Eyes on the road

A review of literature and an in-car study of driving whilst navigating

Ryan Robbins & David Jenkins
TRL
September 2015

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Disclaimer

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Foreword

Navigational assistance for motorists has come a long way from the days when it meant having a road atlas open on the passenger seat. Increasingly vehicle manufacturers are designing satellite navigation systems into the car dashboard as standard equipment. But route-finding help is also available through stand-alone sat-nav devices, smart phones, and potentially other wearable technology.

Our concern is in understanding what needs to be done to ensure that driver-assistance doesn't become driver distraction.

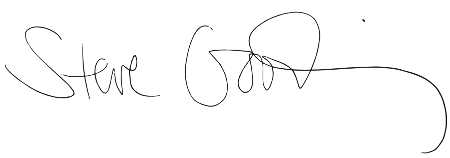
This research by the Transport Research Laboratory will be of interest to businesses developing products that might be available to drivers in the future. Our aim is that the emphasis should not be on specific products – indeed the smart-glass technology tested here is no longer on the market – but on the framework within which they are developed and used. What this report shows is that:

- there is a body of knowledge about driver distraction that can help inform the design and development of new products,
- there are ways of assessing the distraction risk – TRL has adapted what is known as the 'Viennese' approach, described in detail in the report, and
- it is therefore reasonable to expect the developers of new products to undertake their own assessments and ensure that their designs really are assistive and not distractive.

Of course not every product is designed with motoring specifically in mind, something product designers will need to consider in particular for wearable technology.

In a world offering ever increasing connectivity, vehicle-to-vehicle and vehicle-to-roadside, the Foundation will continue to explore what it means to be a 'connected driver'. What helps drivers focus on the task in hand? What makes those systems work? And what role is there for Government and bodies like Highways England in communicating accurate information?

Steve Gooding



Director, RAC Foundation

Executive Summary

The dangers of driver distraction caused by in-vehicle technologies have been widely researched. Since the 1930s and the advent of the first car radios, the variety and complexity of in-vehicle technologies which can distract drivers has grown, and now includes devices such as mobile phones and satellite navigation systems. Each new technology that enters the market has the potential to influence driving behaviour in ways that are difficult to anticipate. 'Smart glasses' are an example of one of these new classes of technologies which may affect driver distraction. Smart glasses are multifunctional wearable computers which are worn on the head and typically display visual information to the user through lenses mounted in or near the eye line.

Presently, the extent to which smart glasses may positively or negatively affect driver distraction is not understood. On the one hand, they offer the promise of reducing driver distraction in comparison to traditional means of satellite navigation by, for example, having a more sophisticated voice control interface, which has been consistently shown to outperform manual control (Basacik, Reed & Robbins, 2011; Caird et al., 2014); and by displaying visual information near the forward visual field, the time a driver spends with their eyes off the road in order to assimilate navigation information may be reduced. However, they may also present information in a more compelling manner, resulting in additional distraction; or the display may potentially obscure important visual information, resulting in a failure to perceive hazards.

This study comprises two parts: a review of current literature on driver distraction related to smart glasses; and an on-the-road experimental study comparing driver behaviour whilst navigating using (1) smart glasses; (2) smartphone-based satellite navigation (satnav); and (3) verbal instructions.

1.1 Literature review summary

The literature review discusses the nature of driver distraction and examines the evidence available, to ascertain the extent to which smart glasses might distract or assist drivers in the primary driving task. Although relatively little research on this technology exists, those papers which have been published are reviewed.

The evidence obtained suggests that smart glasses are likely to distract drivers from the activities required for safe driving; however, it is possible that they will do so to a lesser degree than other in-vehicle information systems, in particular handheld smartphones being used for communication. This is due mainly to the use of voice control, which has been shown consistently to distract less than manual interfaces. However, a note of caution must be sounded, as smart glasses do possess the potential to distract from the visual field[1] by: masking important road features behind a display; diverting driver attention away from the driving task and onto their display; and/or creating ‘cognitive capture’ in users (the phenomenon whereby drivers focus too heavily on the central forward field and ignore important cues in their peripheral vision). The use of smart glasses when driving must therefore be carefully considered until further research conclusively demonstrates their effect on driving performance.

1.2 Experimental study summary

This experimental study focuses on the consequences of having visual information displayed over a portion of the forward visual field.

A representative sample of 16 members of the general driving population completed three successive drives on public roads whilst navigating to an unknown destination. During each drive they followed the directions of one of three different forms, or ‘conditions’, of navigation: standardised voice instructions from a driving instructor (i.e. verbal information only), navigation information displayed on a smartphone (the ‘satnav’ condition – visual information only), or navigation information displayed on smart glasses (visual information only). Driving behaviour was assessed using a modified form of the Viennese Driving Test (VDT) (Chaloupka & Risser, 1995) and questionnaires were administered to gather subjective self-reported data from each participant on their experiences of each drive.

1 The visual field is the “portion of space in which objects are visible at the same moment during steady fixation of gaze in one direction” (Spector, 1990).

Results showed, when assessed by the VDT, that drivers were equally likely to commit a driving error when receiving verbal instructions or using either satnav or smart glasses. Furthermore, the number of times an incorrect turn was taken was also recorded,[2] and this showed that drivers were equally likely to take a wrong turn when using either satnav or smart glasses, but much less likely to take a wrong turn when receiving verbal instructions.

Participant self-reported measures of workload (using the NASA-TLX questionnaire) and their impressions of the drives showed a clear trend for giving verbal instructions the most positive ratings, followed by satnav, and then smart glasses.

A log of technical problems encountered during the trial with the satnav and smart glasses was recorded. There were no technical problems with the satnav. In contrast, only one trial out of 16 did not experience some form of technical problem related to the operation of the smart glasses. These problems were related mostly to overheating and loss of Bluetooth connectivity between the smartphone and smart glasses. Reasons for these technical problems are considered.

The results of this study suggest that the visual distraction caused by presenting navigation information in the upper right portion of the user's forward visual field via smart glasses does not reduce driver performance compared to verbal navigation or use of a satnav. On the other hand, participants demonstrated a clear subjective preference for verbal navigation and least preferred the smart glasses tested. The extent to which this was due simply to their unfamiliarity with smart glasses technology is unclear. The study involved a limited number of participants, so further research on this topic is needed if further confidence is to be gained in the extent to which these results can be generalised to the wider population.

2 The Viennese Driving Test does not record incorrect turns.

1. Introduction

Over the course of less than a decade, smartphones have undergone a transition from being a niche device owned by a few to being a commonplace item owned by at least 61% of the population of the UK (Ofcom, 2014). Many users have become used to being always connected to social networks, email and the Internet though these portable devices.

However, it is not always safe or appropriate – in a literal physical sense – to interact with a smartphone; indeed, the negative consequences of smartphone use on driving have been widely researched (e.g. Basacik, Reed & Robbins, 2011; Caird et al., 2014). It is widely agreed that the increased risk of collision associated with smartphone use when driving is caused by visual, manual and cognitive distraction that these devices can cause.

Some of this distraction is caused by the design of smartphones: they usually require visually guided physical interaction and have large information-rich display screens. Despite public awareness campaigns alerting drivers to the dangers of mobile phone use whilst driving, it is apparent that many drivers find it difficult to disengage from smartphone use when at the wheel; for example, 15% of younger drivers (those aged between 17 and 24) admitted to the RAC (2014) that they text or check social media (or other websites) while driving. Smart glasses, which are relatively new to the market, may have the potential to mitigate distraction through the greater use of verbal interfaces rather than manual ones, and through simplified visual displays presented in a more readily accessible manner. However, they also have the potential to increase distraction by obscuring visual information or by making other content (such as text messages and social media) more accessible.

1.1 Smart glasses and similar wearable technologies

'Wearable technologies' are items of clothing or accessories which possess some sort of mechanical or electrical function designed to aid the user. One of the earliest wearable technologies was the pocket watch. A relatively recently developed subset of wearable technologies is wearable computers. Wearable computers typically provide interactive information to the user, such as communication, navigation, personal health information, and entertainment. Whilst the history of electronic wearable computers stretches back at least as far as the 1980s, it is only in recent years that they have evolved from devices which possess a limited range of functionality, and a correspondingly limited appeal to consumers, to 'smart' devices, similar in flexibility and function to a smartphone and therefore with greater appeal. This offers the chance to exploit the potential benefits of wearable computers over smartphones when carrying out a range of activities; one such activity is the driving task.

Wearable computers can be worn in a variety of ways, with two widely publicised forms being wrist mounted (often referred to as smartwatches or fitness bands) and head mounted (often referred to as smart glasses). The history of smart glasses can be traced back to early developments in head-up displays (HUDs) used in aviation. These present users with visual information closer to, if not overlaying, the main visual field. This can reduce the time spent looking away from the view ahead, and can also potentially improve information-processing by delivering information in readily understood formats. Smart glasses develop this concept further by providing the user with a personal, mobile and visual interface that can be used in a wider range of contexts.

Anything that diverts the driver's attention away from the tasks required for safe control of the vehicle is considered to constitute a distraction (Basacik & Stevens, 2008). Smart glasses offer the potential for the reduction of driver distraction whilst accessing smartphone functionality, as they are designed to require very little manual interaction and to keep the user's visual attention in the forward field. However, we do not yet know how drivers will choose to use smart glasses; they could in fact increase driver distraction beyond manageable levels.

Smart glasses use wearable computing technology to provide augmented reality functionality that places digital information into the sightline of the user. Google expanded the consumer market for this technology with its product 'Google Glass', which was available (as part of an 'open beta' programme) in the US from February 2013 and then in the UK from the summer of 2014 until its withdrawal in January 2015. Aside from Google, other technology manufacturers are developing their own smart glasses systems, such as the Microsoft HoloLens and Sony's SmartEyeglass (see section 2.2 for further examples).

Vehicle manufacturers are gradually increasing the sophistication and connectivity of in-vehicle information and entertainment systems. However, smart glasses can be programmed to function in a wide variety of ways – for access to information (such as searching the Internet), and for photography, communication and navigation, to name but a few. Communication and navigation tasks are especially pertinent to the driving task.

Smart glasses display information close to the user's forward visual field. For a driver, the timely presentation of relevant information close to the normal forward field of view may be a benefit. However, there is also a risk that the display may affect the user's ability to detect important information in this same field. This may occur through the masking of important road features by a display; by diverting driver attention to their display; or by creating 'cognitive capture' in users, whereby they focus too heavily on their central forward field and fail to detect – or fail to respond appropriately to – important cues in the periphery. In view of this, the effects on driver performance of using smart glasses must be carefully considered. Cognitive capture is discussed more fully in section 3.4.1.

1.2 Examples of smart glasses

Smart glasses technology is progressing rapidly, with many different manufacturers offering systems that are either available to purchase already or at an advanced stage of development. A list of several examples is included in Table 1. Note that this list describes some examples of smart glasses which are either commonly available or close to market; a comprehensive study of the many smart glasses under development would require a dedicated review of its own.

Common features of smart glasses are the overlay of visual information over the human visual field, either in the periphery (e.g. Google Glass) or across the entire visual field using augmented reality techniques (e.g. Moverio BT-200). Smart glasses use either full lenses which cover the entire visual field, or smaller lenses which overlay only a small portion of it.

Most smart glasses also produce sound, sometimes through conventional speakers and sometimes using bone conduction techniques.

Table 1: Existing and near market smart glasses products

Google Glass	Google	Google Glass displays visual information in the top right of the user's field of view and is controlled primarily through voice commands. Sound is produced using bone conduction. Google Glass must be paired with a smartphone for full functionality.	No longer available for purchase as of January 2015	https://www.google.co.uk/intl/en/glass/start/
Mirama One	Brilliantservice	Mirama One aims to replace smartphones with smart glasses. The device displays visuals across the full visual field using binocular glasses and is controlled mainly by hand gestures.	In development	http://mira.ma/en/miramaone.html
Meta 1 and Meta Pro	Meta	Uses a 3D stereoscopic display to produce holograph-like images across the user's visual field. Consists of binocular glasses and a camera/sensor array across bridge of glasses.	Presently available to developers only	https://www.spaceglasses.com/products
castAR Glasses	Technical Illusions	castAR Glasses achieve Mixed Reality by using two microprojectors. These projectors cast a stereoscopic scene onto a retroreflective surface, which reflects the image back to the user.	In development	http:// castar.com/
Moverio BT-200	Epson	These binocular, see-through smart glasses use the principles of augmented reality to superimpose images on the user's visual field. The BT-200 runs on Android, the well-known smartphone operating system.	Available at a cost of £569.00	http://www.epson.co.uk/gb/en/viewcon/corporatesite/products/mainunits/overview/12411
SmartEyeglass	Sony	This pair of smart glasses connects to a smartphone and superimposes its monochrome display over the full visual field.	In development, scheduled release 2015	https://developer.sony.com/2015/02/17/announcing-smarteyeglass-developer-edition-sed-e1-pre-order-starting-today-in-uk-and-germany/
Skully AR-1	Skully Systems	The Skully AR-1 is a motorcycle crash helmet with integrated HUD, used to show a wide-angle image from a rear-view camera and GPS navigation instructions.	In development, scheduled release date May 2015	www.skully.com/#smartest-helmet
Microsoft HoloLens	Microsoft	These smart glasses use a 3D optical head-mounted display to overlay augmented reality images over the wearer's view. They are designed to integrate with Windows 10.	In development, scheduled release 2015	www.microsoft.com/microsoft-hololens

To investigate how smart glasses may influence driving behaviour, a literature review of available evidence was conducted to evaluate previous studies of smart glasses and related technologies. This was followed by a novel and innovative on-road study comparing three different forms of navigation system – smart glasses, a smartphone-based satnav system and verbal instructions from a passenger.

