below the assessment time criteria for AAM (2003), NHTSA (2016) and JAMA (2004), which indicates the task may be considered acceptable to conduct whilst driving according to current evaluation methods. Moreover, a visual inspection of the driving performance measures (see Figures 21-25) demonstrates that there was little variation in driving apparent between the text reading task and the baseline drive. Therefore, there does not appear to be a detrimental impact on basic driving performance. Thus, no distraction, as defined in section 1.3, appears to have occurred. Since reading is a complicated task, and is normally cautioned from driving interfaces (e.g., JAMA, 2004 recommends no more than 31 characters, see section 2.5.1), it is likely that an even more complex reading task (with more characters/ words) would reveal a detrimental impact on driving. Similar findings to these have been shown with reading tasks on HDDs (Peng, Boyle, & Lee, 2014), where short reading tasks (which take less than about 5 seconds) do not appear disruptive to driving. Thus, the reading tasks used here may not have been long enough to capture performance deterioration. Future work could expand to longer text tasks to investigate the extent to which HUDs or WSDs may incorporate text before becoming troublesome to glance behaviours and basic driving control.

Secondly, within the same study (Study 1, Chapter 3) participants were also asked to navigate a hierarchical menu on a HUD. As with the text reading task, the average participant in the highest complexity task demonstrated an average glance time (781.43ms) and an average total glance time (7701.73ms), which would not typically raise concerns during assessment (see section 2.5.2). The driving performance measures were generally also often similar to the baseline (Figure 21-25). However, the SRs and the average distance to the lead vehicle were visibly higher than the baseline, and significantly higher than the text task, particularly during the higher complexity menu tasks. Thus, the menu task appeared more disruptive than the text task, thereby indicating the HUD had the potential to be demanding enough to distract from the primary driving task. Therefore, this particular windshield display task may not be considered to be manageable during driving. Many factors such as task length, compensatory behaviours, and manual interaction methods were likely the cause of these differences (see section 3.4).

Finally, a menu task was also examined within the final study (Study 4, Chapter 6) which provided further details on how a near-future task, in combination with different display locations, may be influential. Average glance lengths were shortest for the HDD (640.45ms) and were significantly longer for the HUD-B position (965.65ms), when the display imagery was closest to the lead vehicle, but all were below the typical two second assessment time (see section 2.5.2). Total glance duration did not vary significantly between display positions during the menu task, but it also did not exceed concerning time values (e.g., 9001.31ms). However, the average maximum glance duration was shown to be significantly higher when the Menu task was conducted on HUD-B (3375.89ms) compared to the HDD (1496.37ms). This difference may be indicative of attentional tunnelling (see section

2.3.1) which would be undesirable for a vehicle display and indicates that the task in this windshield display location may not be safely manageable to all drivers. See section 7.4.2 for more important discussions on this topic.

In summary, drivers respond to the demand from these near-future tasks in various ways. The eye-tracking glance findings for the menu tasks did not appear to exceed the assessment glance times which are currently used (e.g., NHTSA, 2016), thereby indicating that these tasks may not be disruptive to driving. However, the driver performance data (Study 1) contravenes this; some of the menu tasks appear to be detrimental to specific driving measures, thereby indicating that distraction occurred and that these tasks are not suitable to conduct whilst driving. Furthermore, the maximum glance times captured in Study 4 show that this task may not be suitable in particular WSD positions due to tunnelling concerns (see section 2.3.1). Some of these conflicts may be due to how drivers understand and respond to the demands of these displays. This is discussed further in section 7.4.2 below.

Considering the text tasks, the findings indicate that simple text tasks, did not lead to concerning visual behaviour (section 2.5.2), and they also did not negatively influence driving performance (Figures 21-25). Therefore, the results suggest that drivers respond to simple, low complexity, text tasks in a manner that means they might be included on a windshield display in specific positions without causing issues to basic driving control or basic visual behaviours. However, caution should be exercised when interpreting this conclusion. Previous work has specifically warned that effective visual behaviours and task time-sharing, whilst possible during simple driving, might fail during particular hazard events or driving demands (Horrey, Alexander & Wickens, 2003). The data collected here only investigated basic driving performance (such as maintaining the vehicle within the lane) in simple driving environments, but driving as a task in totality, is much more complex. Therefore, these tasks may be dangerous to perform in these circumstances; more work specifically aiming to address this point would need to be conducted to confirm whether these tasks are suitable during those types of driving events (see section 7.7). Moreover, these results show that the visual demand imposed by windshield displays is sometimes comparable to HDDs, which have long been present within cars. However, this does not mean they are always entirely safe. For example, radio tuning has been used as an acceptable example task to conduct whilst driving (largely due to the social acceptance of the behaviour, see section 2.5.2) and has been integral to the formation of the current display acceptance guidelines (see section 2.5.2), yet more recent work has demonstrated it has clear negative implications for real-world safety (Lee et al., 2018). Therefore, as with any research, the assumptions of this work should continue to be inspected according to future contributions within the research area. Finally, this work was conducted within driving simulators which limits its applicability to reality (see section 2.2.1 and 7.6). Thus, this work cannot conclude whether these text tasks would be safe across all real-world driving contexts.

Additionally, the work conducted in order to address this research question only considers near-future tasks to be tasks such as text-reading and menu interactions, since these are primary components of current in-vehicle information systems, which are normally positioned at the centre console (see Strayer et al., 2017). However, other components may also feature on near-future HUDs or WSDs which were not addressed within this work. Most notably, navigation information is already implemented into some HUDs (often indicating simple information such as the next direction, see Figure 2). However, previous work has already explored this area more thoroughly and many are now investigating the implementation of AR elements as a next step (e.g., Jose, Lee, & Billinghurst, 2016; Mendoza & Kumar, 2020; Chu, Brewer, & Joseph, 2008; Harkin, Cartwright, & Black, 2005).

7.4.1.1 RQ1 Summary of Conclusions

The findings of this thesis indicate that how drivers respond to near-future tasks on windshield displays is dependent on the exact nature of the task presented on the HUD or WSD (e.g., how complex it is, whether it is resumable etc).

Within the context of these studies, the average glance behaviours which drivers performed were often within the current display assessment time criteria (thereby indicating they may be acceptable to conduct whilst driving, see section 2.5.2). However, in some instances the driving performance measures conflicted with this, and indicated that distraction may have occurred (e.g., the menu tasks in Study 1), thereby indicating that they would not be suitable to conduct whilst driving. The conflicts within these findings further indicate the need for new assessment criteria for these windshield displays to evaluate whether they are safe for real world driving.

The simple text tasks specifically, did not appear to negatively impact driving performance and the average glance performance was within the assessment criteria (see section 2.5.2). Therefore, based on current approaches, drivers might respond to these tasks in a way which may be considered acceptable. However, this conclusion is limited according to the specific tasks, display locations and environments which were used within the study (see discussion above, section 7.4.1). Whilst this work can conclude that a specific windshield display task should not impact basic driving behaviours, it cannot conclude on whether these windshield display tasks should be considered safe throughout real driving until other areas are researched. For instance, their impact in other driving situations where there may be unexpected hazards (see section 7.7). Driver understanding around the dangers involved with engaging with these windshield displays is discussed further in section 7.4.2 below.

7.4.2 RQ2 How does demand vary across windshield display locations?

Display location and position is a commonly discussed area in the literature (see section 2.6). However, most work has focused on identifying an ideal location for HUD or WSD imagery. Yet with the continuing development of these displays there is the potential to present imagery anywhere across the windshield. Thus, this thesis aimed to better establish how demand varies across the whole of the windshield.

Three of the four studies conducted for this work, reviewed display positioning (Chapter 4, 5 and 6). When individual visual behaviours were controlled by the study design (in Chapter 4 and 5) the findings generally indicated some form of an eccentricity effect occured; meaning that basic driving performance was generally better when the display imagery was presented close to the driver’s forward view of the road. However, as the visual angle (eccentricity) away from this location increased (and the display imagery was positioned further along the windshield), driving performance was detrimentally affected. For instance, within Study 2 (Chapter 4), it was found that driving performance significantly worsened at higher eccentricity locations compared to those closer to the forward road view over the same timeframe. Equally, Study 3 (Chapter 5) demonstrated that participants more quickly reached unacceptable driving performance criteria when the display imagery was at a high eccentricity compared to those at lower eccentricities. Since these measures are reflective of demand and distraction (see sections 1.3 and 2.2.1.3) it can therefore be concluded that with increasing eccentricity there is increasing inherent display demand in windshield displays.

The research conducted for this thesis also demonstrated some impact of verticality. Previous, work within this area (see section 2.6) has indicated that increasing vertical eccentricity of HUDs or WSDs may be more disruptive than horizontal eccentricity, although the findings are mixed (Smith, 2018). This specific effect was not readily apparent within the work conducted here. Nonetheless, Study 3 (Chapter 5) did show that low-central display positions enabled drivers to maintain lateral driving performance for longer than high-central display positions (Figure 42). This is most likely due to the construction of the road environment which the display overlays. Vertically low display positions overlaid the simulated road and allowed participants to more easily monitor the lane markings and thereby better maintain their lane keeping performance. In contrast, vertically high display positions overlaid the simulated sky, which provided little visual information about road positioning. Thus, the demand imposed by display positions is likely somewhat dependent on whether they are proximate to important visual information within the environment. If they are, they are likely to be measured as less demanding according to driving performance measures of demand. Hence, why central and low eccentricity positions are measured as less demanding; they enable drivers to use their peripheral or ambient vision to receive road positioning information. This likely explains why lower positioned HUDs may be commonly considered as ideal positioning (section 2.6.3). However, they also pose a greater chance of obscuring this vital road positioning information from the driver (see sections 2.3 and 2.6). Whether or not this positioning is beneficial will likely depend on the exact nature of the interface.

Interestingly, the work here has also shown that visual information sources which are commonly used within vehicles (e.g., the rear-view mirror) can be highly demanding locations. For example, in Study 2 (Chapter 4), position 5 (around where a rear-view mirror is located) resulted in significantly higher driving errors than lower eccentricity display positions. Wittmann et al., (2006) similarly found that a display located in the position of a rear-view mirror resulted in slower responses to a response task, thereby indicating that attending to visual information in this location may delay hazard detection. Whilst a rear-view mirror is limited in its positioning due to its need to reflect the rear-view, these findings indicate that even the sources of visual information which are accepted to be used within vehicles may not be optimal. The advancement of technology, such as video feeds and WSDs, pose as an opportunity to improve these issues by offering alternative information locations.

Overall, these findings show that high eccentricity displays inherently imposed greater demand (Study 2 and Study 3, Chapter 4 and 5). However, the work on naturalistic driving and display location (e.g., Study 4, Chapter 6) demonstrated that there are additional complexities when drivers were able to try and protect the primary task of driving (Horrey, Alexander, & Wickens, 2003).

