The effects of using mobile phones and navigation systems during driving

Knapper, Allert

DOI
10.4233/uuid:2a3aa826-be9d-4663-add9-884a42c23a21

Publication date
2018

Document Version
Final published version

Citation (APA)
Knapper, A. (2018). *The effects of using mobile phones and navigation systems during driving*. [Dissertation (TU Delft), Delft University of Technology]. TRAIL Research School. https://doi.org/10.4233/uuid:2a3aa826-be9d-4663-add9-884a42c23a21

The effects of using mobile phones and navigation systems during driving

Allert Knapper

Dit proefschrift is mede tot stand gekomen met steun van SWOV – Instituut voor Wetenschappelijk Onderzoek Verkeersveiligheid en is ook verschenen in de TRAIL Thesis Series T2018/10, the Netherlands TRAIL Research School, ISBN 978-90-5584-242-1.

Uitgave:
SWOV-Dissertatiereeks
SWOV – Instituut voor Wetenschappelijk Onderzoek Verkeersveiligheid
Postbus 93113
2509 AC Den Haag
E: info@swov.nl
I: www.swov.nl

ISBN: 978-90-73946-18-7

Omslagillustratie: Anke Knapper

The effects of using mobile phones and navigation systems during driving

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. dr. ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op dinsdag 4 december 2018 om 12:30 uur

door

Allert Sake KNAPPER
Master of Science in Psychologie
RU Groningen
geboren in Assen, Nederland

Dit proefschrift is goedgekeurd door de promotoren:
Prof. dr. M.P. Hagenzieker
Prof. dr. K.A. Brookhuis

Samenstelling van de promotiecommissie:

Rector Magnificus	voorzitter
Prof. dr. M.P. Hagenzieker	TU Delft, *promotor*
Prof. dr. K.A. Brookhuis	TU Delft, RijksUniversiteit Groningen *promotor*

Onafhankelijke leden:

Prof. dr. B. van Arem	Civil Engineering and Geosciences, TU Delft
Prof. dr. V.A.W.J. Marchau	Institute for Management Research, Radboud University, Nijmegen
Prof. dr. G.P. van Wee	Technology, Policy and Management, TU Delft
Prof. dr. D. de Waard	Behavioural and Social Sciences, RijksUniversiteit Groningen

Preface and acknowledgements

Early 2008, I was looking for a topic for my Master's thesis. That's when I ran into Prof. Dr. Karel Brookhuis, who was looking for a student for a project involving the use of reverse laning in case of large area evacuations. In all honesty, I had never even realised that a topic such as traffic psychology existed, let alone that studying it would be for me. But, as many others in the field acknowledge, it is most interesting and relevant. Together with some amazing people at Rijkswaterstaat, we conducted a study at the FC Groningen Euroborg stadium, where we closed down the area after a soccer game. This allowed us to install reverse laning on the only road leaving the area, in order to study the efficiency of this measure. Here I found out that doing research in the field, with real people, is great fun (but not always without setbacks and delays).

Not long after I graduated, Karel informed me that he together with Marjan Hagenzieker had a post for a PhD researcher at Delft University of Technology. And although I had never considered myself to be of the researcher kind (no offence to any reader), I remembered I had greatly enjoyed the field study, and the topic of driver distraction was rather appealing. So I applied and I was grateful to be hired. Karel and Marjan: Thanks a million for hiring, supporting, inspiring, trusting, encouraging and teaching me since. You are among the nicest and most patient people I know, and you were a major factor in my completing this thesis.

During my time at Delft University, I met many more great people. Some I haven't seen or spoken in years, others I still occasionally meet. I want to thank the many roommates that I had, Jan-Willem, Randy and later Yashar in particular. I also hugely enjoyed the Transport & Logistics group, with lively lunches and fruitful Friday beers, with Maarten, Caspar, Bert, Jan Anne, Niek, Vincent, Eric, Ron, and of course the excellent support by the secretariat (Betty!). In my research I took on the challenge to program the real world into a driving simulator. The result would not be nearly as neat as it has been without you, Raymond Hoogendoorn. Thanks also for the good discussions, sometimes tiring but always inspiring! Let's have that beer soon.