2. Literature Review

This literature review consists of two broad components: a review of the definitions and theories of driver distraction, and an evaluation of the current evidence base for the causes and effects of driver distraction.

More specifically, the first component consists of three sections: defining driver distraction; describing the importance of understanding driver distraction; and introducing models of cognitive processing which can help us to predict, interpret and explain the findings of the literature reviewed in subsequent sections.

The second component consists of two sections: a description of the state of current knowledge of driver distraction caused by in-vehicle information systems (IVISs) and a review of research specific to smart glasses.

The literature obtained by this review was selected by a systematic search method described in Appendix A.

2.1 Defining driver distraction

Many definitions of driver distraction have been proposed. For example, Ranney (1994) proposed that driver distraction is any activity which draws the driver's attention away from the main driving task. Building on this definition, Basacik and Stevens (2008: 6) proposed a more specific definition:

> "Diversion of attention away from activities required for safe driving due to some event, activity, object or person, within or outside the vehicle."

This sentence neatly encompasses the vast majority of forms of driver distraction, including that potentially caused by use of smart glasses by being an "object… within… the vehicle" that may draw a driver's "attention away from activities required for safe driving".

2.2 The importance of understanding driver distraction

Distraction is a major risk factor in driving incidents. In the UK in 2013, 2,995 collisions (or 3% of all collisions) involving injuries (fatal, serious and slight) involved some form of distraction from within the vehicle, and a further 422 involved the use of a mobile phone[3] (DfT, 2014: 200). In the USA the National

3 These figures are from the "distraction in vehicle" and "driver using mobile phone" categories, respectively.

Highway Traffic Safety Administration estimates that 421,000 people (or 18% of all incidents involving injury) were injured as a result of some form of distracted driving in 2012 (NHTSA, 2015).

In the UK, a recent observational study (Sullman, 2012) on public roads found 14.4% of drivers to be involved in some form of concurrent distraction. Talking to passenger(s) was the most common distraction (7.4%), followed by mobile phone use (2.2%), smoking (2.2%) and eating (1.1%). An observational study completed by Foss et al. (2009) in locations near high schools in North Carolina, USA, where 16- and 17-year-old drivers are common, revealed that 11.0% of drivers were engaged in mobile phone use before their use was banned for under-18s, a figure which increased slightly to 11.8% in the four months following the ban. Whilst there are many potential sources of distraction, mobile phones are of particular relevance since smart glasses are typically designed to replicate and/or replace smartphone functionality.

Texting and driving is recognised as posing a significant risk to drivers, particularly the young, and consequently a large body of research has been undertaken to measure the prevalence of this behaviour. A recent report by the RAC (2014) found that 53% of drivers have seen other drivers texting or checking social media (or other websites) while driving, although only 7% of drivers admit doing it themselves (for younger drivers, aged 17 to 24, admissions of these behaviours rose to 15%) (RAC, 2014). A survey of US students (Atchley, Atwood & Boulton, 2011) found that texting while driving was very common, with 70% initiating texts when driving, 81% admitting to replying to incoming texts, and 92% to reading texts. Surveys by Harrison (2011) and Hill et al. (2015) corroborate this finding: Harrison revealing that 91% of a sample of college students reported texting while driving. Hill et al. also found that 91% of young drivers reported texting while driving. Some of this behaviour may be due to drivers misunderstanding, or not being aware of the legal prohibition on texting whilst driving. In the UK, Reed and Robbins (2008) measured the extent to which a sample of young drivers understood the legal status of sending and receiving text messages whilst driving. Their results showed that participants were confused about the legality of texting whilst driving, but they did feel it should be illegal, and did also recognise that their driving was impaired whilst using their phones.

It is conceivable that users of smart glasses would be similarly likely to use them to text while driving, providing there is no ‘car safe mode’ in operation, which suggests that it is important to understand how smart glasses might affect driver performance when texting, in order to either advise of their dangers or optimise their design to minimise distraction as far as is practicable.

Atchley et al. (2011) found drivers to be aware of the risks of texting while driving, but that they nevertheless continued to text. This may be because drivers are often overconfident about their abilities or because they are poor at judging the extent to which their performance is impaired by secondary tasks. Lesch and Hancock (2004) investigated drivers' ability to evaluate the extent to which their driving was impaired while using a handheld phone. They found a poor correspondence between self-reported performance and actual performance, particularly for female drivers. Horrey, Lesch and Garabet (2008) also found drivers to be poor at estimating how distracted they are by handheld and hands-free phones. It is therefore reasonable to suggest that smart glasses users would also be poor at estimating the level of driving impairment caused by engaging in a concurrent task on their device.

In the UK, the legal status of using smart glasses while driving is ambiguous. Using a handheld device is prohibited; however, the restrictions that apply to head-mounted devices are not clear. There is some doubt as to whether implementing a ban on drivers using head-mounted smart glasses would be effective, or even appropriate. As exemplified by Foss's aforementioned study of areas surrounding high schools in North Carolina (2009), evidence from the USA shows generally poor compliance with bans on mobile phone use while driving.

Further evidence, also from the USA, of the limited effectiveness of banning mobile phone use can be found in the research of Goodwin, O'Brien and Foss (2012). They compared observed changes from 2006 to 2008 in rates of mobile phone use while driving between North Carolina (which banned use of mobile phones by younger teenagers whilst driving in 2006) and South Carolina (which did not ban their use), and found that whilst rates significantly dropped in both states over that period, the ban in North Carolina did not lead to a significantly larger reduction in mobile phone use. Some evidence found that teenagers are shifting away from spoken conversations towards text messaging, which could be accounting for a reduction in the total time spent using mobile phones when driving, but not necessarily in the frequency of phone use in general.

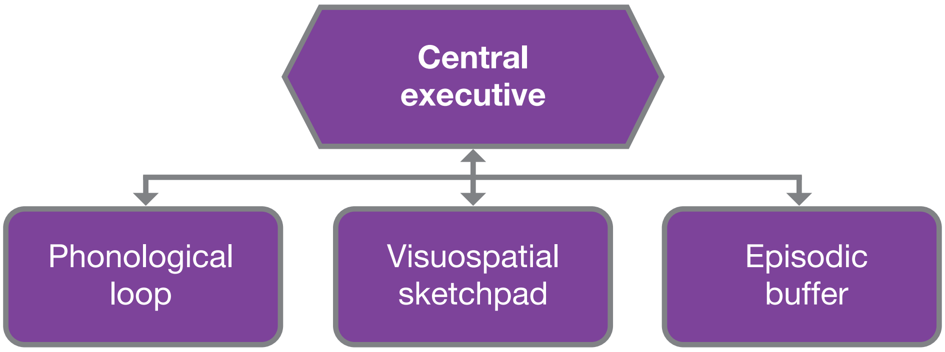
Indeed, the benefits in terms of driving safety of banning mobile phone use have been questioned. Burger, Kaffine and Yu (2013) conducted an analysis of accident rates before and after the introduction of a ban on mobile phone use while driving and found that the its introduction did not in fact reduce traffic accidents. The authors speculate that this is because drivers are not complying with the law, rather than it being the case that mobile phone use does not lead to an increased safety risk; the data from North Carolina seems to support this.

There are no signs that the trend for increasing demand for mobile connectivity is slowing. As a result, vehicle manufacturers and technology providers are working to enable interaction with technology in a manner that is compatible with driving. In-vehicle technologies are consequently becoming more sophisticated, and may discriminate between driver and passengers in the communications functionality available (for example, the mobile phone app Cellcontrol, which uses 'policy-zones' to distinguish drivers from passengers). Furthermore, as vehicle automation progresses, it may be possible for drivers to attend to in-vehicle technologies while on-board monitoring and control systems manage safe control of the vehicle. There is a push in the automotive sector to produce 'connected cars' – vehicles with ever present Internet connectivity made available to vehicle occupants for entertainment and information purposes but also with the potential to share information with other vehicles and infrastructure for the purpose of optimising safety and comfort. The rapid development of these technologies in the automotive sector has created a challenge to the pace with which regulations and legislation can be created in response.

2.3 Cognitive models of driver distraction

When demands placed on an individual's mental resources exceed that individual's capacity for efficient processing, the consequences of this excess is a reduction in the level of task performance. When performance on a task is reduced due an increase resource demands from an additional concurrent task, that concurrent task can be considered a distraction. Baddeley and Hitch (1974) postulated a now widely accepted multicomponent model of how working memory allocates resources amongst tasks, subsequently revised by Baddeley (2000) (Figure 1). The model can be used to elucidate how and why distraction affects performance. Baddeley (2000) defines working memory as the brain system which is responsible for processing and storing recently received information, such as spoken language or visual stimuli. It is vital for undertaking complex tasks such as language comprehension and reasoning. Distraction is a symptom of exceeding the limited capacity and processing speed of working memory. In other words, individuals can only do so many things at once, and the more complex those tasks are, the fewer of them they are able to complete at the same time.

Figure 1: Model of working memory



Source: Baddeley (2000)

As shown in Figure 1, working memory consists of four components. The central executive, responsible for information processing; the visuospatial sketchpad, which stores visual information for short periods; the phonological loop, which stores auditory information – such as spoken language – for short periods; and the episodic buffer, which provides a link between working memory and long-term memory, and binds together information from different sources.

Driving is predominantly a visual task – it has been estimated that over 90% of the task-relevant information is received through this sensory channel (Dewar, 1988); therefore the bulk of the driving task demands are placed on the visuospatial component, leaving other resources such as the phonological loop relatively underutilised. The implications for driver distraction of this model are that if the number or complexity of a set of concurrent tasks exceeds either the capacity of the central executive to allocate tasks between the other components efficiently (i.e. the task-switching costs are too high), or the capacity of the other components once the tasks have been allocated to them, then performance decrements will be observed in one or both of the concurrent tasks; this may then manifest as driver distraction. These forms of distraction have been described as *structural interference* and *cognitive interference* respectively, and will be discussed below.

2.3.1 Structural interference

Until recently, the most commonly referenced theory of driver distraction was the *structural interference hypothesis* (Wickens, 1980). The structural interference hypothesis proposes that tasks that use unrelated resources, such as listening to directions (i.e. using the phonological loop) and scanning the road ahead (i.e. using the visuospatial sketchpad), should compete less for the same resources than related-resource tasks would, and so lead to less distraction. In other words, the distraction that an individual suffers when completing concurrent tasks will be proportional to the degree to which those tasks attempt to draw upon the same mental resources, as the brain's capacity for any one particular mental resource is limited. For example, if a driver attempts to scan for road signs (a visual task) while monitoring a navigation system (predominantly a visual task), their performance of both tasks will be diminished. However, if they were engaged in a spoken conversation while observing directions on a navigation system, their performance of each should be less impaired because they are drawing on separate mental resources. The structural interference hypothesis proposes that driving and the use of a handheld mobile phone use the same mental resources (visual and manual), and therefore that reductions in driving performance are caused by the attempt by each task to access these processes simultaneously (Wickens, 1980).

Much of the evidence for structural interference was collected in the last ten years. Large and Burnett (2014) offer a good summary of evidence for structural interference by reporting that there is an “overwhelming consensus that interactions using the auditory modality, typically through speech-based interfaces and output, is less distracting for drivers than interactions with a visual display”. They suggest that this is because driving is primarily a visual task, and therefore drivers are better able to divide their attention between sensory modalities than within one sensory modality. However, they do not comment on how task complexity may influence these results; would complex auditory stimuli still fail to distract from tasks, like driving, that are more reliant on other sensory modalities? In other words, what role does the central executive play in distraction?

2.3.2 Cognitive interference

An alternative theory of driver distraction is the *cognitive interference hypothesis* (He et al., 2014; also see Kunar et al., 2008). This hypothesises that distraction is a consequence of how the central executive processes information serially. The central executive processes each task in turn, prioritising them and then distributing information and instructions between the different components of working memory. When a new task replaces a previous one in priority, the central executive instructs the different components to switch to a new task as required. This switching taxes the resources of the central executive, and so complex tasks eventually exceed its capacity to switch attention between tasks quickly, accurately, and appropriately. In other words, the central executive must process tasks sequentially, and distraction is therefore the result of tasks having to wait until preceding tasks have been completed. Should a task place demands on the central executive that exceed its available resources, the following tasks will be delayed, and symptoms of distraction will manifest.

Evidence for both structural interference and cognitive interference exists in the literature, although recent studies are persuasive in arguing the case for the greater significance of cognitive interference in driver distraction. Kunar et al. (2008) attempted to resolve whether it is structural or cognitive interference that causes driver distraction by having participants complete a demanding visuospatial task (multiple-object tracking) in three conditions: on its own; whilst concurrently repeating a sequence of words heard over the mobile phone (the ‘shadowing’ task); and whilst concurrently generating a new word which was based on those they heard over the mobile phone. In other words, a purely visuospatial task was compared to a purely (albeit demanding) audioverbal task (the word-generation task). If the structural interference hypothesis was correct, performance should not have been impaired as the two tasks only minimally interfered. However, participant performance was significantly reduced when completing the demanding audioverbal task concurrently with the multiple-object tracking task. Performance did not change from the baseline task when completing the shadowing task. These results are convincing evidence that tasks which appear to use distinct resources, and so should not (according to the structural interference hypothesis) be distracting, can actually reduce performance. Perhaps this is a reflection of our limited understanding of the interconnectedness of our mental processes, and a failure to understand the demands that tasks place on the central executive.