For example, Study 4 found that the number of interactions with the snake game was fewer when it was presented on a higher eccentricity display (see Table 10). Therefore, it appears as though participants may have noticed the detrimental impact of engaging with high eccentricity displays and chose not to. This is also reflected in the eye-tracking results, where shorter glances were performed to higher eccentricity displays regardless of task (section 6.3.2). Equally, throughout this work drivers appeared to experience a strong, inherent desire to look towards the forward road view, and not away to high eccentricity displays, even when instructed to do so (e.g., section 4.4). In summary, although high eccentricity displays may be inherently more demanding, drivers appear to try to mitigate these effects by changing their visual or driving behaviours. This was expected. Hence, this was why driver visual behaviour was controlled within Studies 2 and 3, in order to study intrinsic display demand (and avoid driver behaviour differences confounding the findings).

However, an opposite effect was also apparent in some of the participants from Study 4 (Chapter 6). For example, the total glance durations were particularly high when the HUD was centrally located (HUD-B). Similarly, Study 3 showed that on average participants thought it was acceptable to look continuously to a central display for around one minute. An explanation for these behaviours (see section 5.4 and 6.4 for more discussion) is that when displays are located centrally drivers may feel as though they are looking where they ‘should’ whilst driving: at the road ahead of them. Therefore, they are willing to look to that area for comparatively long time periods. This has negative safety connotations for central windshield display locations when applied to real world driving; this behaviour may cause drivers to neglect important hazard cues.

Overall, this means a drivers' unwillingness to engage with a high-eccentricity display may mean the display does not appear to have a negative impact on driving, even though it is highly demanding. Equally, a driver's willingness to engage with a low-eccentricity display might lead to a negative impact on driving despite it arguably being in a position which should be less demanding on the driver (e.g., see the collision information in 6.3.1). Thus, whilst low eccentricity windshield displays may inherently cause less demand (see Study 2 and Study 3) the driver's natural responses to them may lead to a more detrimental impact on driving.

Beyond these conclusions, this thesis has also established quantifiable time values of how demand varies across a windshield (see Study 3, Chapter 5) and how these times vary according to different driving performance criteria. This is discussed further in section 7.4.3 below.

7.4.2.1 RQ2 Summary of Conclusions

Overall, the results of this thesis demonstrate an eccentricity effect for visual demand. When driver interaction is controlled, as the eccentricity of the display increases so does the resulting demand. Furthermore, the impact of an exact location appears to be influenced by the visual information which surrounds it from the road environment. However, a driver's willingness to engage with the displays or tasks will likely influence the final outcome of this demand (i.e., whether driving is affected).

7.4.3 RQ3 What approaches may be developed to help investigate windshield display demand?

Demand is commonly assessed by measuring basic driving performance differences and visual behaviours. More specifically, it is common to compare different conditions to each other or to a baseline (section 2.2). Within this work, these methodologies were used (e.g., Chapter 3 and 6). However, this work also used different approaches to reveal different findings about the demand experienced by drivers.

Within both Study 2 and 3 (Chapters 4 and 5), highly visually demanding tasks were used in order to study the intrinsic display demand. This was done by preventing the participants from fully controlling their visual behaviour (due to the visually demanding task), which subsequently reduced their ability to protect their driving performance. Thus, display demand could be inspected without individual behavioural differences confounding the results. Additionally, instead of only comparing tasks or conditions, criteria were created which acted as finite points to establish whether or not demand had become too great and, whether as a result, the drivers' performance had degraded to a level where it would likely be considered unsafe. These two features formed the basis of the subsequent approaches which were developed to investigate display demand.

Within Study 2, when criteria were met it was counted in order to produce frequency or count data, which was indicative of the level of demand a display position was causing. Broadly, the counting of driving errors has been used previously to indicate driving performance (e.g., Young, Salmon, & Cornelissen, 2013), though it is uncommon. Within this study it posed as an attractive, quick method to indicate display demand, which it successfully achieved since it reflected the other driving performance measures.

Following the use of criteria in Study 2 (Chapter 4), the premise was built upon, and a novel analysis approach was developed to further quantify visual display demand (see Study 3, Chapter 5). Since the visually demanding tasks forced a continuous glance towards a display position, this work was able to establish how much time into a continuous glance passes before a driver's driving performance became dangerous or 'unacceptable' (section 5.3.1). Thus, a time threshold or 'cut-off-point' could be established which indicated how long an average driver could look towards certain points on a windshield display before their driving became unacceptable. How long a driver can look towards a display safely is a metric currently used to evaluate vehicle displays (e.g., NHTSA, 2012). Therefore, the creation of these times poses as a first step towards achieving equivalent values for displays across the windshield. Contour time maps were also created which can act as guidance for how demanding different WSD locations are to the driver. The longer times indicated a longer period of time before the unacceptable criteria was reached. These could be used as guidance advice for designers when considering the addition of simple tasks to WSDs (as long as the limitations of the data are understood). In summary, this novel approach to analysing visual demand meant that the demand incurred by different WSD locations was able to be quantified by time values. Furthermore, it revealed a complex pattern of visual demand as it occurred according to the simulator study (Study 3, Chapter 5). Future directions for how this data may be used are discussed in 7.7.

However, these approaches did encounter some difficulties. Drivers appear to find looking away from the road for extended periods difficult to maintain even when instructed to complete a task. This suggests that drivers feel an inherent need to look back towards the forward road environment. Within the work conducted here, the simulator setting may also lead to this behaviour; potentially the unusual posturing and visual positioning amplifies any simulation sickness the participants may be experiencing. However, the nature of the testing (deliberately manipulating visual behaviour) makes this somewhat unsafe to replicate within on-road studies to examine whether this is a factor.

Finally, the efficacy of the results from these approaches is entirely dependent on the criteria which are used. The criteria used here (see sections 4.3 and 5.3) should be considered undoubted indications of unsafe driving, but they could be better refined. Specifically, the criteria which was used may be too lenient to apply to real world driving and it would benefit from collaboration and input from different perspectives.

7.4.3.1 RQ3 Summary of Conclusions

Overall, the approaches developed and used within this thesis should be considered functionable for studying and quantifying visual demand. Equally, their use has revealed an alternative perspective on demand by not only identifying whether one position, display or task should be considered better than another, but by initiating the creation of quantifiable time thresholds, after which dangerous driving is likely to occur. In the future, these time thresholds could be further developed and contribute to evaluation approaches which assess the suitability of windshield displays (see section 7.7 for discussions on this).

7.5 Further Implications for Design and Display Evaluation

Previously work on evaluating displays has been a summation of research from multiple sources, disciplines, and research groups. The time values which were established here (Study 3, Chapter 5) would pose as a solid contribution to such a summation, but subsequent work would be required in order to create evaluation time criteria for HUDs or WSDs similar to those developed for HDDs. For further discussion on this potential direction, see section 7.7 below. Prominently, the work presented here is conducted using driving simulators and equivalent work on-road would be beneficial, if the safety concerns could be resolved, considering the common discussions of relative validity around driving simulators (see section 2.2.1).

As discussed above, some drivers appear to be able to effectively self-manage their own visual behaviours. However, others may not be, as is apparent within the final study (Study 4, Chapter 6). Within this study, when a deliberately inappropriate task and a low eccentricity display position was combined, it resulted in undesirable visual and driving behaviours. Some participants appeared to struggle with ignoring the intentionally distracting game in the centre of their vision. Therefore, designers should be particularly wary of what is positioned at low eccentricities, as it may be too tempting for some drivers and lead to unsafe behaviours.

7.6 Limitations

Although, carefully considered throughout, there are a number of limitations which apply to this research. Limitations specific to each study are discussed in the relevant chapters. Here, considerations which apply across numerous studies or the whole thesis are reviewed.

First, throughout the studies conducted for this thesis, a driving simulator was used to replicate a driving environment. As detailed within section 2.2, there are a number of advantages and disadvantages when using this approach which were evaluated and overall, the use of simulators was deemed to be the best approach. However, as mentioned previously (section 2.2), the lack of risk perceived by participants within a driving simulator may have led them to drive inconsistently (Ranney, 2011). Particularly, prominent to some of the findings within this work (e.g., Study 4, Chapter 6) is the participant’s choice to prioritise a secondary task, and not the primary driving task. Potentially, drivers will better protect and prioritise the driving task within a real driving scenario. Thus, participants may have driven more poorly than they would within a real road environment. Conversely, the presence of an experimenter could have led to more vigilant driving from participants. To clarify which would occur, these studies would need to be repeated within a real vehicle to better understand the impact of a real-world context.

The use of driving simulators may have also meant perceptual issues, which would become apparent within a real road environment, were not detected. Within this thesis, real aftermarket HUD devices were used in Studies 1 and 2 (Chapters 3 and 4). As a result, the perceptual properties of the HUD imagery (depth, luminance, colour etc) were reflective of real-world HUDs. However, the study was conducted in a simulator so the relative depth of the HUD imagery in relation to the real environment could not be accounted for. Furthermore, in Studies 3 and 4 (Chapter 5 and 6) the simulated windshield displays were presented at the same focal depth as the environment (they were both projected onto the same projection surface). Bark, Tran, Fujimura and Ng-Thow-Hing (2014) have criticised that, issues with focus switching between HUD elements and the real-world are being overlooked due to the persistent use of driving simulators within the research, since they cannot encompass the depth and complexity of real-world environments. Potentially, these perceptual factors may influence the demand imposed by these displays and could vary the findings of this work. Combinations of virtual and real-world components are becoming more common in driving research in an attempt to improve the real-world applicability of the findings. For example, the use of VR headsets within real-world vehicles (e.g., Silvera, Biswas, & Admoni, 2022;Goedicke, Bremers, Yasuda, & Ju, 2021). However, for this specific application, real-world vehicles and a real-world full WSD would likely be needed to clarify some of these perceptual questions, but this is still largely limited by current technology. However, a test-track based study with the appropriate technology and any safety concerns resolved, would be a highly valuable future study.

Reflecting further on the use of driving simulators, it is worth noting that both left and right-hand simulated vehicles were used due to one study being conducted within the USA, whilst the rest were conducted within the UK. However, since a common vehicle set-up was used in each of the countries, it is assumed that the results are applicable to either vehicle design once mirrored to the alternative layout.

The participants within the studies of this thesis completed a practice or familiarisation drive before starting any main study procedures. This required participants to drive the simulated vehicle along the same road they would within the main study procedure for a few minutes until they reported that they were comfortable and confident with the simulator. However, some research indicates that this does not ensure that the participant is sufficiently adapted to the driving simulator. Sahami and Sayed (2013) argue that a practice drive should not focus on one specific aspect of driving, and it should provide a chance for the participants to modify all their driving skills. Thus, the motorway driving participants experienced in the present studies may not have been fully effective in helping drivers to adapt to the driving simulators, and subsequent driving performance measures could have been affected.

During the studies conducted here, participants were assumed to need their peripheral or ambient vision (Horrey & Wickens, 2004), in order to maintain driving performance whilst using the investigated displays. However, throughout the studies, participants wore SMI eye-tracking glasses in order to monitor their visual behaviour. Several pairs were used, each of which had variably thick arms (see Figure 16 and 47). Therefore, whilst required for the research, the equipment may have obscured the participants’ peripheral vision, and drivers may be able to better maintain their driving performance without them present.