A major part of my research involved participating in the EU-project INTERACTION at SWOV in exchange for data and participants. This collaboration was brilliant for me, and I learned a lot from the deep knowledge of road safety at this institute. I also had great fun with all the colleagues there, especially during those superb lunches. I particularly want to thank Nicole van Nes, also for bearing with me when those data disappeared, and telling me that what does not kill you, makes you stronger. I heartily have used that mantra during later setbacks. Michiel Christoph, my roommate at and guide through SWOV, I have had a great time with you, and still admire your tech and database savvy, and the enthusiasm you showed with road safety research and any object with wheels, really.

When my contract at Delft University ended in 2013, but the work was not done yet, I carried on writing, rewriting and publishing in my spare time, still fantastically supported by Marjan and Karel, who were never stopped by my DIY-in-my-new-home and baby pauses that sometimes lasted months and months. But still I put in a lot of my either or not spare time. This thesis would not have been possible without the endless babysitting help of especially my beloved sister Anke and my mother in law Ria (I'd love to see a study into how many PhD thesis authors thank their mothers in law).

What is more, I want to thank my own family. Eva, thanks for the endless patience, time, and love. Thanks Sake, Wout and Elle for inspiring me, I hope this inspires you to persevere and be loyal, but at the same time make sure your work is fun. Thank God it is finished.

I could probably write another book with thank-you's. I am thinking about all the people I met at TU Delft, all the participants in my studies, reviewers, people at the TRAIL office, in the INTERACTION project, at congresses, at the University of Groningen, phdcomics.com: Thanks! In case you think I have forgotten you: Send me an e-mail and I'll thank you in person. I most certainly owe all the people that frequently asked if the end was nigh yet; I hope you enjoy reading the result!

Rijswijk, September 2018
Allert Knapper

Table of contents

1. Introduction

1.1. Background

Driving might be the most complex task that many engage in on a daily basis. Drivers need to pay attention to other vehicles, cyclists and pedestrians, while keeping the car safely between the road markings and at an appropriate distance from any vehicle in front. They communicate to other cars using different light signals at the right time, complying with traffic rules and reacting to many unexpected events, such as flies in the cockpit, other drivers' unsafe manoeuvres and bad weather. To make driving more comfortable, drivers often tune the radio, eat and talk, thus complicating the task even more. In recent years, both portable navigation systems and mobile phones (smartphones) have become a common integral part of our driving environments. Although both devices may have advantages in terms of uncertainty and stress reduction and shorter routes, and allowing for immediately warning emergency services when needed, they may also have negative impacts in terms of distracting drivers from performing their primary driving task.

1.1.1. Road safety and driver distraction

The WHO estimates that worldwide approximately 1.25 million people die in traffic each year, which makes road traffic injuries the leading cause of preventable death (WHO, 2015). In the Netherlands, annually around 600 road traffic fatalities and 20,000 serious road traffic injuries occur (SWOV, 2016).

Several factors affect the chance of someone being involved in a crash. The WHO (2015) distinguishes speed, drink driving, motorcycle helmets, seatbelts and child restraints, and distracted driving as the key risk factors. Many countries have put distraction as one of their policy priorities for the coming years.

This thesis assesses distracted driving. The precise impact of distracted driving on crash likelihood is not known yet, for instance because of the large variation between available studies. In a recent large scale naturalistic driving study (the Second Strategic Highway Research program Naturalistic Driving Study, SHRP2 NDS), Dingus et al. (2016) found that drivers are engaging in distracting activities for more than 50% of the driving time. Most notably, they estimate that distraction is a contributing factor in up to 4 million of the 11 million annual crashes in the US. How this compares to other countries or even the EU as a whole is largely unknown, however for the Netherlands it is estimated that probably several dozens to just over one hundred fatalities occur annually in which distraction was a contributory factor (Stelling & Hagenzieker, 2015). A study commissioned by the EU shows that current estimates of road user distraction being a contributory factor in accident range from 10 to 30% (TRL, TNO, & RappTrans, 2015).

Distractions occur, among others, when traffic participants are not focused on participating in traffic, because of focusing on something else. This may affect both the traffic participants themselves and other road users. Although a plethora of sources of distraction may be distinguished, this thesis focuses on distractions from mobile phones and navigation systems, and how car drivers' behavioural performance is affected.