Further evidence for cognitive distraction can be found in the research of Harbluk et al. (2007), and Recarte and Nunes (2003). Harbluk et al. examined drivers completing no additional tasks, easy cognitive tasks (single digit addition problems), and complex cognitive tasks (double-digit addition problems involving carrying) whilst driving. They found that drivers increase attention to the forward visual field and decrease monitoring outside of their forward field when completing the complex cognitive task. Recarte and Nunes (2003) showed that drivers are slower to detect lights displayed inside the vehicle and displayed on the road ahead when simultaneously carrying out various mental tasks (summarising a two-minute message, performing approximate currency conversions, and recalling where they were and what they were doing on a given day at a certain time). They also check mirrors and speedometers less often when engaged in the tasks. These findings have implications for smart glasses, which display information closer to the centre of the visual field than many dashboard-mounted smartphones, suggesting that smart glasses might be less prone to these ‘visual tunnelling’ effects as they typically display less information, and in a more readily understood format than smartphones (e.g. Google Glass navigation images vs the Google Maps smartphone application). If tasks are less cognitively distracting to smart glasses usage, their users may have sufficient mental resource to monitor the wider environment whilst driving. In summary, the case for cognitive interference has been supported by a body of recent research which explicitly tested for the effects of both mutually related and mutually unrelated tasks undertaken whilst driving. This suggests that task complexity seems to be a better predictor of distraction than the degree of resource overlap which the tasks share.

2.4 Driver distraction and in-vehicle information systems

Driving whilst using an IVIS, such as a navigation system, a smartphone or smart glasses, requires the user to access several sensory channels and cognitive processes, with each simultaneous task potentially placing demands on the same processes. IVISs typically send information to the user through the visual and auditory channels, and usually accept inputs manually or verbally. Much research has been conducted to look at the effects on driver performance of a variety of sensory channels used by IVISs, seeking to identify which are more or less likely to distract from concurrent driving tasks. This review examines the effects of manual, auditory and visual interfaces on driver distraction, all of which are particular salient when considering the performance of drivers using smart glasses. Note that there is a high degree of overlap in the research on the auditory and manual channels, as the effects of speech and manual interfaces are regularly compared; these modalities will therefore be addressed in the same section.

2.4.1 Visual modality

Given that driving is predominantly a visual task, and that smart glasses are specifically designed to deliver visual information in a more optimal manner than smartphones and similar IVISs, the effects of visual modality on distraction will be considered first.

Firstly, it is useful to understand how often a driver might be likely to attend to the display of their smart glasses. Birrell and Fowkes (2014) studied driver glance behaviour when using an “ergonomically designed” smartphone app designed to give the driver real-time safety and eco-driving information. They showed that drivers spent 4.3% of their time looking at the smartphone, with

those glances being brief (mean = 0.43 seconds, max = 2.0 seconds). Using the smartphone did not significantly reduce glances at mirrors, in-vehicle instruments or the forward visual field. The authors speculated that this is evidence that a well-designed IVIS can take time out from ‘spare’ glances. Whilst we cannot be sure that users of smart glasses would engage with its display to a similar extent, it seems reasonable to expect that glance behaviour would be broadly similar, depending on software design.

The risks of a variety of visual distractions were measured in a naturalistic setting by Klauer et al. (2006) as part of the 100-Car Naturalistic Driving Study (Klauer et al., 2006; see 4.4.1 for further information). This study equipped 100 cars with a package of instruments designed to record driver behaviour, including video of the internal and external driving environment. Data was collected over an 18-month period. This risk posed by typical secondary tasks which were observed to be performed whilst driving were calculated as odds ratios.[4] Results showed that diverting visual attention away from the main driving task was likely to increase collision risk in the case of most, but not all, reasons for so doing. Specifically, for the two visual behaviours *looking at external objects and reading*, the odds ratios were 3.70 and 3.38, respectively (i.e. the behaviours were each associated with a greater than threefold increase in association with safety critical driving events). However, one type of behaviour where drivers diverted their attention away from the forward visual scene actually improved safety: *driving-related inattention to the forward roadway* for more than 2 seconds (odds ratio 0.45) and less than 2 seconds (odds ratio 0.23). Driving-related inattention to the forward roadway behaviours are those where the driver is diverting their attention to an aspect of the driving task which is away from the forward visual field, such as checking mirrors. Klauer et al. (2006) speculate that this improvement in safety is because these behaviours are a sign of greater driver vigilance and engagement with the driving task (i.e. drivers pay more attention to their mirrors when they are paying attention to the driving task). These results indicate that smart glasses could either increase or reduce driver distraction, depending on the task for which they are being used. If smart glasses are providing information designed to ease the driving task or to improve awareness of the driving environment, the cost of diverting visual attention away from the road may be more than offset by the benefits gained by receiving that information. On the other hand, should smart glasses be used to access information unrelated to driving, they could significantly increase risk.

4 An odds ratio is a commonly used measurement of the association between observed behaviours and safety critical events when driving. To illustrate: if a behaviour had an odds ratio of 1.0, safety critical events would be as frequently observed when the behaviour was performed compared to baseline driving (suggesting the behaviour was independent of collision risk); if it had an odds ratio of 0.5, this would indicate that safety critical events were observed half as often when the behaviour was performed compared to baseline driving (suggesting the behaviour reduced collision risk); if, on the other hand, it had an odds ratio of 2.0, it would indicate that safety critical events were observed twice as frequently when the behaviour was performed compared to baseline driving (suggesting the behaviour increased collision risk).

The display of smart glasses has much in common with head-up displays (HUDs). Both present information either directly within the visual field or in a portion of the peripheral field close to the central field. A large quantity of research on HUDs originates from the aviation domain; however, caution must be exercised when generalising from aviation to driving, as task demands across the two domains are distinct as noted by Gish and Staplin (1995): background complexity differs between the domains (open sky vs road scenes); aviation HUDs tend to display information which visually integrates with the scene (or *conformal symbology*, e.g. runway outlines, etc.) whereas driving HUDs are likely to offer a wider variety of less-integrated information (e.g. speed, text messages, etc.); and aviation HUD research usually studies the performance of highly trained pilots whose performance may differ from that of the general driving population. Given that these limitations reduce confidence in generalising aviation HUD research to driving, this review maintained a tight focus on recent driver-specific HUD research.

Jakus et al. (2015) asked participants to navigate to a destination in a driving simulator using a HUD, with provision of auditory information only, or a combination of both systems (the multimodal interface). Results showed faster system interactions when using the HUD modality and in the multimodal configuration than with sound only. All three systems affected driving performance to an equal level; however, drivers preferred the multimodal system. This suggests that there may be little objective advantage in having information displayed in an HUD, but that it is subjectively preferred.

A potential risk associated with HUDs is *cognitive capture*. This is the phenomenon where drivers begin to focus on the forward visual field, relying on the information presented on the HUD and spending less time monitoring the peripheral visual field or the internal vehicle cabin, as a result of the attentional switching costs of moving between tasks (Gish & Staplin, 1995). Gish and Staplin's review of HUDs in driving conclude that there is no robust evidence that HUDs produce advantages in driver performance. However, they concede that limitations of previous research (failures in accounting for the interaction of workload, display complexity, etc.) may be masking the degree to which HUDs could reduce – or increase – distraction.

More recent research by Burnett and Donkor (2011) considered this cognitive capture effect and how it relates to HUD complexity. They conducted a simulator trial with 18 drivers who were asked to retrieve information from a HUD whilst also undertaking a peripheral-detection task (PDT). The complexity of the HUD was manipulated to understand how complexity affected performance. Their results showed that driving performance and PDT performance worsened (i.e. reactions were slower and less accurate) as the HUD complexity increased. They recommend that a HUD should be simply designed, with no more than four distinct symbols shown. This aligns with the design guidelines required by Google for creating applications for its smart glasses product, Google Glass, which required minimal, uncluttered designs (see https://developers.google.com/glass/design/principles).

2.4.2 Manual modality

Reed and Robbins (2008) showed that when a sample of 17 young drivers sent and received text messages on a handheld phone whilst driving a full mission, high-fidelity simulator, they were slower to react to trigger stimuli and more likely to miss these stimuli, and had poorer vehicle control. Similar results were found when a sample of young drivers was asked to interact with a social networking site on their handheld smartphones whilst driving in a simulator (Basacik, Reed and Robbins, 2011). The performance decrements observed in the performance of young drivers, resulting from retrieving and sending text messages by means of a handheld phone, were similarly measured by Hosking, Young and Regan (2006) at Monash University. A sample of 20 young adults (aged 18 to 21) completed two drives which contained eight critical events (such as avoiding a pedestrian, changing lane in accordance with traffic signs). During the drive, participants sent and retrieved text messages. By comparison with their performance with no texting, drivers spent four times as long looking away from the road, missed instructions to change lanes and had poorer lane control. A meta-analysis conducted by Caird et al. (2014) showed a convergence in studies to suggest that reading and writing texts when using a manual interface compromise a wide range of driving behaviours (i.e. accuracy and speed of stimuli detection, collision avoidance, maintenance of appropriate headway and speed, and accurate lane positioning).

As part of the euroFOT project,[5] Metz et al.(2014) compared driving behaviour whilst using a manually operated portable satnav with that shown while using an integrated navigation system. Data from 99 drivers was collected from over one million kilometres of public roads. Drivers were shown to prefer manually interacting with both systems when exposed to low driving demand, and if required to manually interact with a system in higher demand settings, they adapted their speed and following distances to support safer driving. No evidence was found that the using either navigation device led to an increase in dangerous situations.

The 100-Car Naturalistic Driving Study showed the safety consequences of several manual secondary tasks: *reaching for a moving object* (odds ratio 8.82); *dialling a handheld device* (odds ratio 2.79); and *inserting/retrieving a CD* (odds ratio 2.25).

According to Crisler et al. (2008), one advantage of manual texting over verbal conversations on a mobile phone is that drivers have greater control over when and where they choose to text; verbal conversations can make a driver feel obliged to continue, even when they sense that it is distracting them from the main driving task.

Smart glasses may help to avoid these consequences by reducing the need for manual interactions – they typically use verbal interfaces, suggesting that they may reduce driver distraction.

2.4.3 Auditory and manual modalities

Comparisons of auditory and manual channels have proved to be a popular area of research over the past decade. This is likely to reflect the increased performance of speech recognition software, driven by advances in processing power available to IVISs. The reduction in demand for manual interactions with smart glasses is likely to be one of their primary benefits, therefore an investigation of the comparative distraction caused by these two modalities is especially relevant.

Broadly speaking, the research suggests that voice interfaces distract less than manual ones; however, they can still significantly distract a driver from the task at hand. Maciej and Vollrath (2009) used a proxy of driving, the Lane Change Task, to measure how driver performance was affected by the use of several hands-free or handheld IVISs, including a navigation system. Speech interfaces showed a mild improvement over manual interfaces, suggesting that whilst speech interfaces are less distracting, they are not yet able to significantly reduce cognitive demand. He et al. (2014) compared speech-based texting

5 euroFOT stands for "European Field Operational Test on active safety functions in vehicles"; the project ran from 2008 to 2012 and brought together 28 diverse organisations to test intelligent vehicle systems across Europe. See www.eurofot-ip.eu/en/about_eurofot.

whilst driving with handheld texting, and showed that speech-based systems distract less than handheld but still caused significant distraction.

Horberry et al. (2006) compared driving performance levels in a driving simulator for two tasks completed by drivers: manipulation of the vehicle's entertainment system, and having a hands-free conversation. Whilst results showed that both tasks interfered with driving performance, the hands-free conversations impaired driver performance the least.

The role of speech interfaces and IVIS positioning were investigated by Xie et al. (2013) who also found that secondary tasks distracted from on-road driving performance less when they used voice control as the input mechanism. They also found that audio and audiovisual information led to faster reactions than visual information on its own (Xie et al., 2013; Liu, 2001).

Owens, McLaughlin and Sudweeks (2011) found that driver performance when receiving text messages was not different to baseline when using their test vehicle's factory-fitted text-to-speech functionality. However, performance decreased when sending a text message using a handheld mobile phone, and also decreased when sending a text message when using the text-to-speech functionality. Therefore, we can infer that even though sending a text message using the speech-to-text functionality was a verbal task, it still interfered with the driving task, which is primarily visual.

Few attempts have been made to compare the effects of mobile phone use on driver performance with other sources of driver distraction. A notable exception is the work of Burns et al. (2002), who tested 20 participants in a driving simulator by comparing their driving performance when conducting hands-free and handheld conversations on a mobile phone with their performance whilst under the influence of alcohol (completed with no concurrent phone task). Results showed that performance was generally lower when using a handheld mobile phone (but not when completing a simple verbal shadowing task), and in some respects even worse than being intoxicated to the UK drink drive limit.

Similarly, Leung et al. (2012) showed that hands-free and handheld conversations are distracting, with a simple conversation being about as distracting as being intoxicated, but under the US legal limit (participants tested at 0.04% blood alcohol concentration (BAC) – the US federal limit is 0.08% BAC), and complex conversations impairing performance about as much as being approximately at the US legal limit (participants tested at 0.07% to 0.10% BAC).

Navigation devices (including smartphones operating as navigation systems) can also be distracting. Harms and Patten (2003) measured driver distraction by use of the PDT method when drivers were engaged in a route navigation task. Drivers completed two routes: one from memory, and one by following a navigation system. The navigation system delivered either visual information only, verbal information only, or both visual and verbal (with each participant only experiencing one of these conditions). They observed no change in driving performance in any condition, suggesting that drivers did not divert attention to the navigation tasks to an extent that would result in impairment. However, they were slower and slightly less accurate when reacting to the PDT during the visual and verbal navigation condition, and only slightly less accurate during the visual-only condition. Verbal only did not change PDT performance.

In line with the majority of the laboratory-based research published on the effects of auditory distractions on driver performance, the 100-Car Naturalistic Driving Study also showed that handheld mobile phone conversations increase the likelihood of safety-critical events (odds ratio 1.29).