Reflecting on eye-tracking; its use within this thesis has revealed some limitations specifically regarding the use of this equipment with HUDs and WSDs. Due to the HUD or WSD imagery overlaying the road environment and being transparent, it is not always clearly possible to determine whether the driver is looking at the windshield display or whether they are attending to the road environment beyond. There are some eye-tracking methods which have the ability to calculate focal depth (e.g., Lee, Cho, Shin, Lee, & Park, 2012) which could arguably alleviate this issue. However, HUDs and WSDs also have the potential to have a focal depth of infinity (Tönnis, Klein, & Klinker, 2008). Equally, in the work reported here, the display imagery and the driving environment were often presented at the same depth, on the same projection surface (e.g., Study 3 and 4). Thus, measuring the depth of focus may not help with differentiating the two stimuli in all circumstances. Within the work conducted here, glances were manually assigned values by the experimenter, and while it assumed they were mostly accurate in their interpretation of where a participant was looking, it is possible that mistakes were made.

Also, on the topic of materials, the simulated HUDs and WSDs used within Studies 3 and 4 were created by projecting the display imagery over the road environment. As a result, the imagery was clearly visible to the driver regardless of their head position or posture. Current HUDs, such as those used in Studies 1 and 2 are not visible from all angles. Thus, participants may have been able to perform better with the simulated displays as a result. However, this thesis is investigating speculative near-future displays, and it appears likely that more robust viewing angles would be present within such displays in the future.

Throughout this work, lateral driving performance measures (i.e., lane keeping performance) has been more explicitly impacted than longitudinal (e.g., Chapter 5). This may be due to the presence of the lead vehicle throughout the studies impacting the measurement of longitudinal performance. A lead vehicle was present in order to provide a clear method of measuring longitudinal driving performance, indicate situational awareness, and also to impose longitudinal driving performance demand (since the vehicle always changed speed) (see section 2.2.1.3 for justification). However, the presence of the lead vehicle may have also influenced the findings. Tivesten and Dozza (2014) found that the presence of a lead vehicle, when participants were asked to complete tasks on a mobile phone while driving, resulted in shorter glance durations to the secondary task. Therefore, Tivesten and Dozza's (2014) findings suggests that the lead vehicle could stop a driver from continuing unlimited interactions with a display since it is a clear collision risk, particularly when the lead vehicle brakes and the distance or time between vehicles changes dramatically. A lead vehicle may motivate drivers to look to it more frequently and/or perform shorter glances to secondary tasks as demonstrated by Tivesten and Dozza (2014).

Alternatively, (and also discussed by Tivesten and Dozza, 2014) a relatively consistent headway to the lead vehicle could give drivers a false sense of security since the driving environment is fairly consistent. Other work specifically on naturalistic driving and car-following (Tijerina, Barickman, & Mazzae, 2004) showed that drivers appear to look away from the road when there is no optical expansion or looming, i.e., driver engage in secondary tasks when the lead car is not becoming closer and is not consuming more of the driver's visual space. Furthermore, the lead vehicle could have acted as a guide of how to drive within the participants' peripheral vision, whilst they were focally attending to the displays (see section 4.4 for further clarification). Potentially, the lead vehicle could help by providing a demonstration of where upcoming changes in road curvature were, and where good lateral positioning in the road would be. Overall, this indicates that whilst the presence of a lead car provided good insight into longitudinal driving behaviours, it is also a limitation of the findings and therefore the conclusions which can be drawn. Tijerina et al., (2004) argue that studies regarding interaction with in-vehicle technology should investigate visual behaviour both when a lead vehicle is present and in an open-road environment. However, this was not done within the present work.

The studies conducted here were all conducted in similar simulated environments: motorways or highways with the participant being limited to the outside lane. Thus, the demand from the driving task was relatively consistent. However, there is expansive research on road environment variation and how this can impact driving demand including: lighting (Robbins & Fotios, 2021), time of day (Lenné, Triggs, & Redman, 1997), traffic complexity (Teh et al., 2014) and road curvature (Tsimhoni & Green, 1999). This is a common limitation within the area (e.g., NHTSA evaluations are instructed to be conducted within simple highway environments, section 2.5.2, NHTSA, 2010). Future work may evaluate how different environmental conditions impact display usage and overall demand.

Across the driving performance literature, measures are influenced by individual differences. Whilst representative samples were strived for, the recruitment for these studies was conducted within universities, so the participants tended to be young (the average participant ages were 23.73, 36.5, 28.18 and 28.44 years within this thesis). Young and inexperienced drivers are associated with higher fatal crash rates (Levy, 1990), whereas experienced drivers appear to develop additional skills or strategies which help them identify peripheral hazards (Crundall, Underwood, & Chapman, 1999). Yet the reaction times to hazards may also be better in younger participants. Some research has shown that younger drivers using cell-phones merely leads to their reaction times becoming the equivalent of older drivers (Strayer & Drew, 2004). Furthermore, driver attitudes and compensatory strategies appear to vary with age (Isabelle Milleville-Pennel & Marquez, 2020). There are also individual differences beyond age and experience which were unidentified within this work. For instance, visual scanning approaches are subject to many individual differences and drivers may find alternative approaches even if limited by a visual deficit (Milleville-Pennel, Zanlonghi, & Barrucand, 2021). Peng and Boyle (2015) demonstrated in a simulator that some drivers, who they referred to as high-risk, performed significantly more long eyes-off-road glances (>2 seconds) than other drivers. Overall, individual differences are factors which cannot easily be controlled for, and this is arguably a pervasive issue across many areas. The participants used here were active drivers and therefore are largely representative of the target population. The variance within that population is naturally present and displays will need to be appropriate for as much of that population as possible.

Several of these limitations, while they may limit the scope of the present conclusions, can easily be absolved through future research which incorporates elements which were not used here.

7.7 Future Work

Beyond those previously mentioned (e.g., in section 7.6) this thesis prompts several topics of further research.

The work conducted here controlled for specific road environments, traffic conditions, and display technologies. All of the conclusions drawn here (see sections 7.4.1.1, 7.4.2.1 and 7.4.3.1) could be expanded if future work aimed to answer similar questions but used different measures, study conditions or study mechanics. For example, only simple road environments (motorways/highways) were used within these studies. The use of residential, city, or remote roads may result in different findings due to the variance in demand from the driving task. As discussed previously (Liu, 2003) high driving demand from complex driving environments may lead to drivers prioritising their driving over secondary tasks. Equally, hazard detection is a common measure of SA (situational awareness) within the research area, which would enable it to be examined more explicitly. Whilst a lead vehicle was present in the studies conducted for this thesis, responses to an otherwise unexpected hazard may have been very different. Alternative measures of visual behaviour may also reveal previously unexplored elements of display demand. For example, recent work has demonstrated that it may be important to consider eyes-on-road time rather than solely eyes-off-road times (Seppelt et al., 2017) as this may differentiate a crash or near-crash event.

As mentioned previously (see section 2.5.2.1 and section 7.5), there is little work on evaluating displays which is directly applicable to windshield displays. This thesis has provided several areas of insight to progress this area. However, future work could evolve this further with the formation of predictive models, equations, guidelines, or a scoring system. Predictive modelling, equations or scoring methods generally involve analysing data patterns in order to anticipate likely outputs when applied to other designs. These methods have long been sought within the area of user-centred design to evaluate and assess the suitability of user interfaces (Shneiderman, 1986). They can be beneficial because they can act as fast or automated evaluation methods (Galitz, 2007) which can efficiently and comparably indicate suitability.

Previous work within the area of user interfaces has used modelling to evaluate screen complexity (Comber & Maltby, 1994; Goldberg, 2014) and effective screen formats (Ngo & Byrne, 2001; Galitz, 1997). Within driving research, topics such as autonomous driving collision risk have been included (Strickland, Fainekos, & Amor, 2018). For in-vehicle displays, researchers have modelled the visual distraction potential from different menu structures (menu depth and breadth) by restricting glance times to reach a target menu item (Burnett, Lawson, Donkor & Kuriyagawa, 2013). Researchers have also adapted the Fitts law equation and Hick-Hyman law equations to develop novel predictive equations (Fitts, 1954; Hick, 1952; Hyman, 1953). These can forecast the visual demand of touch screen displays within a vehicle, according to the number of target items present on the display (Large et al., 2018). Applied to the work within this thesis, some of the data collected here (see section 5.3 and 5.5) could be used to develop models or a scoring system to evaluate windshield displays by suggesting the likelihood of whether a particular task, in a particular windshield display position, will result in driver distraction. Ideally, further studies using different road and traffic environments, as mentioned above, could be incorporated into this. Equally different or stricter 'unacceptable' or 'unsafe' driving criteria may be incorporated. Furthermore, data from different sources (e.g., other research groups) would supplement the strength of the work; as has been done previously in the development of evaluation methods (e.g., NHTSA, 2012).

Considering another topic, HUDs and WSDs remain largely novel to many drivers (section 2.3.3). Once a driver becomes more comfortable with new technology within the vehicle there's evidence to suggest that the driver may interact and behave differently with it (Peng & Boyle, 2015). Equally, increasing familiarity with the technology could lead to increasing complacency, and unsafe engagement decisions (as was seen within the snake game, Study 4, Chapter 6). Thus, naturalistic longitudinal studies may be enlightening as to whether or how interactions with HUDs and WSDs vary with familiarity.

Furthermore, much of the work conducted here on display position, highlights the importance of peripheral vision and its role within the driving task. The use of peripheral vision in everyday life is influenced by factors such as expertise, age, distraction, emotional state, task importance and previous knowledge (Vater, Wolfe, & Rosenholtz, 2022). More work could be conducted on peripheral vision and the individual differences which influence its use in driving specifically.

Compensatory and adaptive behaviours (as discussed by others in the literature e.g., Young & Lenné, 2010) were evident within some of the work conducted here. As has been highlighted previously (e.g., Young & Regan, 2007) the role of compensatory behaviours has been under researched by the driver distraction research area. Since distraction is commonly defined to have occurred once a degradation in driving performance is detected (Pettitt, Burnett, & Stevens, 2005; Young & Regan, 2007), compensatory behaviour is sometimes captured as a form of distraction whilst other times it may be dismissed. Future work could aim to expand and clarify some of these behaviours.

Finally, participant performance on the secondary task was largely dismissed for the current work due to the focus on measuring demand and distraction. However, inadequate, or unsuccessful interactions with a secondary task on a windshield display could cause frustration, which would have further implications on the implementation of HUD and WSDs. If they are unacceptable to the consumer, car companies will be unlikely to place them within their vehicles. Furthermore, within a naturalistic setting, frustration may also cause unwanted driver behaviours which were not evident in the current work; future work could include this assessment.