Mobile phones are predominantly smartphones nowadays, with touchscreens, downloadable apps and e-mail. According to Pew Research Center (Poushter, 2016), about two thirds of all adults in developed countries own a smartphone, and in emerging and developing nations ownership percentages are rising fast, from 21% in 2013 to 37% in 2015. According to GfK (GfK, 2016b), in 2016, 83% of 1251 respondents (representing 13.4 mln aged 13+) own a smartphone. It is not precisely known how often phones are used while driving, but in 2011 the WHO (2011), estimated that 1% to up to 11% of drivers use mobile phones while driving. And these numbers are increasing steadily over time: A recent Dutch survey, for example, found that 65% of Dutch people report to use their phone at least once in a while when participating in traffic (Christoph, Van der Kint, & Wesseling, 2017).

Navigation systems may help the driver navigate, providing both efficient routes and comfort, and avoiding uncertainty and stress. However, navigation systems often simultaneously take the driver's eyes off the road, hence posing a distraction. Navigation systems are used widely, in the Netherlands 91% of households possess some kind of navigation system, for instance a portable navigational device, a phone application or built-in system, while two third of all Dutch households own a portable navigation system in 2015 (KiM, 2015). Exact usage numbers are unknown, however a study by Jamson (2013), who surveyed 1,500 people across the EU (Italy, Spain, UK, Poland, and Sweden), showed that about 75% of respondents use a portable navigational device (pnd) sometimes or often during driving.

1.2. Scope

This thesis focuses on the effects on driver performance when they use their mobile phone or navigation system. A lot of research is available on how devices distract drivers and affect their performance. However, research usually focuses on either mobile phones or navigation systems, or their subtasks. Furthermore, only seldom more than one research method is applied, while each method has its pros and cons. One of the disadvantageous consequences is a somewhat incoherent landscape, providing bits and pieces but not always a complete picture. Furthermore, although many governments, especially in western countries, have taken measures against distracted driving (most often against handheld phoning and operating phones), it is still unclear which measure(s) work best or have any effect at all. Moreover, the problem seems to increase rather than decrease.

The present thesis takes a broad approach. It does so by providing an extensive overview regarding the current state of knowledge with respect to the behavioural consequences of using mobile phones and navigation systems while driving, and how these affect safety and efficiency of driving. Furthermore, it assesses mobile phones as well as navigation systems, which allows for comparing the effects of these devices. This provides a better understanding of how and why drivers engage in using mobile phones and navigation systems during driving. Moreover, next to assessing the vast amount of literature, this thesis investigates how a group of drivers use navigation systems and mobile phones while driving, and what are the consequences, using various other methods.

1.3. Research questions and outline

The general question overarching this dissertation is:

What are the road safety and efficiency effects of using a mobile phone or a navigation system while driving?

In order to answer this question, drivers are observed in their natural habitat, using cars fitted with observation equipment for an extended period. Using naturalistic driving observations is in itself a method that is not commonly applied yet, due to its relatively recent availability and high cost. It allows for actual observing drivers behaving as they would normally do. In addition, a driving simulator experiment is conducted to investigate the reactions of the same group of drivers to the several task components of using mobile phones and navigation systems under controlled circumstances. This even enhances the possibility to deliver comparable, strong and unique insights in road safety effects of distracted driving. In order to assess the validity of the simulator data, participants completed a track in the simulator that was similar to a specific route in the real world, while also completing similar tasks.

As the driving task is complex and the used methods do not allow for every kind of data to be collected (due to cost, time, and nature of the task/method), the following questions are used as building blocks for an answer to the main question:

1. *How should we understand the effects of using mobile phones and navigation systems on the driving task and on driver behaviour?*

The complexity of the driving task, and the fact that this complexity changes every second due to the changing road scene makes it difficult to interpret many results. Therefore, this question aims at providing context, which may ease interpreting the results. In Chapter 2 an attempt to answer this question is made, by providing a closer look at what distracted driving is, what the driving task entails, and how the driver is capable – or not – to perform the driving task.

Consequently, Chapter 3 regards how researchers in practice assess the effects of using mobile phones and/or navigation systems while driving. The pros and cons of the different methods that have been applied are described, showing that maybe not one method suffices to provide definitive answers (cf. Carsten, Kircher, & Jamson, 2013). That is, Chapter 3 assesses which methods could be applied and which variables and measurements should be recorded then, and what is their relative value?