From the research described thus far, we can infer that the degree to which hands-free smart glasses may distract a driver is related to the sophistication of the speech recognition software and the complexity of its user interface. Complex or poorly performing voice interfaces are likely to distract drivers to an unacceptable level, even if their performance is still superior to that demonstrated while using handheld devices.

2.4.4 Driver distraction caused by smart glasses and related technologies

In recent years there has been a dramatic increase in the development of smart glasses systems, with the most widely recognised being Google Glass. As described in section 2.1, Google Glass was released relatively recently, before being withdrawn from sale (it was available for almost two years, from February 2013 to January 2015). As a result of this limited timeframe, only three studies have been published using Google Glass in a driving context. One non-driving-related study, describing how Google Glass obstructs a portion of the visual field, is also reviewed because of its implications for driver distraction. No research examining any other smart glasses in the driving domain was located.

Tippey et al. (2014) conducted a small-scale preliminary study which compared texting while driving using Google Glass, voice-to-text and handheld texting, all against baseline. Seven participants completed the trial; each was asked to read and respond to text messages whilst driving a medium-fidelity driving simulator. The texting tasks required reading brief questions consisting of no more than three lines of text, and responding with simple answers. The data revealed that handheld texting caused the greatest reduction in performance, followed by voice-to-text, and then Google Glass. In fact, Google Glass was observed to produce driving performance that did not differ significantly from baseline. This is broadly in line with the cognitive interference hypothesis, as whilst the texting tasks required some simple processing, they were probably not enough to tax executive function significantly.

The second paper identified by this review also tasked drivers with responding to text messages using a hands-free smartphone and Google Glass. Sawyer et al. (2014) tested 40 undergraduate college students using a driving simulator. Participants were asked to send and receive messages whilst driving with the smartphone and with Google Glass (in separate simulator drives). Experimenters interrupted participants during their text messaging with an emergency-braking event. Performance in brake reaction time was compared against a baseline (driving only) condition. Results indicated that Google Glass was not as distracting as the smartphone; however, it did not eliminate it altogether. Whilst the results of this study were positive for Google Glass as an IVIS, the authors suggested:

> “Even if Glass reduces the attentional resources necessary to multitask while reading and replying to messages, it cannot minimise the impact of information that unduly occupies a driver’s mind (e.g. an emergency at home).”

Sawyer et al also noted that performance was poorer during the drive-only condition (when wearing an inactive Google Glass) than when driving with an inactive smartphone. This could be because the Glass was novel, and simply wearing it was cognitively distracting. It is conceivable that participants were somehow preoccupied by some discomfort from wearing Glass or pondering how it might affect their driving experience if such devices were in common use.

The third paper review, by Beckers et al. (2014), investigated the distraction involved in inputting a destination when using Google Glass as a navigation device, compared with using a smartphone to do so. The authors also used a driving simulator task to investigate the change in performance caused by entering destinations into Google Glass (verbally) and into a Samsung Galaxy S4 smartphone (both verbally and using the touch interface). The study of 24 young drivers showed that all methods caused distraction from the main driving task. However, the voice interfaces caused less distraction compared to the touch interface. Furthermore, the authors observed that participants using Google Glass had a higher error rate when entering a destination (i.e. users gave the correct command but Google Glass failed to respond correctly), but this was offset by its shorter task completion time, which led to similar performance levels for both devices overall. Finally, Google Glass was shown by Ianchulev et al. (2014) to produce a “clinically meaningful visual field obstruction in the upper right quadrant”. Speaking of the results, one of the study’s authors noted that the device: “produces a significant blocking effect of the right peripheral vision. The defect would not be compensated by the left eye and thus may negatively impact daily activities such as driving, cycling and running.”

3. Discussion of Literature Review

This literature review has produced evidence about which cognitive model of driver distraction is most accurate (structural interference or cognitive interference), and about how difference tasks are likely to affect performance.

3.1 Evidence supporting structural or cognitive interference

Whether distraction is caused by structural or cognitive interference is a subject for debate. This potentially has direct consequences for the optimal design of smart glasses (or any other IVIS): if structural interference is the dominant factor in causing driver distraction, it would be best to design tasks which draw on the working memory processes which are used least during driving – for example auditory processes – to minimise task overlap. On the other hand, should cognitive interference be the dominant factor in causing driver distraction, we might be less concerned about the working memory processes (and so the sensory channels) by which the information is delivered, and more concerned about the general complexity of the information.

When considering the evidence above, this review suggests that the cause of much of the debate about which is the most appropriate model may be traced to the nature of the secondary tasks examined in the literature. The extent to which any secondary task truly draws upon the same mental resources as the driving task is critical in understanding whether the changes in performance that it prompts are evidence of structural interference or of cognitive interference. Unfortunately, much of the research into the cognitive sources of driver distraction fails to control adequately for the degree of task overlap between the secondary task tested and the driving task. For example, if we are to be persuaded that auditory tasks are less likely to lead to driver distraction than other kinds, we must also ask the follow-on question: how does the complexity of those tasks affect performance? Are complex and simple auditory tasks similarly distracting?

When attempts are made to control for the degree of task overlap, for example in the work of Kunar et al. (2008), the case for structural interference weakens. Kunar et al. (2008) demonstrated that driving performance is impaired by a purely auditory secondary task, one which structural interference suggests should not have led to significant impairment. This suggests that cognitive interference is a more likely to be the cause of driver distraction whilst using an IVIS.

The evidence reviewed suggests that the effects of complex tasks which require the central executive to switch attentional resources between different components have not been fully understood. In other words, much research has focused on the benefit/disbenefit of interacting with an IVIS using different sensory modalities; however, comparatively little research has examined the role of task complexity in driver distraction. This suggests that although the neat compartmentalisation of mental resources offered by Baddeley (2000) might be a useful guide to understanding working memory processes, it could be masking a deeper interrelated relationship between these processes. When it comes to smart glasses, this implies the need to prioritise keeping tasks simple and efficient above any concerns about which sensory modalities they interact with. In other words, the complexity of a task may matter more than the way (visual, verbal, manual, etc.) in which it is completed.

3.2 Secondary tasks and driver performance

This review has revealed evidence about how smart glasses could be used most appropriately by drivers. The weight of evidence suggests that verbal interfaces will be of benefit to drivers, with the caveat that the software needs to be sufficiently accurate to interpret a driver's instructions without the need for excessive correction or manual control. The potential for complex interaction with handheld interfaces to cause distraction suggests that voice interaction via smart glasses may offer a possible safety improvement.

Furthermore, if visual displays are appropriately designed to avoid visual clutter and not obstruct safety-critical portions of the visual field, there may be safety benefits to be achieved through these ergonomic visual displays, which may in turn translate to similar safety benefits for smart glasses users; the evidence suggests, however, that only mild improvements are likely to be achieved.

Evidence from HUD research indicates that developers of smart glasses must also be aware of the challenge of designing systems which do not lead drivers to become over-reliant on the information provided by them, and so fail to attend to the environment beyond the forward visual field, thereby potentially missing safety-critical information.

Research specifically using smart glasses is rare. Whilst the evidence from other IVISs, and smartphones in particular, can be used as a foundation for understanding smart glasses, we must be mindful that their users will almost certainly find unforeseen ways to operate smart glasses when driving that will result in distraction issues unique to this technology. However, the research which has been published to date suggests a broadly positive case for mitigating driver distraction by their use. These results, combined with our understanding of related technologies such as smartphones, suggest that smart glasses could be an important means of managing driver distraction; however, limitations inherent in current hardware suggest that this promise has not yet been realised.

4. Experimental Study

This experimental study investigates how smart glasses may affect driver behaviour, using navigation as an example of a typical task for which they are likely to be used. Google Glass was selected for use in the trial, owing to their commercial availability at the time, and also because they are supplied with Google Maps, a navigation application optimised for use by Google Glass wearers and that also has an equivalent smartphone application that uses the same mapping and instruction set enabling direct comparison.

The research sought to understand the effects on driver performance of displaying navigation instructions in the upper right portion of the visual field as an example of how smart glasses may typically present navigation information. The effects of smart glasses were compared with both verbal instructions and a dashboard-mounted smartphone satnav displaying Google Maps navigation instructions identical to those shown on the Google Glass.

The research approach taken was to use a naturalistic on-road driving study. This enabled the navigation systems to be used as they normally would be by drivers. An alternative approach would have been to use the DigiCar driving simulator at TRL to investigate driver performance. However, this would have required the development of systems to mimic the behaviour of both the satnav and the smart glasses systems which, although possible, would have added significant complexity to the study design. Furthermore, the navigational element of the study meant that we were not able to use simulator test routes that have been used for other studies which examined the influence of technology on driver behaviour (e.g. Reed & Robbins, 2008; Basacik, Reed & Robbins, 2011). However, by using an on-road study design, it was possible to use the Viennese Driving Test (Chaloupka & Risser, 1995) – a validated and standardised technique for the assessment of on-road driving behaviour, and one in which TRL research staff are trained. Although our choice to use an on-road study design meant that there was inherently less experimental control than there would be in a simulator study, the use of real roads and a real vehicle meant that challenges regarding the validity or realism of the driving task could not be levelled at the design.

4.1 Research hypotheses

In accordance with the above literature on driver distraction, the study design applied enabled the following hypotheses to be tested:

H1: The number of driving errors committed by participants when using smart glasses, satnav and verbal instructions for navigation will differ.

H2: Participant subjective ratings of ease of use, enjoyableness of use, feelings of distraction or feelings of safety will differ when using smart glasses, satnav and verbal instructions for navigation.

H3: Participants' self-reported mental workload will differ between smart glasses, satnav and verbal instructions for navigation.

H4: The number of navigation errors made by participants will differ when using smart glasses, satnav and verbal instructions for navigation.

5. Method

5.1 Overview

A representative sample of the general driving population completed three successive drives on public roads whilst navigating to a destination unknown to them. During each drive they used one of three forms of navigation: voice instructions (verbal), satnav, or smart glasses (visual). Participant performance was assessed using the Viennese Driving Test (Chaloupka & Risser, 1995 – see section 5.4 for a description) and questionnaires were administered to gather subjective self-reported data from each participant on their experiences of each drive.

5.2 Sample

A sample of 16 drivers, representative of the general public, was recruited (see section 7.1 for the demographic information). They were recruited through TRL's participant database, which consists of over 3,000 volunteer drivers from the Berkshire area. Although early adopters of emerging technologies such as smart glasses tend to be young people, participants for this study were drawn from a range of age groups and from both genders, to provide results that were more applicable to wider society.

5.3 Facilities, equipment and test routes

Participants drove three routes on UK public roads in a right-hand drive car (a 2010 Volkswagen Golf) fitted with dual pedal controls. In each drive, participants were monitored by at least one observer sitting in the back of the vehicle, and an advanced driving instructor (ADI) in the front passenger seat.

5.3.1 Navigation conditions

During each of their three drives, drivers received either verbal navigation instructions, visual satnav navigation information, or navigation information via visual smart glasses. These three modes are henceforth referred to as the three 'conditions'. During each condition, only the navigation method in question was available to the participant, the others being removed. As explained above, Google Glass was used as the current market-leading example of available smart glasses with navigation functionality. A smartphone (Samsung Galaxy S4) was used as the dashboard-mounted satnav, mounted in a cradle attached to the lower right corner of the windscreen (see Figure 2).

Figure 2: Position of dashboard-mounted satnav

Source: Author's own

The purpose of the trial was not to test the effectiveness of any navigation software in particular, nor the effectiveness of the control interface. Therefore, the same navigation instructions were shown on the smartphone and on the smart glasses. Participants were not required to program their destination into either device. This task was completed by experimenters, who were responsible for operating both the satnav and the smart glasses, prior to the start of the test drive. When ready, participants would then follow the instructions given by each device.

Identical navigation information was displayed on the satnav and smart glasses by using an application on the smartphone to mirror the display of the smart glasses during the satnav condition. Figure 3 shows an example of the smartphone displaying the navigation instructions concurrently shown on the smart glasses. This approach eliminated the confounding variable of the quality of the navigation software between technologies.

Figure 3: Smart glasses (left) and smartphone (right) both showing identical navigation information

Source: Author's own

Extensive pilot testing revealed that the smart glasses display frequently turned off when being used for navigation – presumably to save power by design. It then reactivated when new information was available to the driver. Given that most satnavs continuously show navigation information, the smart glasses were configured to display navigation instructions constantly.

Verbal instructions were given by the ADI. The written instructions were taken from the same Google Maps software that enabled navigation in the satnav and smart glasses conditions, and therefore closely matched the navigation instructions provided by the visual information in them. The ADI was highly familiar with giving clear and consistent verbal instructions to drivers undergoing training, which ensured that all participants received almost identical verbal instructions.

No audible instructions were given during either the satnav or smart glasses condition. Pilot users of the smart glasses reported difficulty in hearing the auditory instructions (delivered by bone conduction to the inner ear) over the road and other driving noises. Wearing headphones whilst driving was judged to present a risk to safety, therefore audible information was excluded from the trial for both the satnav and smart glasses conditions. It is recognised that this differs from the typical use of satnav systems by many drivers but in the context of this experimental study on the means of presentation of visual information for navigation when driving, this was considered to be an acceptable compromise.

5.3.2 Observers and advanced driving instructor

The observer in the rear of the vehicle recorded standardised errors – for example inappropriate speed, indicator use, and non-standardised and unpredictable behaviour, such as complex interaction with other traffic – with the help of an observation sheet (as required by the Viennese Driving Test). The ADI gave participants standardised navigation instructions in the verbal navigation condition. The ADI was also responsible for bringing the vehicle safely to a halt using the secondary controls if deemed necessary to avoid any emerging hazards that the driver had failed to perceive.