7.7.1 Augmented Reality (AR)

This thesis has focused on the demand of near-future HUDs and WSDs by investigating interface components which are otherwise commonly situated at the centre console of current vehicles. However, as discussed within the introduction (see section 1.4.1), the work conducted here on display and imagery location is also relevant to the study of AR displays. Namely, by addressing how display imagery, in various locations, demands visual attention from the driver (see section 7.3).

Future work in this area could explore the intricacies of AR demand by applying some of the research approaches used here to developing AR WSD concepts. Going forward, AR is increasingly exploring world-fixed AR concepts (Riegler et al., 2021) with largely encouraging results. For instance, Riegler, Riener and Holzmann (2019c) investigated how, with future WSD and AR technology, text information could be dynamically presented over other traffic so that it appears 'stuck' to the back of a lorry. The authors found displaying text in this way lowered error rates and improved take-over times compared to presenting text in a static screen-fixed manner. Similarly, Merenda et al., (2018) investigated world-fixed and screen-fixed windshield display interfaces for navigation and pedestrian detection. The authors found that world-fixed AR cues supported locational accuracy and spatial judgments. However, the results also indicated that these designs may result in slower response times, which may make them unsuitable for certain applications.

Extensive future work is required to investigate exactly how the unique attributes of world-fixed AR imagery may impact the demand imposed on the driver. Currently, a degree of speculation is required throughout the investigation of future HUDs and WSDs, as the technology needed to incorporate these into road vehicles is not readily available or sometimes is not fully developed. Once these displays are more accessible and are more commonly used, particular human factors concerns may be more readily identifiable and more sensitively examined in future work.

7.7.2 Automated Driving

With automated driving becoming an increasingly prominent aspect of the driving landscape (Ayoub et al., 2019) it is also important to consider how the present work would apply, and how this may tie into future work.

Assuming a driver may be responsible for driving control in some instances, understanding the attentional demands of HUDs and WSDs, as studied here, remains important (SAE International, 2021). Therefore, the findings of this work may be relevant (see section 7.3). However, there are several areas of automation which were not studied within this work which would be beneficial to investigate in the future.

For example, the transitionary periods between automated, assisted, and manual driving were not investigated here, yet display demand will likely be an important feature in these driving situations. In SAE level 3 vehicles, drivers need to maintain an awareness of the driving environment, so that if the vehicle requests a take-over (TOR) the driver can safely regain control of the vehicle. During these events, displays may demand attention in a disruptive manner, or they may support the process (see Riegler, Riener, & Holzmann, 2022a) . Regardless, this interaction will likely be very different from what was examined here. Whilst take-over requests are commonly investigated (for a review see Morales-Alvarez, Sipele, Léberon, Tadjine, & Olaverri-Monreal, 2020) there remains many questions. The investigative approaches which were developed within this work could be used to contribute and progress this area in future studies.

Additionally, the intended interactions with displays may change with increasing automation. For instance, the content of these displays may focus more on entertainment, productivity or comfort. For example, Schroeter and Steinberger (2016) investigated how windshield displays could be intentionally demanding during automation, to encourage the drivers' visual attention towards the external real-world environment. The authors speculate that doing this should lead to drivers maintaining higher situational awareness, and therefore they will be better equipped to take control of the vehicle if necessary. In order to achieve this, the authors conceptualised an AR WSD game which required drivers to respond to virtual creatures placed within the driving scene. The authors propose that this form of approach should result in drivers who are motivated to attend to the road environment even when not in control of the vehicle. Similarly, Gerber et al., (2020) monitored participants watching TV shows either on a smart phone or on a HUD during automated driving within a simulator. The authors found that participants more commonly self-interrupted their viewing of the TV show, to look elsewhere in the environment, when it was presented on a HUD. Thus, the use of a windshield display, over other displays, may encourage drivers to remain more vigilant to the road environment and help them maintain situational awareness while within an automated vehicle, thereby making them better prepared for a TOR, where they must regain control over the vehicle.

Within this future context, windshield displays may also have other benefits. For instance, they may be able to prevent motion sickness, by allowing drivers to both engage with the media they want to watch during the journey, whilst also receiving visual sensory cues from the external world (which should prevent motion sickness from starting). The displays could even show cues of how the vehicle will move next to further facilitate passenger comfort (Riegler et al., 2021; Dandekar, Mathis, Berger, & Pfleging, 2022).

In summary, the work conducted within this thesis is applicable to automated vehicles when the automation is low and the driver is responsible for the vehicle's behaviours. Future work may be conducted to investigate the role of display demand in the transition periods as automation engages or disengages. Looking further forwards, windshield displays may become increasingly demanding in order to encourage the driver's visual attention up, and towards the outside of the vehicle in an attempt to assist with the retention of situational awareness during automation. Generally, research appears to be moving towards investigating the safety of non-driving related tasks, which include AR, that may be completed by the driver during high vehicle automation (Riegler et al., 2021). Future work should examine these new roles which windshield displays may have.

7.8 Closing Remarks

In closing, the work of this thesis shows that windshield displays are subject to the same concerns as any other in-vehicle display (e.g., display location and task design), yet are also subject to additional issues due to their unique nature (e.g., tunnelling and obscuration). However, they also present a novel opportunity to aid the driver with the driving task and provide complex information, if designed with care, without disruption. Overall, the findings of this work demonstrate that demand from WSDs and HUDs varies with both the nature of the task and the eccentricity of the display positioning. The final impact of this demand is somewhat dependent on driver behavioural responses.

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Appendix A

Simulation Sickness Questionnaire (SSQ)

(Used throughout in paper and digital versions to monitor participant well-being)

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.

Appendix B – Materials used in Study 1

Consent Form and Information Sheet

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: _Measures of Visual Distraction for Automotive Augmented Reality Head-Up Displays

Investigator(s):

Name	E-mail	Phone number
Bethan Topliss, Nottingham	bethan.topliss@nottingham.ac.uk	-
Dr. Joe Gabbard, Virginia Tech	jgabbard@vt.edu	540-231-3559

I. Purpose of this research Project

The purpose of this project is to understand the effects of different tasks presented on a head-up display (HUD), while in simulated driving scenarios. The research will be shared with the collaborating institution (The University of Nottingham, UK) and may be published at a later time.

II. Procedure

You will be provided with instructions and asked to drive a simulated vehicle. The simulated vehicle uses the physical components of a real vehicle (the front half of Mini Cooper) to control a car in a virtual environment. A ceiling mounted projector is used to display the virtual road. First you will complete some surveys. Next, you will be asked to complete a series of short drives, where you will drive the simulated vehicle along a highway whilst following another vehicle. Each drive should last approximately 15 minutes. During each drive you will also be asked to complete tasks using a Head-up Display (HUD). These tasks involve pressing buttons on the steering wheel and reading aloud information.

During the drives data will be recorded through eye-tracking glasses, the driving simulator, forward facing cameras and audio recorders. Glasses worn for vison correction cannot be worn with the eye-tracking glasses. However, contact lenses may be worn. The only identifying audio and video recorded will be your eyes and your voice. After the drives you will complete another short survey. The total process is expected to take under 2 hours.

III. Risks

You should be aware that when using a driving simulator there is some risk of motion sickness (also known as simulation sickness). If you are pregnant or particularly susceptible due to severe motion sickness, migraines, epilepsy, dizziness or blurred vision then you should not take part. If you do take part, you are free to stop the evaluation at any time for any reason, without penalty. Brief surveys during the study procedure will be conducted to ensure your wellbeing and comfort is maintained. If you do withdraw at any point your data will be held anonymously and securely as with all data collected.

We advise that you wait for 30 minutes before driving your own car after the end of the study. Any expenses accrued for seeking or receiving medical or mental health treatment will be the responsibility of the subject and not that of the research project, research team, or Virginia Tech.

IV. Benefits

The data collected from this study can be used help researchers better understand methods and tasks that should be used to evaluate new head-up display (HUD) technology. No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

No personal or identifiable information will be included in publication of presentations. Please note that these records will be held by a state entity and therefore are subject to disclosure if required by law. The Virginia Tech (VT) Institutional Review Board (IRB) may view the study's data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

Note: in some situations, it may be necessary for an investigator to break confidentiality. If a researcher has reason to suspect that a child is abused or neglected, or that a person poses a threat of harm to others or him/herself, the researcher is required by Virginia State law to notify the appropriate authorities. If applicable to this study, the conditions under which the investigator must break confidentiality must be described.

VI. Compensation

You will be compensated with $10 at the end of your participation.

VII. Freedom to Withdraw

It is important for you to know that you may withdraw from the study at any time without explanation or penalty. Please note that there may be circumstances under which the investigator may determine that a subject should not continue as a subject.

Should you withdraw or otherwise discontinue participation, you will be compensated in accordance with the Compensation section of this document.

VIII. Questions or Concerns

If you have any questions about this study, you may contact the researchers listed at the beginning of this document.

If you have any questions during the study, please speak to the researcher who is present.

Should you have any questions or concerns about the study's conduct or your rights as a research subject, or need to report a research-related injury or event, you may contact the Virginia Tech Institutional Review Board at irb@vt.edu or (540) 231-3732.

IX. Subject's Consent

I have read the Consent Form and conditions of this project. I have had all my questions answered. Further,

- I agree to take part in the above study and am willing to:
  - Participate in a car driving simulation activity
  - Be recorded in audio and/or video whilst engaged in the study
- I understand that my information will be held in line with Virginia Tech privacy policies and used for the following purposes:
  - Investigation into vehicle display systems.
  - Dissemination of findings through academic publications.
- I am aware of the potential risks associated with using the driving simulator and confirm that I do not suffer from any of the aforementioned conditions.
- I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without being penalized or disadvantaged in any way.

I hereby acknowledge the above and give my voluntary consent:

Date

Subject signature

Subject printed name

Advertisement/ Recruitment Materials

PARTICIPANTS NEEDED

DRIVING SIMULATOR STUDY

SIGN UP HERE

The COGENT Lab at Virginia Tech (https://cogent.ise.vt.edu/) needs volunteers for a research study investigating Head-up displays (HUDs) and how they impact drivers. During the study, you will be asked to drive a mini cooper in a driving simulator wearing eye-tracking glasses. You will also be asked to complete questionnaires about your experience.

OR SEND AN EMAIL TO: BETHAN.TOPLISS @NOTTINGHAM.AC.UK

You are eligible to participate if:

- Active driver with valid US driver's license
- Drive a minimum of 3,000 miles per year
- Age 18+ and be in good-health
- Have normal or corrected-to-normal vision (after corrected using contact lenses, not glasses)

Be aware!

Please be aware that there is a risk of induced motion sickness when using a driving simulator. If you are susceptible to severe motion sickness, migraines, epilepsy, dizziness or blurred vision, or are pregnant, then you should not volunteer.

The study should take under 2 hours, and you will receive $10 compensation. Participation is voluntary and confidential. If you are interested in participating, sign up the Doodle form using the QR code above or contact **Bethan Topliss (bethan.topliss@nottingham.ac.uk)**

HUD Driving Simulator Study
Contact: Bethan Topliss
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Questionnaires/ Forms Conducted Within Qualtrics

Start

Please enter the participant ID number

Introduction

Thank you for volunteering to complete this study.
First you will need to complete a few questionnaires.