5.3.3 Test routes

Three test routes were used, with each one taking approximately 15 minutes to complete depending on traffic conditions. As far as was practicable, the routes were matched for complexity, number of junctions, expected traffic densities and speed limits. Each route contained roundabouts, signalised crossroads, give-way junctions and stretches of road with 30 mph, 40 mph and 50 mph speed limits.

5.3.4 Video recording

Two video cameras were mounted in the driven vehicle, recording the forward view and the driver respectively. These recordings were taken primarily to permit review of any specific exceptional incidents (none of which were identified).

Figures 4 and 5 show example screen captures from the two cameras.

Figure 4: View from in-vehicle camera

Source: Author’s own

Figure 5: View from forward-facing camera

Source: Author's own

5.4 Viennese Driving Test

The 'Wiener Fahrprobe', or Viennese Driving Test (VDT), was developed in the 1980s (Risser & Brandstätter, 1985) and is a recognised in-depth observational method of assessing an individual's driving behaviour.

In the VDT, participants' general driving behaviour is monitored by two in-vehicle observers – a coding observer and a free observer. The coding observer records standardised variables (e.g. speed, lane choice, indicator use) on a coding sheet. The free observer notes non-standardised and unpredictable behaviour; these would include, for example, unusual driving errors (e.g. driving with the handbrake on, suddenly stopping for no apparent reason, etc.) and conflicts with other road users. See Appendix B for examples of the materials used in the VDT.

Standard VDTs usually last approximately 40 minutes; however, the method used required drivers to complete three drives in succession. Drives of these lengths were considered to be too onerous for participants, and therefore shorter drives, approximately 15 minutes long, were selected. This allowed a single participant testing session to be completed within two hours. Each session comprised 15 minutes for familiarisation with the equipment and test vehicle; 45 minutes in total for the three test drives; 20 to 30 minutes for questionnaire completion; and the remainder for comfort breaks and staff handover between participants.

The VDT coding sheet is split into 11 categories, with further subcategories. A brief description of the main categories is as follows:

- Speed – how appropriate is the vehicle speed for the given situation?
- Adaptation of speed – how well does the participant adapt the vehicle speed when approaching junctions or obstacles?
- Indicator usage – does the participant use their indicators, and if so is that use appropriate, too early, or too late?
- Lane change – does the participant change lane too early or late when approaching junctions/roundabouts? Is their manoeuvre dangerous or hesitant?
- Lane use – does the participant drive far to the left or right of their lane? Do they drift in their lane, or cross solid lines/hatching?
- Behaviour at give-way and stop signs – is the participant hesitant or unclear in their behaviour? Is their behaviour dangerous, and do they fail to stop or give way when they should, or pull into inappropriate gaps?
- Priority – does the participant observe priority rules, for example when passing parked vehicles?
- Headway – is the participant too close (or too far away from) the vehicle ahead?
- Overtaking – does the participant perform any illegal or dangerous overtaking manoeuvres? Do they make an overtaking attempt only to abandon it?
- Vulnerable road users – how does the participant behave when they encounter vulnerable road users (e.g. pedestrians, cyclists)?

5.5 Experimental procedure

A standard procedure was used for each trial. Participants were initially briefed on the purpose and procedure of the trial at TRL, before completing a short vehicle familiarisation drive. After the familiarisation, the participants were introduced to the smart glasses and given the opportunity to ask questions before embarking on the first of their three drives.

All participants completed each of the three routes in the same order; however, the sequence of the navigation conditions was counterbalanced between each participant to control for familiarity effects with the vehicle and any tendency for weariness.

At the end of each drive participants completed the NASA-TLX questionnaire (see Hart & Staveland, 1988) to record their subjective workload during the completed drive. See Appendix C for an example NASA-TLX scoring sheet. Finally, once the driven component of the trial was complete, participants completed a battery of questionnaires at TRL to elicit their subjective experience of each navigation condition. See Appendix D for an example of the subjective experience questionnaires.

6. Results

6.1 Demographics

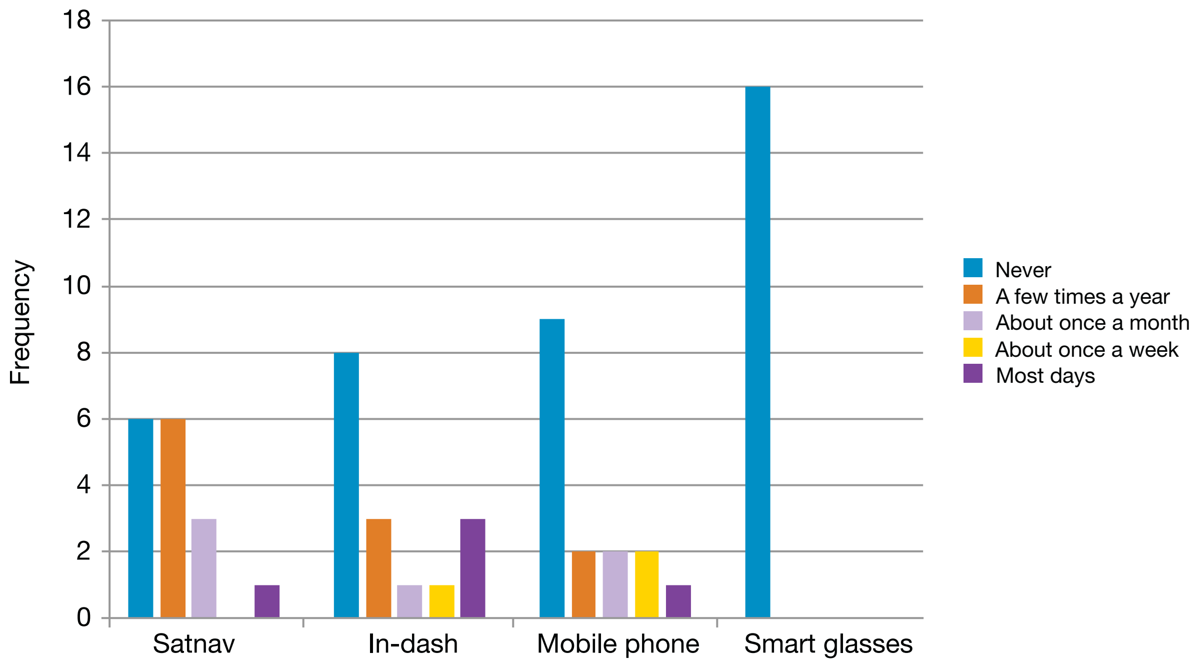
A total of 16 participants completed the trial. Restrictions on recruitment timescales resulted in an uneven gender split of six males and ten females. Ages ranged from 17 to 65 years (mean (M) = 44.6, standard deviation (SD) = 14.0). Driving experience was also reflective of the wider driving population, with experience ranging from six months to 45 years (M = 25.7 years, SD = 12.5). The fewest miles driven annually was 4,000 and the most 75,000 (M = 15,031, SD = 17,257).

The VDT includes a rating of a driver's general driving style, in which the assessor chooses one of four categories which best describes them: 'patient and careful'; 'sporty'; 'reckless and careless'; and 'aggressive'. The ADI was responsible for judging to which category each participant was assigned after all the driven components of the drive were completed. A majority of participants (13 of the 16) were judged to be 'patient and careful'; one was judged to be 'sporty' and two were judged to be 'reckless and careless'.

6.2 Frequency of navigation system use

Participants were asked to report how often they used four forms of technologies: a dedicated portable satnav system (e.g. TomTom, Garmin, etc.); a factory fitted, in-dash(board) satnav system; a mobile phone using a navigation app; and smart glasses (see Figure 6).

Figure 6: Bar chart to show frequency of use of different navigation technologies



Source: Author's own

Results indicate that portable satnavs are the most commonly used device (10 cases), followed by in-dash systems (8 users) and then mobile phones (7 cases).

There was significant overlap in technology use between participants with most (10) participants using at least two different forms. Only one participant reported never using any navigation technology (despite being screened at the recruitment stage, at which point they reported that they did use navigation technologies).

Finally, no participants reported ever previously using smart glasses; therefore, participants were all equally naïve as to their functionality.

6.3 Traffic conditions

Subjective measures of traffic conditions were recorded throughout each drive. This data showed that 93% of the drive lengths were completed in 'low' traffic conditions, and 7% of the drive lengths were completed in 'moderate' traffic conditions. No drivers experienced 'no traffic' or 'heavy traffic / traffic jam' on any of their routes. These results demonstrate a good degree of consistency in traffic conditions, reducing the probability that other results were influenced by a variation in the mental demands of the driving task between drives.

6.4 Viennese Driving Test behaviours

Instances of inappropriate driving behaviour were recorded by the experimenters, in accordance with the VDT protocol. The VDT comprises of 11 main categories, with most categories being further subdivided into specific subcategories of the related behaviour – for example the main category of *Speed* consists of the subcategories *too fast, too slow and no change*. Analyses were performed on the main categories only; there were insufficient examples of behaviours across the many subcategories to permit reliable statistical analysis.

Analysis of this data showed very few observable differences in driver behaviour across the navigation conditions. Only the *Use of indicator* category produced a significant result ($X^2(16) = 7.29$, $p = .03$), with drivers less likely to use their indicators when turning in the smart glasses condition than during either the verbal or satnav conditions.

H1: The number of driving errors committed by participants when using smart glasses, satnav and verbal instructions for navigation will differ.

Results showed that drivers were only likely to commit one type of error more often when using Google Glass: they were less likely to indicate correctly.

6.5 Participant subjective impressions

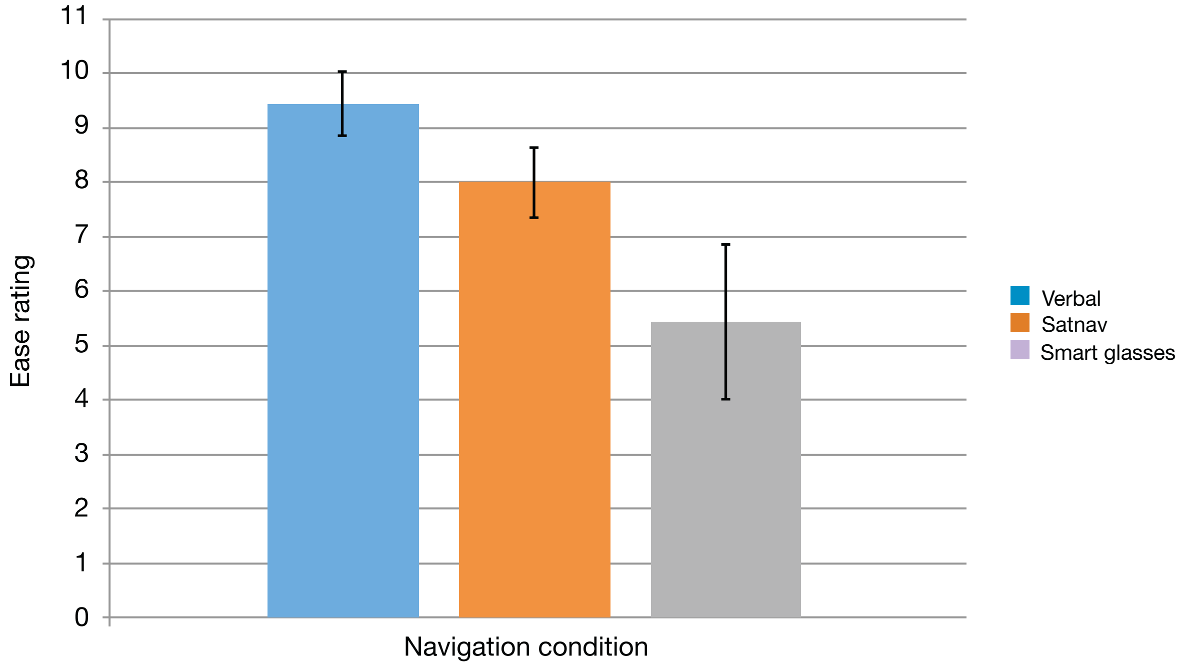
Following the driving component of the trial, participants completed a subjective questionnaire designed to gain insight into their impressions of the three forms of navigation (verbal, Google Glass and satnav). The data was found to not be normally distributed; non-parametric tests were therefore conducted.

6.5.1 Ease/difficulty of navigation across conditions

Participants were asked to rate, on a scale of 1 to 10, the ease of using the three different navigation conditions when driving, where 10 represented ‘easy’ and 1 represented ‘hard’.

Participants reported finding the following of verbal instructions the easiest ($M = 9.4$, $SD = 1.2$), followed by satnav (8.0, $SD = 1.3$), with smart glasses the least easy ($M = 5.4$, $SD = 2.9$). The distributions for scores can be seen in Figure 7.

Figure 7: Bar chart showing mean scores for ease of navigation across the navigation conditions (conditions were rated on a scale of 1 to 10, where 10 represented 'easy' and 1 represented 'hard')



Source: Author's own
(error bars: 95% confidence interval)

Statistical analysis (using Friedman's ANOVA) showed that the differences between navigation forms were highly significant ($\chi^2(16) = 0.2$, $p < .001$). Pairwise comparisons showed that all means were significantly different from each other.