Screening Questions

Do you have a US driver's license?

- Yes
- No

Do you drive at least 3,000 miles per year?

- Yes
- No
- Unsure

Are you 18+ years old, and in good health?

- ○ Yes
- ○ No

Do you have normal or corrected to normal vision (not using glasses)?

- ○ Yes
- ○ No

Are you susceptible to severe motion sickness, migraines, epilepsy, dizziness or blurred vision, or are pregnant?

- ○ Yes
- ○ No

Demographic Questionnaire

Please complete the following questions

Please indicate your age (Please indicate the number of years)

[ ]

Please indicate your gender

- ○ Other
- ○ Male
- ○ Female

How many mile do you drive in a year? (Please indicate the number of miles)

Does the car you typically drive include a display in the center console?

- Yes
- No
- Unsure

Do you ever use a navigation device when driving?

- Yes (built-in)
- Yes (portable)
- No

Have you previously used a touch-screen device in a car?

- Yes
- No

Does the car you typically drive include a touch-screen device?

- Yes (built-in)
- Yes (portable)
- No

Have you previously used a head-up display or "HUD" in a car?

- Yes
- No
- Unsure

Have you previously driven a driving simulator?

- Yes
- No

Please click the arrow to continue

Driving Risk Questionnaire

Please complete the following questions

Please select the response which best fits your experiences or opinions

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1. Many traffic rules must be ignored to ensure traffic flow	O	O	O	O	O
2. It makes sense to exceed speed limits to get ahead of slow drivers	O	O	O	O	O
3. Traffic rules must be respected regardless of road an weather conditions	O	O	O	O	O
4. Speed limits are exceeded because they are too restrictive	O	O	O	O	O
5. It is acceptable to drive when traffic lights change from yellow to red	O	O	O	O	O

Please select the response which best fits your experiences or opinions

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
6. taking chances and breaking a few rules does not necessarily make bad drivers	O	O	O	O	O
7. It is acceptable to take chances when no other people are involved	O	O	O	O	O
8. Traffic rules are often too complicated to be carried out	O	O	O	O	O
9. If you are a good drive it is acceptable to drive a little faster	O	O	O	O	O
10. When road conditions are good and nobody is around, driving at 100mph is OK	O	O	O	O	O

Please select the response which best fits your experiences or opinions

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
11. Punishments for speeding should be more restrictive	O	O	O	O	O
12. It's OK to ride with someone who speeds if that's the only way to get home at night	O	O	O	O	O
13. It's OK to ride with someone who speeds if others do	O	O	O	O	O
14. I don't want to risk my life and health by	O	O	O	O	O

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
riding with an irresponsible driver					
15. I would never drive after drinking alcohol	O	O	O	O	O
16. I would never ride with someone I knew has been drinking alcohol	O	O	O	O	O

Developed by:
Iversen, H. (2004). Risk-taking attitudes and risky driving behaviour. Transportation Research Part F: Traffic Psychology and Behaviour, 7(3), 135-150.

Please click the arrow to continue

Susceptibility to Driving Distraction Questionnaire

Please tick the response that best fits your experiences or opinions

You think it is alright for you to drive and:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
a. hold phone conversations	O	O	O	O	O
b. manually interact with a phone (e.g. send text messages)	O	O	O	O	O
c. adjust the settings of in-vehicle technology (e.g. radio channel or song selection)	O	O	O	O	O
	O	O	O	O	O

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
d. read roadside advertisements					
e. continually check roadside accident scenes if there are any	O	O	O	O	O
f. chat with passengers if you have them	O	O	O	O	O

You believe you can drive well even when you:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
a. hold phone conversations	O	O	O	O	O
b. manually interact with a phone (e.g. send text messages)	O	O	O	O	O
c. adjust the settings of in-vehicle technology (e.g. radio channel or song selection)	O	O	O	O	O
d. read roadside advertisements	O	O	O	O	O
e. continually check roadside accident scenes if there are any	O	O	O	O	O
f. chat with passengers if you have them	O	O	O	O	O

Most drivers around me on the road drive and:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
a. hold phone conversations	O	O	O	O	O
b. manually interact with a phone (e.g. send text messages)	O	O	O	O	O
c. adjust the settings of in-vehicle technology (e.g. radio channel or song selection)	O	O	O	O	O
d. read roadside advertisements	O	O	O	O	O
e. continually check roadside accident scenes if there are any	O	O	O	O	O
f. chat with passengers if there are any	O	O	O	O	O

Most people who are important to me think it is alright for me to drive and:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
a. hold phone conversations	O	O	O	O	O
b. manually interact with a phone (e.g. send text messages)	O	O	O	O	O
c. adjust the settings of in-vehicle technology (e.g. radio channel or song selection)	O	O	O	O	O
d. read roadside advertisements	O	O	O	O	O
e. continually check roadside accident	O	O	O	O	O

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
scenes if there are any					
f. chat with passengers if there are any	O	O	O	O	O

When driving, you find it distracting when:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
a. your phone is ringing	O	O	O	O	O
b. you receive and alert from your phone (e.g. incoming text message)	O	O	O	O	O
c. you are listening to music	O	O	O	O	O
d. you are listen to talk radio	O	O	O	O	O
e. there are roadside advertisements	O	O	O	O	O
f. there are roadside accident scenes	O	O	O	O	O
g. a passenger speaks to you	O	O	O	O	O
h. daydreaming occurs	O	O	O	O	O

Developed by:
Feng, J., Marulanda, S., & Donmez, B. (2014). Susceptibility to driver distraction questionnaire: development and relation to relevant self-reported measures. Transportation Research Record: Journal of the Transportation Research Board, (2434), 26-34.

Please click the arrow to continue

Simulator Sickness Questionnaire - Baseline

Instructions: Select how much each symptom below is affecting you right now.

	None	Slight	Moderate	Severe
1. General discomfort	O	O	O	O
2. Fatigue	O	O	O	O
3. Headache	O	O	O	O
4. Eye strain	O	O	O	O
5. Difficulty focusing	O	O	O	O
6. Salivation increasing	O	O	O	O
7. Sweating	O	O	O	O
8. Nausea	O	O	O	O
9. Difficulty Concentrating	O	O	O	O
10. Fullness of Head*	O	O	O	O
11. Blurred vision	O	O	O	O
12. Dizziness with eyes open	O	O	O	O
13. Dizziness with eyes closed	O	O	O	O
14. Vertigo**	O	O	O	O
15. Stomach Awareness***	O	O	O	O
16. Burping	O	O	O	O

* Fullness of head is the slight pressure experience before a headache

** Vertigo is experienced as a loss of orientation with respect to vertical upright

*** Stomach awareness is usually used to indicate a feeling of discomfort which his just short of nausea

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. *The international journal of aviation psychology*, *3*(3), 203-220.

Thank you for completing the starting questionnaires
Please read the instructions on the next page

Instructions For Practice Drive

Please Note: If at any point whilst driving you feel uncomfortable or nauseous please inform the researcher
First you will be completing **two** practice drives along a highway.
Start moving slowly and a yellow car will appear in front of you. Stay behind the yellow car, it will be your lead vehicle throughout the study. Try and keep a distance to the yellow car that is close but safe, and maintain that distance throughout the study. Throughout the study, at any point, the yellow car may change its speed - when the yellow car slows or speeds up try and keep the same distance to it.
At the beginning of drive one, you will practice controlling the vehicle and following the the yellow car as it changes speed.
Towards the end of drive one, you will be asked to complete **TEXT** tasks on the Head-up display.When you hear the beeps look at the HUD and read aloud the text that is presented. Speak clearly so that the researcher can hear you.

At the end of the practice drive you will see **orange drums** blocking to road. Please stop in front of the orange drums.
If you are unsure of anything please ask the researcher. Then the first practice drive will start.
PLEASE HAND THE TABLET BACK TO THE RESEARCHER

SSQ Post Practice1

Instructions: Select how much each symptom below is affecting you <u>right now.</u>

	None	Slight	Moderate	Severe
1. General discomfort	O	O	O	O
2. Fatigue	O	O	O	O
3. Headache	O	O	O	O
4. Eye strain	O	O	O	O
5. Difficulty focusing	O	O	O	O
6. Salivation increasing	O	O	O	O
7. Sweating	O	O	O	O
8. Nausea	O	O	O	O
9. Difficulty Concentrating	O	O	O	O
10. Fullness of Head*	O	O	O	O
11. Blurred vision	O	O	O	O
12. Dizziness with eyes open	O	O	O	O
13. Dizziness with eyes closed	O	O	O	O
14. Vertigo**	O	O	O	O
15. Stomach Awareness***	O	O	O	O
16. Burping	O	O	O	O

* Fullness of head is the slight pressure experience before a headache
** Vertigo is experienced as a loss of orientation with respect to vertical upright
*** Stomach awareness is usually used to indicate a feeling of discomfort which his just short of nausea

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. *The international journal of aviation psychology*, 3(3), 203-220.

PLEASE CONTINUE TO THE NEXT INSTRUCTIONS

Practice2

Please Note:
If at any point whilst driving you feel uncomfortable or nauseous please inform the researcher

During the second practice drive you will be asked to complete **MENU** tasks on the Head-up display.
When you hear the beeps look to the HUD which will display a target word. Remember the target word. A menu will appear with alphabetical options (e.g. A-C). Navigate through the menu to find the target word using the buttons on the steering wheel and select the correct word.

At the end of the practice drive you will see orange drums blocking to road. Please stop in front of the orange drums.
If you are unsure of anything please ask the researcher. Then the practice drive will start.

PLEASE HAND THE TABLET BACK TO THE RESEARCHER

SSQ Post Practice2

Instructions: Select how much each symptom below is affecting you right now.

	None	Slight	Moderate	Severe
1. General discomfort	O	O	O	O
2. Fatigue	O	O	O	O
3. Headache	O	O	O	O

	None	Slight	Moderate	Severe
4. Eye strain	O	O	O	O
5. Difficulty focusing	O	O	O	O
6. Salivation increasing	O	O	O	O
7. Sweating	O	O	O	O
8. Nausea	O	O	O	O
9. Difficulty Concentrating	O	O	O	O
10. Fullness of Head*	O	O	O	O
11. Blurred vision	O	O	O	O
12. Dizziness with eyes open	O	O	O	O
13. Dizziness with eyes closed	O	O	O	O
14. Vertigo**	O	O	O	O
15. Stomach Awareness***	O	O	O	O
16. Burping	O	O	O	O

* Fullness of head is the slight pressure experience before a headache
** Vertigo is experienced as a loss of orientation with respect to vertical upright
*** Stomach awareness is usually used to indicate a feeling of discomfort which his just short of nausea

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. *The international journal of aviation psychology*, *3*(3), 203-220.