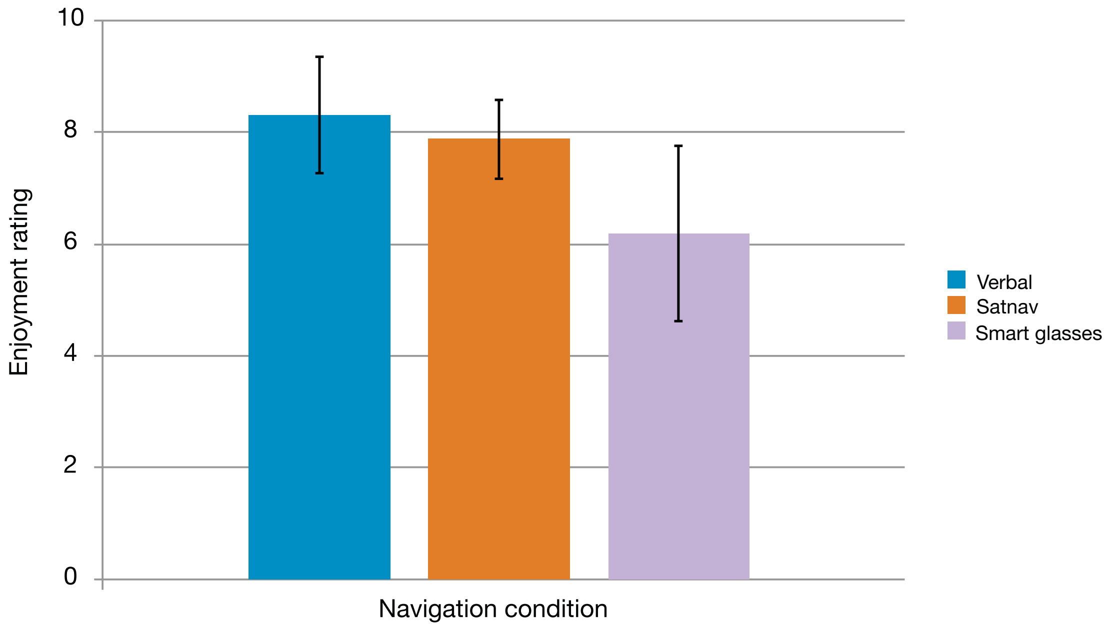
Verbal instructions were rated easiest, followed by satnav, followed by smart glasses.

6.5.2 Enjoyment/unpleasantness of navigation across conditions

Participants were asked to rate their enjoyment of experiencing the three different navigation conditions on a scale of 1 to 10, where 10 represented 'enjoyable' and 1 represented 'unpleasant'.

A similar pattern for enjoyment emerged to the one found in the case of ease, with verbal instructions being rated as the most enjoyable ($M = 8.3$, $SD = 2.1$), followed by satnav ($M = 7.9$, $SD = 1.45$) and then smart glasses ($M = 6.2$, $SD = 3.2$) (see Figure 8).

Figure 8: Bar chart showing mean scores for enjoyment of navigation across the navigation conditions (conditions were rated on a scale of 1 to 10, where 10 represented 'enjoyable' and 1 represented 'unpleasant')



Source: Author's own
(error bars: 95% confidence interval)

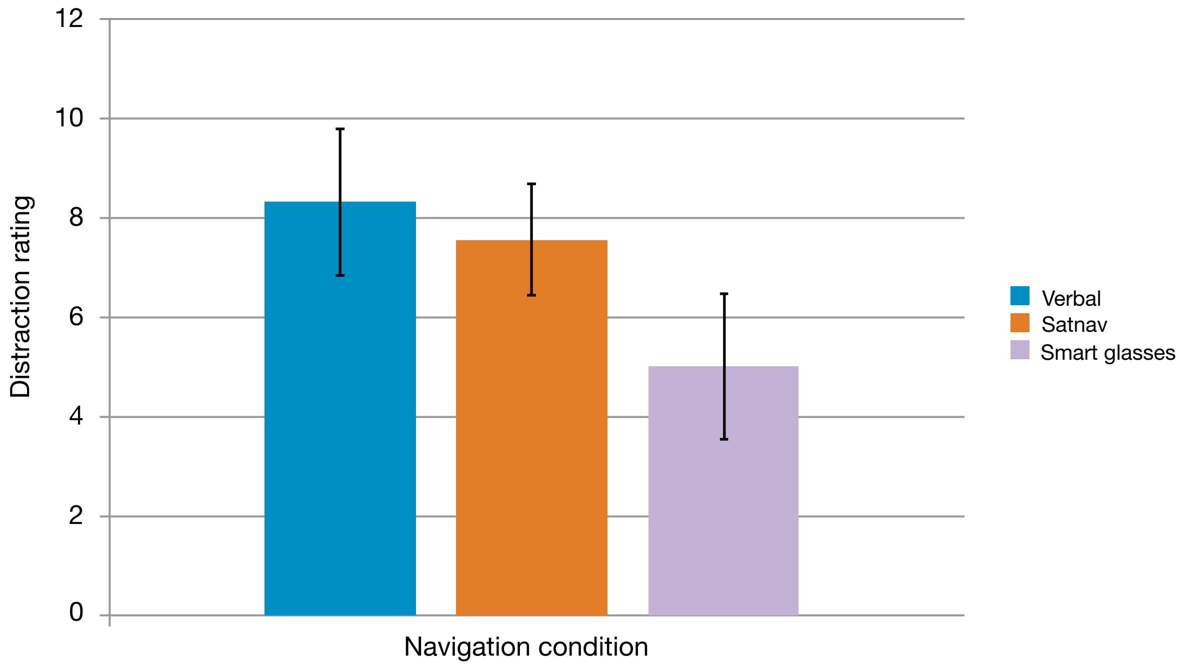
Statistical analysis showed these differences to be significant ($\chi^2(16) = 7.13$, $p = .03$). Pairwise comparisons showed no difference between verbal and satnav forms; however, participants found the smart glasses condition significantly less enjoyable than either verbal or satnav.

6.5.3 Distraction across navigation conditions

Participants were asked to rate the level of driver distraction experienced in the three different navigation conditions on a scale of 1 to 10, where 10 represented 'not distracting' and 1 represented 'very distracting'.

The difference in reported feelings of distraction was also significant ($\chi^2(16) = 18.37$, $p < .01$), with the verbal condition being the least distracting ($M = 8.3$, $SD = 3.0$), closely followed by satnav ($M = 7.6$, $SD = 2.3$), with smart glasses being the most distracting ($M = 5$, $SD = 2.9$) (see Figure 9).

Figure 9: Bar chart showing mean scores for driver distraction across the navigation conditions (conditions were rated on a scale of 1 to 10, where 10 represented 'not distracting' and 1 represented 'very distracting')



Source: Author's own
(error bars: 95% confidence interval)

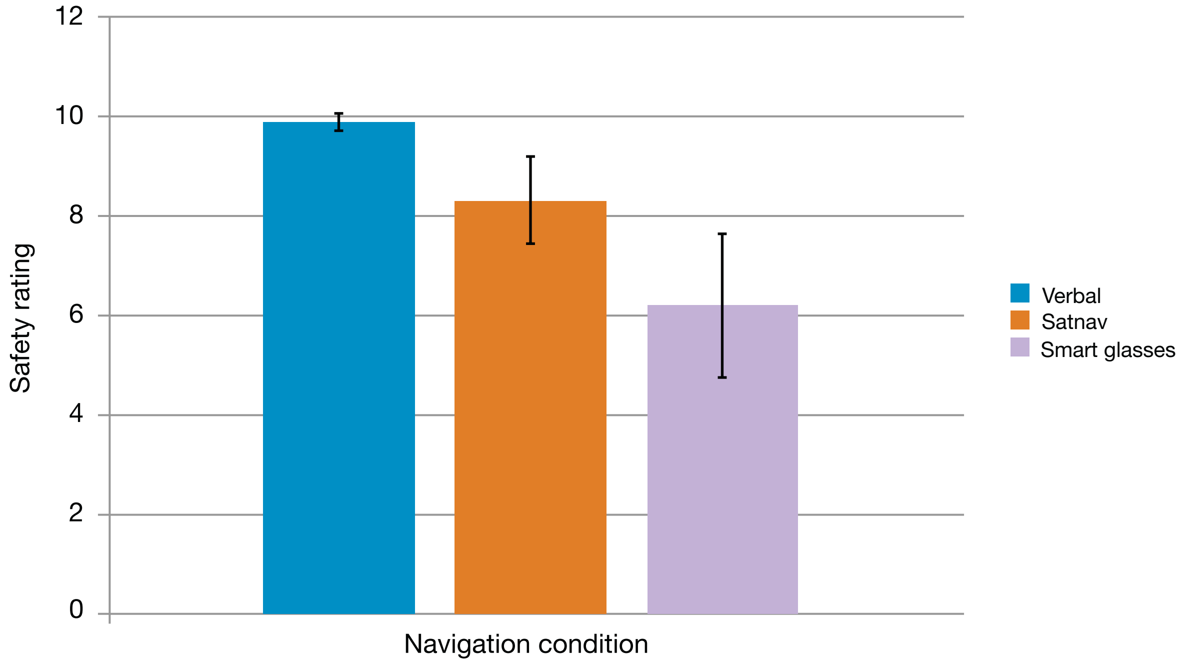
Pairwise comparisons showed that distraction related to the verbal and satnav conditions was not significantly different; however, the smart glasses condition was rated as causing significantly more distraction than either the verbal or satnav conditions.

6.5.4 Safety of system

Participants were asked to rate the level of safety experienced in the three different navigation conditions on a scale of 1 to 10, where 10 represented 'safe' and 1 represented 'unsafe'.

Again, the verbal instruction (M = 9.9, SD = 0.3) and satnav (M = 8.3, SD = 1.8) conditions performed better than the smart glasses condition (M = 6.2, SD = 3.0). Friedman's ANOVA showed the differences in means to be significant ($\chi^2(16) = 19.48$, $p < .01$), with pairwise comparisons showing all means to be significantly different from each other. Figure 10 shows the distribution of safety ratings given to the navigation forms.

Figure 10: Bar chart showing mean scores for feelings of safety across the navigation conditions (conditions were rated on a scale of 1 to 10, where 10 represented 'safe' and 1 represented 'unsafe')



Source: Author's own
(error bars: 95% confidence interval)

H2: Participant subjective ratings of ease of use, enjoyableness of use, feelings of distraction or feelings of safety will differ when using smart glasses, satnav and verbal instructions for navigation.

Results showed a consistent and significant pattern, in which the smart glasses condition was given the lowest ratings, followed by the satnav and then verbal instructions for each of the following indicators: ease of navigation; enjoyableness of navigation; feelings of distraction; and feelings of safety.

6.6 Subjective workload (NASA-TLX)

When interrogating the NASA-TLX data, in which participant self-reported measures of workload, analyses were initially conducted on the overall workload scores, before examining the subscales. These subscales are defined by the NASA-TLX as:

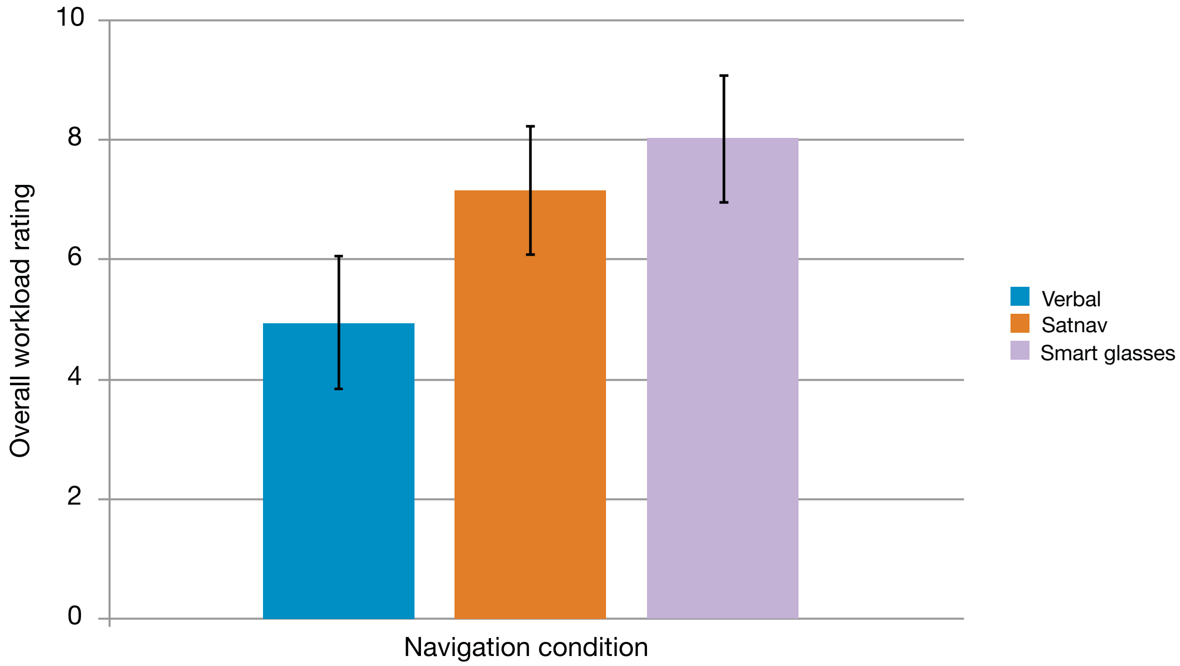
- **Physical demand:** How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the drive easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
- **Frustration:** How discouraged, stressed, irritated, and annoyed verses gratified, relaxed, contented, and complacent did you feel during your drive?

- **Mental Demand:** How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the drive easy or demanding, simple or complex, exacting or forgiving?
- **Temporal demand:** How much time pressure did you feel due to the rate or pace at which the drive occurred? Was the pace leisurely or rapid and frantic?
- **Effort:** How hard did you have to work (mentally and physically) to accomplish your level of performance?
- **Performance:** How successful do you think you were in accomplishing the goals of the drive? How satisfied were you with your performance in accomplishing these goals?