PLEASE CONTINUE TO THE NEXT INSTRUCTIONS

Instructions for Baseline Drive

Next you will complete the baseline drive. During this drive you will follow the same road and follow the yellow vehicle while we monitor your driving.
It will take approximately 5 minutes.

PLEASE HAND THE TABLET BACK TO THE RESEARCHER

Simulator Sickness Post Baseline

Instructions: Select how much each symptom below is affecting you right now.

	None	Slight	Moderate	Severe
1. General discomfort	O	O	O	O
2. Fatigue	O	O	O	O
3. Headache	O	O	O	O
4. Eye strain	O	O	O	O
5. Difficulty focusing	O	O	O	O
6. Salivation increasing	O	O	O	O
7. Sweating	O	O	O	O
8. Nausea	O	O	O	O
9. Difficulty Concentrating	O	O	O	O
10. Fullness of Head*	O	O	O	O
11. Blurred vision	O	O	O	O
12. Dizziness with eyes open	O	O	O	O
13. Dizziness with eyes closed	O	O	O	O
14. Vertigo**	O	O	O	O
	O	O	O	O

	None	Slight	Moderate	Severe
15. Stomach Awareness***				
16. Burping	O	O	O	O

* Fullness of head is the slight pressure experience before a headache
** Vertigo is experienced as a loss of orientation with respect to vertical upright
*** Stomach awareness is usually used to indicate a feeling of discomfort which his just short of nausea

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. *The international journal of aviation psychology*, *3*(3), 203-220.

PLEASE CONTINUE TO THE NEXT INSTRUCTIONS

Instructions for Main Drive

Next you complete the main experiment drives. There will be two drives, each lasting under 15 minutes. During one drive the text task will appear on the HUD. During the other the menu task will be used.
The researcher will let you know which one you will be completing first.

At the end of the practice drive you will see orange drums blocking to road. Please stop in front of the orange drums.

If you are unsure of anything please ask the researcher. Then the first main drive will start.
PLEASE HAND THE TABLET BACK TO THE RESEARCHER

Simulator Sickness - Block1

Instructions: Select how much each symptom below is affecting you right now.

	None	Slight	Moderate	Severe
1. General discomfort	O	O	O	O

	None	Slight	Moderate	Severe
2. Fatigue	O	O	O	O
3. Headache	O	O	O	O
4. Eye strain	O	O	O	O
5. Difficulty focusing	O	O	O	O
6. Salivation increasing	O	O	O	O
7. Sweating	O	O	O	O
8. Nausea	O	O	O	O
9. Difficulty Concentrating	O	O	O	O
10. Fullness of Head*	O	O	O	O
11. Blurred vision	O	O	O	O
12. Dizziness with eyes open	O	O	O	O
13. Dizziness with eyes closed	O	O	O	O
14. Vertigo**	O	O	O	O
15. Stomach Awareness***	O	O	O	O
16. Burping	O	O	O	O

* Fullness of head is the slight pressure experience before a headache
** Vertigo is experienced as a loss of orientation with respect to vertical upright
*** Stomach awareness is usually used to indicate a feeling of discomfort which his just short of nausea

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. *The international journal of aviation psychology*, *3*(3), 203-220.

PLEASE HAND THE TABLET BACK TO THE RESEARCHER

Simulator Sickness - Block2

Instructions: Select how much each symptom below is affecting you right now.

	None	Slight	Moderate	Severe
1. General discomfort	O	O	O	O
2. Fatigue	O	O	O	O
3. Headache	O	O	O	O
4. Eye strain	O	O	O	O
5. Difficulty focusing	O	O	O	O
6. Salivation increasing	O	O	O	O
7. Sweating	O	O	O	O
8. Nausea	O	O	O	O
9. Difficulty Concentrating	O	O	O	O
10. Fullness of Head*	O	O	O	O
11. Blurred vision	O	O	O	O
12. Dizziness with eyes open	O	O	O	O
13. Dizziness with eyes closed	O	O	O	O
14. Vertigo**	O	O	O	O
15. Stomach Awareness***	O	O	O	O
16. Burping	O	O	O	O

* Fullness of head is the slight pressure experience before a headache
** Vertigo is experienced as a loss of orientation with respect to vertical upright

*** Stomach awareness is usually used to indicate a feeling of discomfort which his just short of nausea

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. *The international journal of aviation psychology*, *3*(3), 203-220.

PLEASE HAND THE TABLET BACK TO THE RESEARCHER

Post Procedure Questionnaire

Would you consider the Head-up Display (HUD) you experienced is "safe to use" whilst driving?

- Strongly Disagree
- Disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Agree
- Strongly agree

Would you commonly use the HUD you experience?

- Not at all
- Rarely
- Sometimes
- Often
- All the time

Did you feel in control whilst using the HUD?

- Not at all
-

Rarely

- Sometimes
- Often
- All the time

Did you feel aware of your surroundings?

- Not at all
- Rarely
- Sometimes
- Often
- All the time

To what degree did you feel aware of the lead car when it braked?

- Not at all
- Rarely
- Sometimes
- Often
- All the time

Do you agree that the tasks you completed are like the tasks you typically perform whilst in a car?

- Strongly Disagree
- Disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Agree
- Strongly agree

Thank you for completing the questionnaire.

PLEASE HAND THE TABLET BACK TO THE RESEARCHER

Powered by Qualtrics

Appendix C – Materials used in Study 2

Information Sheet

Information Sheet

"The Visual Demand of Head-Up Displays across Windscreens"

This study is aiming to assess the visual demand of in-vehicle displays. The entire procedure will take approximately 1 hour.

The study will take place within a driving simulator. During the study you will first be asked to drive along the motorway for a few minutes to familiarise yourself with the simulator. Within the main phase of the experiment you will complete a task on a display within the car. Alternating letters will be displayed and you will be asked to verbally repeat any that appear on the display for a longer time period. The location of the display imagery will vary several times and the same task will be repeated.

This study will use a video camera to record you in order to capture your verbal responses to the task. The video footage will only be used for this purpose. Your gaze will also be tracked using an eye-tracker, to analyse where you look during the simulation. At the end of the study you will be asked your preference for display location.

The simulator used in this study may make you feel nauseous. Please inform an experimenter if you are feeling uncomfortable and please do not take part if you are pregnant or commonly experience severe motion sickness.

The data collected from this experiment will be stored securely for up to 7 years. The data will be made anonymous through a numbering system so that no personal information will not be connected to the responses you provide. The data will be used for the purposes of reports and publications.

Please be aware that you may withdraw from the study at any point without explanation or reason.

Please take the opportunity now to ask any questions you may have.

Thank you for volunteering to participate in this study.

If you would like further information regarding the study please use the following contact information:

Researcher: Bethan Topliss

Email: bethan.topliss@nottingham.ac.uk

Consent Form

Consent Form

This form is to be completed in order to provide consent for participating in the study “The Visual Demand of Head-Up Displays across Windscreens” conducted by Bethan Topliss and supervised by Prof. Gary Burnett and Dr. Sanna Pampel.

Please read the below statements and tick where appropriate.
Please read the entire form before signing.
If you have any questions, please ask the researcher.

- ☐ I hold a full driving licence
- ☐ I have read the information sheet, I understand what is expected of me and have had the opportunity to ask questions
- ☐ I understand that the data collected will be used of the purposes of reports and publications.
- ☐ I understand the data will be held securely in a database for up to 7 years in-line with the University policy
- ☐ I understand that I am able to withdraw from the study at any point without having to provide an explanation and without penalty
- ☐ I confirm that I am voluntarily agreeing to participate in this study
- ☐ I understand that I will be filmed in order to record verbal responses to the task
- ☐ I am not pregnant
- ☐ I do not have severe motion sickness

Participant name (Please print)

____

Participant Signature

____

Date

____

Researcher name (Please print)

____

Researcher Signature

____

Date

____

Simulation Sickness Questionnaire (SSQ)

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.

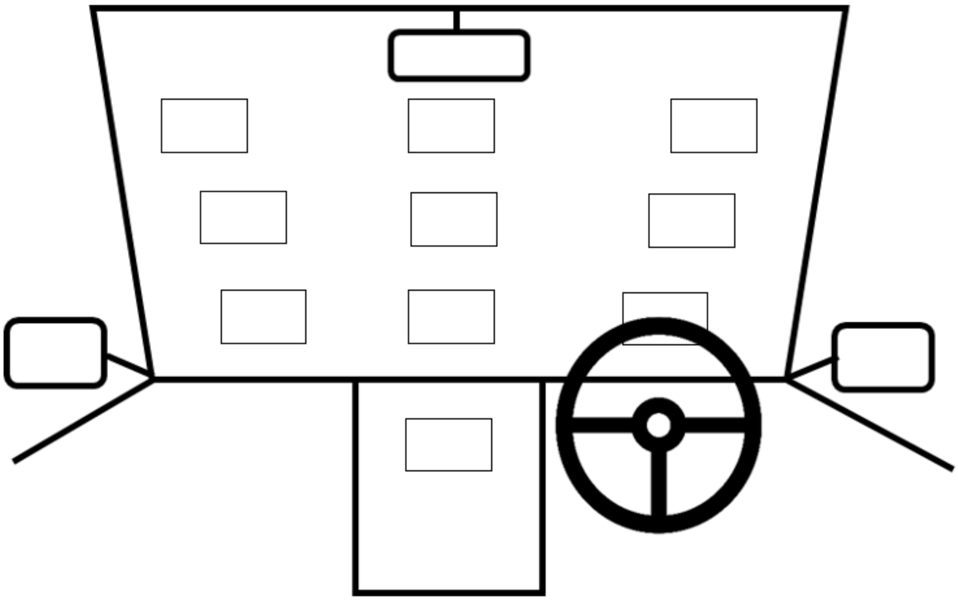
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

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.

Questionnaire for Location Preference

Please place a number (1 -10) in each box to rank your favourite location for the display imagery to your least favourite, with number 1 being your favourite and number 10 being your least favourite.



Thank you for your time.

Demographic Questionnaire

Please indicate your age. (Please circle the appropriate range)
18-25   26-35   36-45   46-55   56-65   65+

Please indicate your gender. (Please circle)
Male   Female   Other

How long have you held your driving licence? (Please indicate the number of years)

__________ (years)

How much do you drive in a year? (Please indicate the number of miles)

__________ (miles)

Debrief Sheet

Debrief Sheet

"The Visual Demand of Head-Up Displays across Windscreens"

You have just participated in a study aiming to quantify how visually demanding HUD imagery is at various locations across a car windscreen. Please see the information sheet provided before the experiment for details.

Thank you for your participation.

If you would like any further information regarding the study or wish to withdraw your data, please use the following contact information:

Researcher: Bethan Topliss

Email: bethan.topliss@nottingham.ac.uk

Appendix D – Materials used in Study 3

Advertisement/ Recruitment Materials

PARTICIPANTS NEEDED
DRIVING SIMULATOR STUDY

During the study you will be asked to drive the simulator for several short drives and interact with some in-vehicle displays. You will also be asked to complete some questionnaires.