6.6.1 Overall workload scores

The results obtained for the smart glasses condition were not normally distributed; non-parametric statistics were therefore calculated. A Friedman's ANOVA analysis showed the differences between the means across navigation conditions to be significant ($\chi^2(14) = 6.87$, $p = .03$) (Figure 11). Pairwise comparisons showed that the difference between the smart glasses condition and the satnav condition was not statistically significant. However, the verbal condition was different from the smart glasses and satnav conditions.

Figure 11: Bar chart showing mean overall NASA-TLX workload scores across the navigation conditions

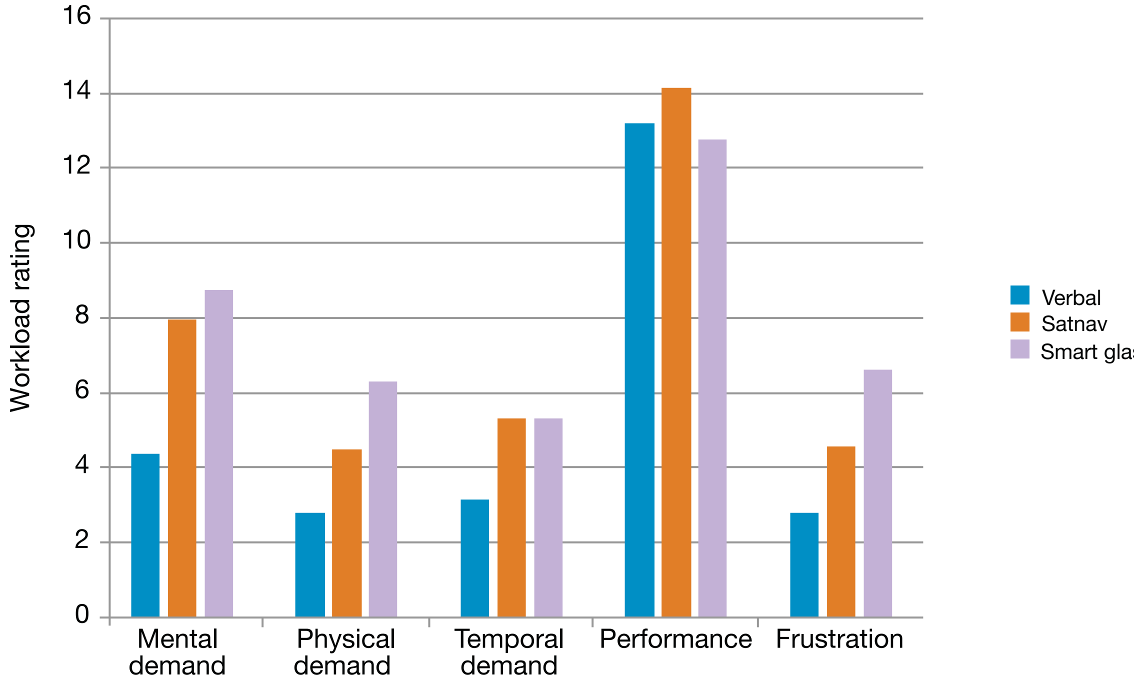


Source: Author's own
(error bars: 95% confidence interval)

6.6.2 Workload scores for each subscale

Differences in mental workload for each of the NASA-TLX subscales were then calculated (Figure 12).

Figure 12: Subjective workload ratings for NASA-TLX subscales



Source: Author's own

Statistical comparisons across the navigation conditions revealed one significant result ('Effort'), and four results which approach significance ('Frustration', 'Mental demand', 'Physical demand' and 'Temporal demand').

The results of Friedman's ANOVAs for each subscale can be seen in Table 2.

Table 2: Results of statistical analysis of NASA-TLX subscales

Subscale	Condition	Mean	Friedman's ANOVA result*			
			N	Fr	df	p
Mental demand	Verbal	4.36	14	5.69	2	.058
	Satnav	7.94				
	Smart glasses	8.75				
Physical demand	Verbal	2.79	14	5.15	2	.076
	Satnav	4.50				
	Smart glasses	6.31				
Temporal demand	Verbal	3.14	14	4.83	2	.090
	Satnav	5.31				
	Smart glasses	5.31				
Performance	Verbal	13.21	14	2.28	2	.320
	Satnav	14.13				
	Smart glasses	12.75				
Effort	Verbal	3.43	14	6.15	2	.046
	Satnav	6.44				
	Smart glasses	8.38				
Frustration	Verbal	2.79	14	5.91	2	.052
	Satnav	4.56				
	Smart glasses	6.63				

Note: * N= number of observations; F_r = Friedman test statistic; df = degrees of freedom; p = p-value
Source: Author's own

Pairwise comparisons of the 'Effort' data showed all means to be significantly different for each subscale.

It should be noted that whilst there was no difference between scores across the three navigation conditions in the 'Performance' subscale, this category had much higher ratings than the other five subscales. This indicates that drivers felt under significant pressure to perform well. This is despite being instructed to drive as naturally as possible, as the experimenters were interested in the performance of the technologies and would in no way be judging the personal quality of their driving. It is possible this was due to one or more of: the novelty of the smart glasses; the presence of the ADI – who might have been seen as authoritative and/or judgemental; driving an unfamiliar vehicle belonging to someone else; and the short duration of the drives, which may not have given participants enough time to relax fully and drive as normal.

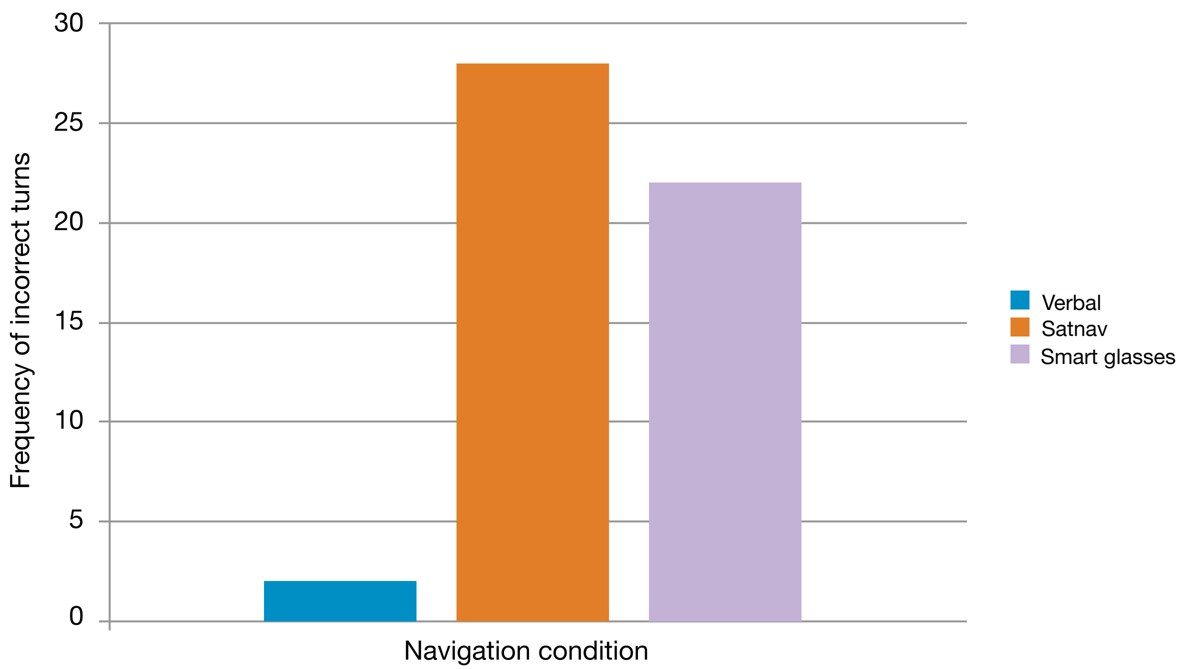
H3: Participants' self-reported mental workload will differ between smart glasses, satnav and verbal instructions for navigation.

Results showed that workload was lowest in the verbal condition, followed by the satnav condition, with Google Glass producing the highest feelings of workload.

6.7 Incorrect turns

A record was kept of how often participants failed to follow correctly the instructions that they were given at junctions. Instances where the participant failed to follow the instructions correctly were recorded as incorrect turns. Results show that drivers were much less likely to take an incorrect turn when given verbal instructions (2 incorrect turns) than when using the smart glasses (22 incorrect turns) or satnav (28 incorrect turns) (see Figure 13).

Figure 13: Bar chart to show the total number of incorrect turns recorded in the study across the navigation conditions



Source: Author's own

Statistical analysis showed a significant difference between the verbal condition and both the satnav and smart glasses conditions ($\chi^2(16) = 17.26$, $p < .01$), but no difference between the smart glasses and satnav conditions.

H4: The number of navigation errors made by participants will differ when using smart glasses, satnav and verbal instructions for navigation.

Results show that drivers were much less likely to take a wrong turn when receiving verbal instructions than when using either of the other two methods of navigation, but no more or less likely to take a wrong turn when using satnav then when using smart glasses.

6.8 Technical problems with smart glasses

During the trials a record was kept of any technical problems with smart glasses. Only one participant's drive in the smart glasses condition was completed without some form of technical problem. The problems encountered and their frequencies were:

- Overheating: 9
- Loss of Bluetooth connectivity: 3
- Freezing: 4
- Switching to route overview (unintentionally): 4
- Slow route updating: 3

Experimenters reported that the smart glasses were prone to overheating, sometimes after only a few minutes of use. This resulted in system performance degradation. To address this problem, a cool bag was taken on each trial, containing cool pads to chill the headset when not in use in the event of overheating. Without this measure, the trial would not have been able to proceed owing to frequent problems with overheating.

The method used in the study required the smart glasses to be constantly displaying directions, rather than blanking between instructions, and this is likely to have been at least partially responsible for the overheating problems.

It should also be noted that the difficulties encountered by participants during pilot testing in hearing the auditory navigation instructions provided by the smart glasses using the bone conduction technique represents a significant constraint on their potential use when driving.

7. Discussion

Smart glasses are a relatively new consumer product, yet there are many innovative ways in which their use can be envisaged. If they were to become more prevalent, it can be expected that a subset of consumers would choose to use them whilst driving.

This study was undertaken to examine the use of smart glasses for navigation, and how this would compare with more traditional forms of navigation. Of particular interest was how the presentation, via smart glasses, of visual information close to the normal forward field of view for a driver may differ from a traditional satnav system, which may require longer glances away from the road.

On the basis of the sample of participants tested, the results suggest that drivers' objective performance was largely unaffected by using verbal instructions, satnav or smart glasses. Very few differences in erroneous behaviour rates were recorded between the three conditions. By contrast, when errors were measured as incorrect turning at junctions, the results showed that verbal instructions were less likely to lead to drivers making an incorrect turn than either the satnav or smart glasses, and that drivers were equally likely to take a wrong turn when using either satnav or smart glasses. Given that the navigation displays and instructions were identical on both devices, this lack of a difference between technologies may not be surprising. Therefore, these results suggest that having navigation information displayed in the upper right peripheral field neither aids nor impairs decision making at junctions when compared with a traditional satnav. The results obtained from the subjective data strongly indicated a preference for verbal communication, followed by the satnav condition, with visual instructions presented through smart glasses as the least preferred condition.

It should be recognised that the driven component of the test session was shorter than is typical for the full Viennese Driving Test protocol, as dictated by the need to minimise demands on drivers and complete each trial in a timely fashion. The VDT would usually be conducted over a period of 30 to 45 minutes, whereas drives in this trial were completed in around 15 minutes. This may have been too short a time to provide opportunities for drivers to behave in a manner such that significant differences across conditions could be identified from the sample size of 16 participants. Furthermore, it is possible that drivers did not have sufficient time to relax and drive normally. The results of the 'Performance' subscale of the NASA-TLX suggested that drivers were applying considerable effort to drive well, which may have reduced the incidence of driving errors that might be expected in a more natural setting.

When judging the usefulness of smart glasses to drivers, it is important that we do not conflate the effects of displaying visuals in the upper right portion of the visual field with user experiences of smart glasses. The technology used is not mature, and many of the problems which reduce user preference for the device could no doubt be solved by improvements to either the software or hardware. They are not necessarily caused by how the visual information was displayed. However, the many technical problems with the hardware encountered in the trial make it hard to envisage its frequent use by drivers as a viable navigation tool in its current form. These could be expected to be a source of frustration to drivers, and may also cause distraction if a driver were to attempt to remedy any problems experienced with the technology on the move.

It is also recognised that within this trial the smart glasses were only tested in relation to their function as a navigation device. Of course, they have far wider functionality, including Internet browsing, watching videos, social networking and messaging. This wider functionality of smart glasses could tempt drivers to divert their attention away from the activities required for safe driving, leading to an increase in collision risk. The extent to which this will occur, and whether drivers can adapt their driving behaviour to mitigate risk in that context, remains to be explored. However, with the potential proliferation of smart glasses and wearable technology, it will be important to understand how they influence driving styles.

If a reliable and user-friendly smart glasses system were to be developed, the protocol established in this study could be reused to investigate the effectiveness of the new system and to investigate potential distraction effects further. It is recommended that a larger sample size be recruited to gain statistical power, and that longer drives be used (conducted on different days to avoid fatigue problems), to allow a more extensive assessment of driving behaviour. If this technology does become more commonplace, it would also be of interest to compare the behaviour of experienced and inexperienced users of the technology, to understand how familiarity with the systems might change driving behaviour. High-fidelity driving simulator systems would also enable trials which examine potentially riskier aspects of smart glasses use to be conducted. Such aspects might include obscuring of hazards by the display, and distraction by responding to social media through the smart glasses interface.

8. Conclusion

This on-road study sought to evaluate how the use of smart glasses for navigation would affect driver behaviour compared to the use of a satellite navigation (satnav) device, or high-quality verbal instruction. The results have provided evidence that the visual display method typical of smart glasses neither helps nor hinders drivers when used for navigation, in comparison to satnavs. However, neither smart glasses nor satnavs led the drivers to perform as well as when given verbal instructions by a passenger.

Despite the smart glasses producing similar performance levels to satnavs, participants expressed a clear subjective dislike of the smart glasses technology in its current form. However, some caution in generalising from the results to the wider population should be exercised as a consequence of the study's modest sample size and the immaturity of the smart glasses device.

The literature reviewed suggested that, by greater use of voice interaction and presentation of visual information close to a driver's normal forward field of view, smart glasses may provide drivers with useful and convenient access to navigation information. Clearly, a driver accessing functions of smart glasses which are unrelated to navigation – such as calls, texts, social media and the Internet – are potentially at risk of visual and cognitive distraction effects.

Despite the withdrawal of the product tested from the market, similar systems continue to be developed by other manufacturers. It is likely that smart glasses systems will once more become available, and that users may choose to wear them when driving. The multiple functions and novel interface of smart glasses mean that the legislative position on their use remains to be clarified by the Department for Transport.

The results obtained represent evidence that smart glasses can potentially be used safely for navigation, but that users do not enjoy the experience at present: they feel less safe and more distracted than when using a traditional satnav. This, together with the many technical problems encountered, suggests that more development work is required to create a compelling proposition for the use of smart glasses in the driving task.

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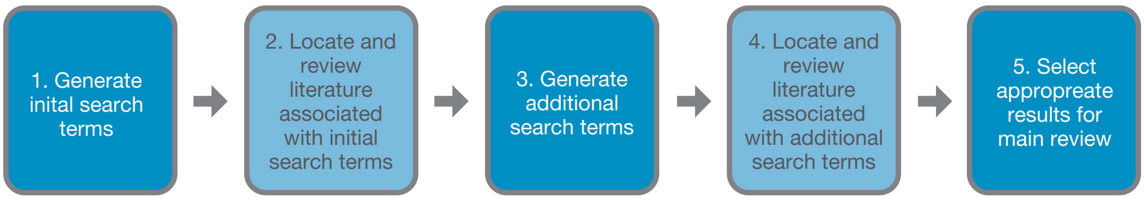
Appendix A Literature Review Methodology

This literature review adopted a systematic approach to identifying relevant literature which comprised of five stages:

1. Firstly, a list of search terms was generated through consultation with TRL experts in driver distraction and in-vehicle technologies.
2. Secondly, a comprehensive search and review of the literature available was conducted, based on the initial search terms generated in the first stage.
3. Thirdly, additional terms were added to the list of search terms.
4. Fourthly, the search was repeated with the additional search terms.

Finally, all papers were reviewed and the appropriate results were selected for review (see Figure A1).

Figure A1: Five-stage methodology employed in literature review



Source: Author's own

The literature search identified the most important, influential, and valid research on the selected topic. All evidence was subjected to scrutiny to ensure that it was from a reliable source and applied a sound methodology, and that the results demonstrated acceptable statistical validity.

The literature review made use of three sources of information: a search of academic journals and databases (including TRL's Knowledge Base, which contains more than 400,000 abstracts); a general Internet search using Google and Google Scholar; and reference to both the personal libraries of TRL experts in driver distraction and in-vehicle technologies, and the TRL reference library.

Appendix B Viennese Driving Test materials

Participant number:__________________

General information sheet

Participant name	
Participant Number	

Coding observer	
Free observer	

Date	

Start time		**End time**	

Road conditions	**dry**		**wet**		**other:**
Weather	**good visibility**		**poor visibility**		**other:**
Temperature	**°C**				

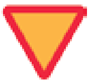
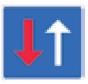
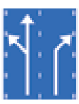
Driving style	Sporty driving style		Aggressive driving style		other:
	patient and careful driving style		reckless and careless driving style		

General comments on the driving behaviour:

Traffic situation for each section

Section	no traffic	light traffic	medium traffic	traffic jam
Drive 1				
1				
2				
3				
Drive 2				
4				
5				
6				
Drive 3				
7				
8				
9				

Coding sheet

	2 Variable			Route and Section
	Speed		Too fast according to the situation	
			Too slow according to the situation.	
			No change of speed	
	Adaptation of speed before/in intersection or before obstacles		late, abrupt	
			Bad, too fast	
	Behaviour as one who has to yield (also at Stop signs)		Narrow, dangerous	
			Hesitant, unclear	
			Stop line	
	Stick to own priority			
	Distance to the road user ahead		Dangerous	
			Too long	
	Use of the indicator		Too early	
			Inappropriate	
			Too late	
			Not at all	
	Lane	Lane change before intersections	Too early	
			Too late	
			Incorrect lane choice	
		Lane change	Dangerous	
			Hesitant	

	3 Variable		Route and Section
	Lane use	Extremely on the left side of the lane	
		Extremely on the right side of the lane	
		Inaccurate, drifting	
		Crossing solid line, hatching	
	Overtaking	Illegal	
		Dangerous	
		Abort manoeuvre	
	Vulnerable road-users	Ignores pedestrian/ cyclist	
		Gives priority late	
		Forces Pedestrian/ cyclist to stop	
		Hazards pedestrian/ cyclist	
	Wrong turns and nearly wrong turns	Misunderstood directions (intentionally went wrong way)	
		Missed directions (didn’t realise they have to turn)	
		Confused and indecisive (couldn’t work out which was to go)	
		Turned correctly but very late, or on second attempt (went around roundabout twice).	
	Eyes off of road	Dangerously long gaze at device	
		Dangerously frequent gazes at device	

Participant number:__________________

Free observation sheet observation ride – Navigationsystem

Start time NavSat part: __________________

End time NavSat part: __________________

Section ________________________________

Category	Description of the event	
Hand position		
Use of SL/SA controls		
Error **without** the involvement of other road users		
Interaction/ communication (only description of non-erroneous behaviour)		
Errors within interaction or communication		☐ dangerous ☐ reckless ☐ both
Conflict		☐ heavy ☐ light ☐ guilty ☐ not guilty ☐ defence ☐ no defence
Others		

Participant number:________________

Free observation sheet observation ride – Google Glass

Start time Google Glass: ________________

End time Google Glass: ________________

Section ____________________________

Category	Description of the event	
Hand position		
Use of SL/SA controls		
Error **without** the involvement of other road users		
Interaction/ communication (only description of non-erroneous behaviour)		
Errors within interaction or communication		☐ dangerous ☐ reckless ☐ both
Conflict		☐ heavy ☐ light ☐ guilty ☐ not guilty ☐ defence ☐ no defence
Others		

Participant number:_______________

Free observation sheet observation ride – Verbal Instructions

Start time Verbal Inst part: _______________

End time Verbal Inst part: _______________

Section ___________________________

Category	Description of the event	
Hand position		
Use of SL/SA controls		
Error **without** the involvement of other road users		
Interaction/ communication (only description of non-erroneous behaviour)		
Errors within interaction or communication		☐ dangerous ☐ reckless ☐ both
Conflict		☐ heavy ☐ light ☐ guilty ☐ not guilty ☐ defence ☐ no defence
Others		

Questionnaire for the observation ride

General part:

How did you feel during the ride?

In comparison to your "normal" driving style, did your driving behaviour change due the presence of the observers?

Where there any specific situations during the observation ride? If so can you please describe them? Can you describe how you reacted and why? Did the IVT have an influence on what happened?

If the observers noticed any critical situations or problems during the observation, and the test person did not mention them, these situations have to be checked additionally!!

Do you remember the situation where … (description of the situation by the observer) … happened? Can you describe the event as you remembered it? Can you describe how you reacted and why? Did the IVT have an influence on what happened?

Definition of driving style

Sporty driving style: includes taking corners fast, braking and accelerating hard, using high revs in every gear and changing down before corners

http://www.motorera.com/dictionary/sp.htm

Aggressive driving style: exceeding the posted speed limit, following too closely, erratic or unsafe lane changes, improper signalling of lane changes, failure to obey traffic control devices (stop signs, yield signs, traffic signals, railroad grade cross signals, etc.).

http://www.nhtsa.gov/people/injury/enforce/aggressdrivers/aggenforce/define.html

The **patient and careful driving style reflects** a well-adjusted driving style that has received less attention in previous studies (e.g. French et al., 1993; Harré, 2000). This style refers to planning ahead; attention, patience, politeness, and calmness while driving; and keeping the traffic rules.

Orit Taubman-Ben-Ari, Mario Mikulincer, Omri Gillath 2004, The multidimensional driving style inventory—scale construct and validation, Accident Analysis and Prevention 36 (2004) 323–332

The **reckless and careless driving style** refers to deliberate violations of safe driving norms, and the seeking of sensations and thrill while driving (e.g. French et al., 1993; Reason et al., 1990). It characterizes persons who drive at high speeds, race in cars, pass other cars in no-passing zones, and drive while intoxicated, probably endangering themselves and others.

Orit Taubman-Ben-Ari, Mario Mikulincer, Omri Gillath 2004, The multidimensional driving style inventory—scale construct and validation, Accident Analysis and Prevention 36 (2004) 323–332

Appendix C NASA-TLX

To be completed by TRL		
Date: _____/_____/_____	Drive number: **1**	Participant Number: ______________________
NASA TLX		

Your experience of the last drive	NASA TLX
	For the following questions please think about the drive you just completed an "X" inside a box along each scale at the point that best indicates your experience. Some of the scales may seem strange at first glance. If you're not confident that you have understood the descriptions of the scales, please do not hesitate to ask an experimenter for further clarification
1	**Mental Demand:** How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the drive easy or demanding, simple or complex, exacting or forgiving?
Low	High
2	**Physical demand:** How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the drive easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Low	High
3	**Temporal demand**: How much time pressure did you feel due to the rate or pace at which the drive occurred? Was the pace leisurely or rapid and frantic?
Low	High
4	**Performance**: How successful do you think you were in accomplishing the goals of the drive? How satisfied were you with your performance in accomplishing these goals?
Low	High
5	**Effort**: How hard did you have to work (mentally and physically) to accomplish your level of performance?
Low	High
6	**Frustration**: How discouraged, stressed, irritated, and annoyed verses gratified, relaxed, contented, and complacent did you feel during your drive?
Low	High

Appendix D Subjective experience questionnaires

Post-Trial Questionnaire

To be completed by Researcher		
Participant Number: ____________	Trial time:__________	Date: _____/_____/_____

SECTION A. Background information		
1. What was your age at your last birthday?		
2. Are you Male or Female? (*please tick*)	Male	Female
3. Are you left or right-handed? (*please tick*)	Left	Right
4. For how many years have you held a driver's licence?		
5. Approx. how many miles do you drive per year?		
7. How often do you use each of these navigation types?		

Nomadic Satnav (i.e. portable ones you can stick to the inside of your vehicle).				
Never	A few times a year	About once a month	About once a week	Most days
In-dash Satnav (i.e. one preinstalled in a vehicle)				
Never	A few times a year	About once a month	About once a week	Most days
Mobile phone navigation app				
Never	A few times a year	About once a month	About once a week	Most days
Smartglass (Google Glass) navigation app				
Never	A few times a year	About once a month	About once a week	Most days

SECTION B. System preferences

Today you followed three forms of navigation:

- Verbal instructions
- Google Glass
- Satnav

Please answer the following questions on your experiences of each form of navigation.

8. How **easy/hard** did you find it to follow the navigation instructions:

Verbal instructions									
Not at all easy									Very easy
1	2	3	4	5	6	7	8	9	10
Google Glass									
Not at all easy									Very easy
1	2	3	4	5	6	7	8	9	10
Satnav									
Not at all easy									Very easy
1	2	3	4	5	6	7	8	9	10

8a. If there was anything in particular that you found easy or difficult about each type of navigation please note it here:

Verbal Instructions

Google Glass

Satnav

9. How **enjoyable/unpleasant** did you find it to follow the navigation instructions:									
Verbal instructions									
Not at all enjoyable									Very enjoyable
1	2	3	4	5	6	7	8	9	10
Google Glass									
Not at all enjoyable									Very enjoyable
1	2	3	4	5	6	7	8	9	10
Satnav									
Not at all enjoyable									Very enjoyable
1	2	3	4	5	6	7	8	9	10

9a. If there was anything in particular that you found enjoyable or unpleasant about each type of navigation please note it here:
Verbal Instructions
Google Glass
Satnav

10. How **distracting** did you find it to follow the navigation instructions:									
Verbal instructions									
Very distracting									Not at all distracting
1	2	3	4	5	6	7	8	9	10
Google Glass									
Very distracting									Not at all distracting
1	2	3	4	5	6	7	8	9	10
Satnav									
Very distracting									Not at all distracting
1	2	3	4	5	6	7	8	9	10

10a. If there was anything in particular that you found distracting about each type of navigation please note it here:
Verbal Instructions
Google Glass
Satnav

11. How **safe/unsafe** did you feel when following the navigation instructions:									
Verbal instructions									
Not at all safe									Very safe
1	2	3	4	5	6	7	8	9	10
Google Glass									
Not at all safe									Very safe
1	2	3	4	5	6	7	8	9	10
Satnav									
Not at all safe									Very safe
1	2	3	4	5	6	7	8	9	10
11a. If there was anything in particular that you found made you feel safe or unsafe about each type of navigation please note it here:									
Verbal Instructions									
Google Glass									
Satnav									

SECTION D. General comments

If you have any other comments you would like to make regarding the three forms of navigation, please do here.

We are particularly interested in any strengths or weaknesses you felt the navigation types had.

Verbal instructions

Google Glass

Satnav

Please use the space below to provide any general comments or suggestions you have regarding your experiences today.

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