The study should take under 2 hours, and you will receive a £10 amazon voucher as compensation for your time.

Participation is voluntary and confidential. If you are interested in participating, sign up the using the QR code above or contact **Bethan Topliss** (bethan.topliss@nottingham.ac.uk) or visit https://calendly.com/bethan-nottingham/driving-simulation-study

SIGN UP HERE

OR SEND AN EMAIL TO: BETHAN.TOPLISS @NOTTINGHAM.AC.UK

To participate you need:

- ✓ To be an active driver with a valid license
- ✓ Be 18+ and in good health
- ✓ Have normal or corrected-to-normal vision

Please be aware that you may experience some motion sickness whilst using the driving simulator.

If you are susceptible to severe motion sickness, migraines, epilepsy, dizziness or blurred vision, or are pregnant, then you should not volunteer.

Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk	Driving Simulator Study Contact: Bethan Topliss bethan.topliss@nottingham.ac.uk

Information Sheet

Information Sheet

"The Visual Demand of Vehicle Displays"

This study is aiming to assess the visual demand of in-vehicle displays. The entire procedure will take approximately 1 hour and 30 minutes.

The study will take place within The University of Nottingham Human Factors fixed-based driving simulator. During the study you will first complete a practice drive, to familiarise yourself with the car. In the following drives you will complete tasks with 13 different displays whilst you are driving.

During all the drives you will be following a yellow car in the left lane. Try to maintain a consistent distance behind the yellow car, and try not to fall too far behind. If you fall too far behind, an audio cue will remind you to catch up.

You will be notified that a task is going to start by three quick beeps. The task will involve rapidly alternating letters on the display. Occasionally, one of the letters will remain on the screen for slightly longer, you will be required to speak-aloud that letter. The task is designed to require your full visual attention, so when the task is occurring **keep your eyes focused on the task, and not the road.** When you hear a second tone you are allowed to look back towards the road. The location of the display imagery will vary and the same task will be repeated several times during the drive. You will have the opportunity to practice the task.

Please remember to look at the task/display, and not the road, during the tasks.

During each task, you also have the option to press a button. Please press the button once you feel you have been looking towards the task, and away from the road for too long, and you believe it would be unsafe or dangerous to do on a real road. Please continue looking at the task and complete the task, even after pressing the button.

This study will use video cameras to record you in order to capture your verbal responses to the task. Your gaze will also be tracked using an eye-tracker, to analyse where you look during the simulation.

The simulator used in this study may make you feel nauseous. Please inform an experimenter if you are feeling uncomfortable and please do not take part if you are pregnant, epileptic or commonly experience severe motion sickness.

The data collected from this experiment will be stored securely for up to 7 years. The data will be made anonymous through a numbering system so that no personal information will not be connected to the responses you provide. The data will be used for the purposes of reports and publications.

Please be aware that you may withdraw from the study at any point without explanation or reason.

Please take the opportunity now to ask any questions you may have.

Thank you for volunteering to participate in this study.

If you would like further information regarding the study, please use the following contact information:

Researcher: Bethan Topliss

Email: bethan.topliss@nottingham.ac.uk

Consent Form

Consent Form

This form is to be completed in order to provide consent for participating in the study "The Visual Demand of Vehicle Displays" conducted by Bethan Topliss and supervised by Prof. Gary Burnett and Dr. Cath Harvey.

Please read the below statements and tick where appropriate.
Please read the entire form before signing.
If you have any questions, please ask the researcher.

- ☐ I hold a full driving licence
- ☐ I have read the information sheet, I understand what is expected of me and I have had the opportunity to ask questions
- ☐ I understand that the data collected will be used of the purposes of reports and publications
- ☐ I understand the data will be held securely in a database for up to 7 years in-line with the University policy
- ☐ I understand I may experience simulation sickness
- ☐ I understand that I will be video recorded in order to record responses to the tasks
- ☐ I am not pregnant, epileptic or have severe motion sickness, migraines or blurred vision
- ☐ I understand that I am able to withdraw from the study, or withdraw my data, at any point without having to provide an explanation and without penalty
- ☐ I consent to my video data being used in academic presentations in order to highlight results
- ☐ I confirm that I am voluntarily agreeing to participate in this study

Participant name (Please print)

____

Participant Signature

____

Date

____

Researcher name (Please print)

____

Researcher Signature

____

Date

____

Demographic Questionnaire

Demographic Questionnaire

Please indicate your age. (Please indicate the number of years)

_______(years)

Please indicate your gender. (Please circle)
Male Female Other Prefer not to say

How long have you held your driving licence? (Please indicate the number of years)

_________ (years)

How much do you drive in a year? (Please indicate the approximate number of miles)

_________ (miles)

Have you previously used a head-up display or "HUD" in a car? (Please circle the appropriate response)

Yes No

Have you previously used a touch-screen device in a car? (Please circle the appropriate response)

Yes No

Have you previously driven a driving simulator? (Please circle the appropriate response)

Yes No

Do you have any issues with your peripheral vision?

Yes No

If you responded YES to the previous question, please add details below (otherwise leave blank):

____
____

Thank you for completing this questionnaire. Please let the researcher know you have finished.

To be completed by the researcher

Participant eye height when seated in simulator

____

Simulation Sickness Questionnaire (SSQ)

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.

Perspective Questionnaire

Perspective Questionnaire

For each of the questions please **place a cross** on the line to indicate your response.

Do you think your driving became dangerous or unsafe at all during that journey?

No, absolutely not — Yes, completely

How successfully do you feel you completed the tasks?

Poorly — Perfectly

Do you think you looked away from the road for too long at any point?

No, absolutely not — Yes, completely

Did you feel aware of your surroundings throughout the journey?

Not at all — Completely

To what degree did you feel aware of the lead car during the journey?

Not at all — Completely

Did you feel in control during the journey?

Not at all — Completely

What is the longest time you think you looked away from the road for (please write your answer in seconds)?

___________________________seconds

How long do you think is an acceptable time to look away from the road, and towards that location (please write your answer in seconds)?

___________________________seconds

Preference Questionnaire

Preference Questionnaire

Below is a photo of the interior of the simulator vehicle you were just in.

On both photos below place a GREEN "X" where you thought the image was EASIEST to see.
On both photos below place a RED "X" where you thought the image was HARDEST to see.

Middle view

Driver's perspective

On both photos below, place a GREEN “X” on the location that had the LEAST impact on safe driving (i.e. the location where you could best maintain your driving performance).
On both photos below, place a RED “X” on the location that had the GREATEST impact on safe driving (i.e. the location where you could least maintain your driving performance).

Middle view

Driver’s perspective

Do you have any other thoughts? Please write them below.

- -

Debrief Sheet

You have just participated in a study aiming to establish how visually demanding HUD imagery is at various locations across a car windscreen in comparison to other in-vehicle displays.

Thank you for your participation.

If you would like any further information regarding the study or wish to withdraw your data, please use the following contact information:

Researcher: Bethan Topliss

Email: bethan.topliss@nottingham.ac.uk

Post-Trial Form

Thank you for taking part in this experiment. Your time and efforts are greatly appreciated.

Please sign below to confirm that the following actions have taken

- I have received a £10 Amazon voucher as reimbursement for my time.
- Any feelings of discomfort I may have felt during or immediately after the trial have now subsided.
- I have been advised to wait for at least 30 minutes before driving my own vehicle.

Name (please print)

....

Signed

....

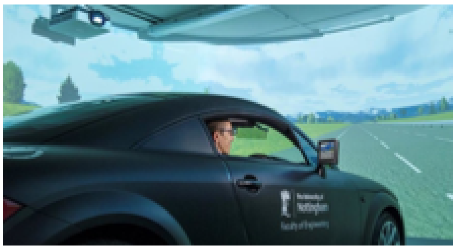
Date and Time

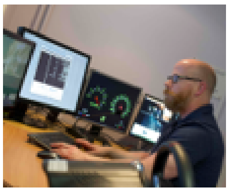
....

Appendix E – Materials used in Study 4

Advertisement/ Recruitment Materials

PARTICIPANTS NEEDED
DRIVING SIMULATOR STUDY





SIGN UP HERE

Send an email to: bethan.topliss@nottingham.ac.uk

For more information:

Remotely, you will complete several questionnaires online via Microsoft forms. At University Park campus you will be asked to drive the simulator for several short drives whilst you interact with some in-vehicle displays (to play a game, read text and navigate a menu).

During the simulation you will be in the driving simulator room, whilst the researcher remains in the control room. The researcher will only enter the same room as you to calibrate the eye-tracking equipment. Face coverings will be worn, and social distance (>1m) will be maintained as possible. Before and after each participant all equipment will be cleaned. You will also have access to alcohol wipes and hand sanitiser as you desire.

You will also be asked to complete some questionnaires via a mobile device during the procedure.

The study will take around 45-60 minutes to complete. You will receive a £10 Amazon voucher as compensation for your time.

Participation is voluntary and confidential. If you are interested in participating, please contact **Bethan Topliss** (bethan.topliss@nottingham.ac.uk) or for more information please follow the QR code above.

To participate you need:

- ✓ To be an active driver with a license
- ✓ Be 18+ and in good health
- ✓ Have normal or corrected-to-normal vision (glasses/contact lenses are OK)
- ✓ Have access to a mobile device to answer questionnaires remotely during

Please be aware that you may experience some motion sickness whilst using the driving simulator. If you are susceptible to severe motion sickness, migraines, epilepsy, dizziness, or blurred vision, or are pregnant, then you should not volunteer. If you are experiencing symptoms of Covid-19, have been in recent contact with someone who is experiencing symptoms, are considered vulnerable due to an underlying condition, share a household with anybody who is currently shielding, or are in isolation, then you should not volunteer.

This study follows the University of Nottingham guidance: https://workspace.nottingham.ac.uk/pages/viewpage.action?spaceKey=safety&title=Covid-19+Recovery as well as the "Covid-19 (Coronavirus)-Specific Guidance and Requirements for Participation in Human Factors Research Group Driving Simulator Studies". If you have any questions or concerns, please contact the researcher.

Information Sheet

Information Sheet

This study is aiming to assess how drivers interact with novel vehicle displays. The study will take place partially remotely and partially within The University of Nottingham Human Factors fixed-based driving simulator. Please note, you will require a smart mobile device with you during the simulator procedure, which can connect to the internet, so that you can answer questionnaires remotely during the study.

Before, during and after the simulation you will be asked to complete some questionnaires and consent forms on Microsoft Forms. During the simulation you will first complete a practice drive, to familiarise yourself with the car. Throughout the study please drive as you would on a real road.

During the simulation you will be in the driving simulator room, whilst the researcher remains in the control room. The researcher will only enter the same room as you to calibrate the eye-tracking glasses, which involves the researcher interacting with a laptop the equipment is connected to. Face coverings will be worn, and social distance (>1m) will be maintained as possible. Before and after each participant all equipment will be cleaned. You will also have access to alcohol wipes and hand sanitiser as you desire. Before and after every participant, the driving simulator and equipment will be thoroughly cleaned according to current guidelines.

In the four main drives a display will show you:
Some text to read aloud, a menu which you need to navigate in order to find the target word, or a game you can choose to interact with if you wish. These tasks will be demonstrated to you so you can also practice them beforehand. You can interact with the task by pressing the Up/Down/Left/Right keys on the steering wheel.

During all the drives you will be following a yellow car in the left lane. Try to maintain a consistent distance behind the yellow car and try not to fall too far behind. If you fall too far behind, an audio cue will remind you to catch up. Between drives you will be asked to complete a questionnaire on your smart phone.

This study will use video cameras in order to capture your responses, these videos will only be viewed by the researcher unless you consent to them being shared. Your gaze will also be tracked using eye-tracking glasses, to analyse where you look during the simulation.

The simulator used in this study may make you feel nauseous. Please inform an experimenter if you are feeling uncomfortable and please do not take part if you are pregnant, epileptic or commonly experience severe motion sickness.

The data collected from this experiment will be stored securely for up to 7 years. The data will be made anonymous through a numbering system so that no personal information will not be connected to the responses you provide. The data will be used for the purposes of reports and publications.

This study follows the University of Nottingham guidance:
https://workspace.nottingham.ac.uk/pages/viewpage.action?spaceKey=safety&title=Covid-19+Recovery /
https://www.nottingham.ac.uk/coronavirus/safety-on-campus.aspx as well as the "Covid-19 (Coronavirus)-Specific Guidance and Requirements for Participation in Human Factors Research Group Driving Simulator Studies".
You will be asked to provide contact details (name and telephone number/email address) in order to support "track and trace" (https://www.gov.uk/guidance/nhs-test-and-trace-how-it-works) and so that the experimenter can more easily communicate with you when you are in a separate rooms. Contact details will subsequently be kept for a period of 21 days. Thereafter, contact details will be destroyed. If you have any questions or concerns, please contact the researcher.

Please be aware that you may withdraw from the study at any point without an explanation or reason.
Please ask any questions you may have by emailing bethan.topliss@nottingham.ac.uk before your appointment time.
Thank you.

Health Form

Specialised Health Form

* Required

This information is being collected in order to contact you remotely and to follow the Track and Trace guidelines (https://www.gov.uk/guidance/nhs-test-and-trace-how-it-works).
Contact details will subsequently be kept for a period of 21 days. Thereafter, contact details will be destroyed.

1. Please state your full name *

Enter your answer

2. Please provide your mobile phone number (we ask for this so that we can more easily communicate with you in separate rooms throughout the procedure). *

Enter your answer

3. Please provide your email address *

Enter your answer

Next

Page 1 of 2

Specialised Health Form

* Required

Please confirm the following statements are true

Please confirm whether the following statements are true. If you have any questions or concerns please contact the researcher (bethan.topliss@nottingham.ac.uk)

4. I have read, understand, and agree to follow the current University of Nottingham "Safety on Campus" guidelines: https://www.nottingham.ac.uk/coronavirus/safety-on-campus.aspx *

◯ I confirm this is correct

5. I am not currently experiencing symptoms of Covid-19 (Coronavirus), which includes a high temperature, a new, continuous cough, and a loss or change to my sense of smell or taste, or have been diagnosed with Covid-19 *

◯ I confirm this is correct

6. I have not been in contact with someone who is suspected, or is known to have contracted Covid-19 within the last 14 days *

◯ I confirm this is correct

7. I have not received a letter from the NHS advising me that I am clinically extremely vulnerable *

◯ I confirm this is correct

8. I do not have an underlying health condition that could make me vulnerable *

◯ I confirm this is correct

9. I do not share a household with anybody who is currently shielding *

◯ I confirm this is correct

10. I am not in self-isolation for 14 days after returning to the UK, or have been advised to do so *

◯ I confirm this is correct

11. There are no other reasons, related to Covid-19, which prevents me from taking part *

◯ I confirm this is correct

12. I am willing and able to provide 'social distancing' as far as is practicable (i.e. a separation of at least "1m plus" from University staff) for the duration of the study *

◯ I confirm this is correct

Back | Submit | Page 2 of 2

Never give out your password. Report abuse

Consent Form

Study Consent Form

This form is to be completed in order to provide consent for participating in the study "Interaction with Vehicle Displays" Please read the below statements and select where appropriate. Please read the entire form. If you have any questions, please contact the researcher (bethan.topliss@nottingham.ac.uk).

* Required

1. Please state your assigned participant number *

   Enter your answer

2. I confirm that I will be able to bring a personal smart device to the driving simulator in order to answer questionnaires remotely during the procedure *

   ◯ I confirm

3. I have read the information sheet, I understand what is expected of me and have had the opportunity to ask questions *

   ◯ I confirm

4. I understand that the data collected will be used of the purposes of reports and publications *

   ◯ I confirm

5. I understand the data will be held securely in a database for up to 7 years in-line with the University policy *

   ◯ I confirm

6. I understand I may experience simulation sickness *

- ◯ I confirm

7. I understand that I will be video recorded in order to record responses to the tasks *

- ◯ I confirm

8. I am not pregnant, epileptic or have severe motion sickness, migraines or blurred vision *

- ◯ I confirm

9. I understand that I am able to withdraw from the study, or withdraw my data, at any point without having to provide an explanation and without penalty *

- ◯ I confirm

10. I hold a full driving licence (your licence may be from another country) *

- ◯ Yes

11. I consent to my video data being used in academic presentations in order to highlight results *

- ◯ Yes
- ◯ No

12. I confirm that I am voluntarily agreeing to participate in this study *

- ◯ I confirm

Submit

Demographic Questionnaire

Demographic Questionnaire

...

* Required

1. Please state your assigned participant number *

Enter your answer

2. Please indicate your age *

Enter your answer

3. Please indicate your gender *

- ◯ Male
- ◯ Female
- ◯ Other
- ◯ Prefer not to say

4. How long have you held your driving licence? (Please indicate the number of years) *

Enter your answer

5. How much do you drive in a year? (Please indicate the approximate number of miles) *

Enter your answer

6. Have you previously used a head-up display or "HUD" in a car? *

- ◯ Yes
- ◯ No
- ◯ Unsure

7. Have you previously used a touch-screen device in a car? *

- ◯ Yes
- ◯ No
- ◯ Unsure

8. What displays do you have in your current vehicle. If you do not have a vehicle, what sort of displays were present in the last vehicle you drove? For example any touch screens, navigation devices, digital menus?
Please describe below *

Enter your answer

9. Have you previously driven a driving simulator? *

- ◯ Yes
- ◯ No
- ◯ Unsure

10. Do you have any issues with your peripheral vision? *

- ◯ Yes
- ◯ No

Submit

Simulation Sickness Questionnaire (SSQ)

Simulator Sickness Questionnaire

* Required

Reference:
Kennedy, R. S., Norman, L. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The International Journal of Aviation Psychology, 3(3), 203–220. Retrieved from https://doi.org/10.1207/s15327108ijap0303_3

1. Please state your assigned participant number *

Enter your answer

2. Select how much each symptom below is affecting you right now.

* Vertigo is experienced as a loss of orientation with respect to vertical upright
**Stomach awareness is usually used to indicate feeling of discomfort which is just short of nausea. *

	None	Slight	Moderate	Severe
General Discomfort	○	○	○	○
Fatigue	○	○	○	○
Headache	○	○	○	○
Eye strain	○	○	○	○
Difficulty focusing	○	○	○	○
Salivation increasing	○	○	○	○
Sweating	○	○	○	○
Nausea	○	○	○	○
Difficulty concentrating	○	○	○	○
Fullness of Head	○	○	○	○
Blurred vision	○	○	○	○
Dizziness with eyes open	○	○	○	○
Dizziness with eyes closed	○	○	○	○
Vertigo*	○	○	○	○
Stomach awareness**	○	○	○	○
Burping	○	○	○	○

Submit

After Drive Questionnaire

After Drive Questionnaire

* Required

1. Please state your assigned participant number *

Enter your answer

2. How safe did you feel using that display method and doing that task? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
	○	○	○	○	○

3. Do you believe you can drive well even while interacting with that display/task? *

	Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree
	○	○	○	○	○

4. Do you feel confident that you could always interact safely with that display? *

	Confident	Somewhat confident	Unsure	Somewhat unconfident	Unconfident
	○	○	○	○	○

5. Would you like to use that display if it was in your vehicle? *

- ◯ Yes
- ◯ No
- ◯ Unsure

6. Please state the reason for your answer to Q5 *

Enter your answer

7. How long do you think you could look at that display (in one glance) before your driving became unsafe in a real car? Please answer in seconds. *

Enter your answer

8. Do you have any other thoughts or comments on what you just experienced? Please answer "no" if you have no further comments *

Enter your answer

Submit

End of Procedure Questionnaire

End of Procedure Questionnaire

* Required

1. Please state your assigned participant number *

Enter your answer

2. Did you prefer the Head-up display (which was projected), or the Head-down display (the LCD on the centre console)? *

- ◯ Head-up display (which was projected)
- ◯ Head-down display (the LCD on the centre console)
- ◯ Both equally

3. Throughout the study you were asked to drive as you would on a real road. Do you feel you achieved this? *

- ◯ Yes
- ◯ No
- ◯ Unsure

4. Do you think you would have responded any differently on a real-road? *

Enter your answer

5. Would you be comfortable with only a HUD (on the windshield) within your vehicle, and nothing on the centre console or anywhere else? *

- ◯ Yes
- ◯ No
- ◯ Unsure

6. If you completed the study again, do you think you would do anything differently? *

Enter your answer

7. Do you think the menu/reading task was something you would typical do while driving? *

Enter your answer

8. Do you think the game task was something you would typically do whilst driving? *

Enter your answer

9. Please indicate your thoughts on the statements below *

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Displays which present imagery on the windshield, over the road ahead, are not dangerous to look at whilst driving	○	○	○	○	○
Displays which present imagery on the windshield, over the side of the road, are not dangerous to look at whilst driving	○	○	○	○	○
Displays which are on the centre console are not dangerous to look at whilst driving	○	○	○	○	○
Displays at the instrument cluster are not dangerous to look at while driving	○	○	○	○	○

10. Please indicate your thoughts on the statements below *

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
It's OK to look away from the road to change the air temperature	○	○	○	○	○
It's OK to look away from the road to change the music	○	○	○	○	○
It is OK to look around at the scenery while driving	○	○	○	○	○
It is OK to only look ahead while in traffic	○	○	○	○	○
Its OK to only look ahead when you are not on a busy road	○	○	○	○	○
It's OK to look away from the road because you are bored	○	○	○	○	○

11. Are there any other comments or thoughts you would like to express to the researcher? *

Enter your answer

12. We recommend waiting at least 30 minutes after completing a simulator drive before driving a vehicle. Please confirm that you understand this recommendation. *

○ I understand

Submit