2. *How can we investigate the effects of phones and navigation systems use on driving?*

Next to these relatively fundamental questions, and in order to provide a picture that is as complete as possible, in Chapter 4, other researchers' findings regarding the use of mobile phones and navigation systems are presented, showing that especially mobile phone use while driving has been heavily studied in recent years. However, there also appears to be much debate on the topic. Furthermore, Chapter 4 shows that the use of navigation systems may not have received the research attention needed. Likewise, drivers may not only think about their safety (or not) while driving, efficiency (shorter trips, multitasking) may also play an import role in their decision to engage in distracting activities. However, drivers using devices while driving may also affect for instance other traffic. Chapter 4 specifically deals with the following question:

3. *What results* have *been reported in the research literature so far?*

This question is disentangled in the following questions:

- Which impacts on safety are the result of drivers using mobile phones and navigation systems?
- How do these safety impacts relate to efficiency?
- How comparable are these impacts across the two types of devices?
- What knowledge gaps are there in the current body of research?

Chapter 5 describes the results of a driving simulator study. Driving performance is investigated by four distinct tasks related to mobile phones and navigation systems: Having phone conversations, texting, following route guidance advice, and performing navigation system programming tasks. The study compares driving performance while also performing these tasks to driving performance while not performing a secondary task. The research question posed in Chapter 5 is:

4. *To what extent is driving in a driving simulator affected by navigation system and mobile phone use?*

Although it is relatively easy to perform a study in a driving simulator, it is always debatable to what extent the results compare to real road driving. Therefore, Chapter 6 compares two datasets, one from the driving simulator and one from a specific road test, to compare several conditions that were designed to be as similar as possible. The research questions involved in this study are to what extent the driving simulator study results are valid in the relative sense (would the research findings point in the same direction, and to what extent do they have a similar amplitude?) and, regarding driving speed in the absolute sense (are the exact numbers comparable?). The main question in this chapter is:

5. *To what extent are results from a driving simulator study comparable to results from the real road?*

After discussing the results from an experimental setup, in which effects were isolated (Chapter 5 and 6), Chapter 7 describes the results of the naturalistic driving study part of this thesis. The effects of distracting tasks found on driving performance may decrease when drivers only perform those distracting tasks when the driving task allows this. For instance, it may be argued that programming new destinations only during traffic jams and red light stops, will not increase crash risk, even more so when compared to doing so while driving at 50 km/h in an urban area. Therefore, behavioural patterns are studied in order to attain more insight how drivers perform secondary tasks in real driving. The naturalistic driving study regards the results of the same drivers that participated in the driving simulator and field test study, asking:

6. *How do drivers use their navigation systems in real driving?*

More specifically, the following research questions are answered:

- On what kinds of trips, how often, when and for how long do drivers use navigation systems?
- What are the effects on speed behaviour of driving with a navigation system?

Chapter 8 reflects on the research questions and the responses provided and answers the main thesis' question. Furthermore, this thesis' limitations are discussed. Finally, recommendations for policymakers and research are provided.

1.4. Relationship to other research: The Interaction project

The naturalistic driving observations as well as the field test were carried out in the framework of a European project called Interaction, funded by the European Commission 7th Framework Programme (FP7). This project focused on understanding driver interactions with in-vehicle technologies. The Interaction consortium consisted of partners from the United Kingdom, Finland, Czech, Spain, Portugal, France, Austria and the Netherlands. In this thesis, the data gathered in the Netherlands by SWOV (the Dutch institute for road safety research) were made available for additional analyses performed for this thesis. The participants in the Dutch part of the Interaction project were politely requested to also participate in the driving simulator research.

2. What is distracted driving?

2.1. Introduction

This chapter provides an overview of several definitions of distracted driving. It describes tasks related to using mobile phones and navigation systems while driving, and how these distract drivers. Finally, it explains a selection of driving-related theories, concepts and classifications that identify components of a driver distraction framework.

2.2. What is driver distraction?

One way to look at driver safety is as the end result of interactions between road users, leading either to undisturbed passages (driver is not influenced by another driver), conflicts (drivers are on a collision course), or accidents (vehicles collide), see Figure 2.1 (adapted from Hydén, 1987) . Since actual accidents are a relatively rare occurrence, they have limited value as an indicator of safety. It is more useful to observe how well drivers perform their driving task. Drivers who are distracted by navigation systems and/or mobile phones are generally less able to attend to all relevant events and dynamics within traffic. This may increase the level of danger they face (see the coloured adjustment in Figure 2.1). To put Figure 2.1 in perspective, driver distraction and inattention has been shown to influence almost 70% of crashes and near-crashes (Dingus et al., 2016).

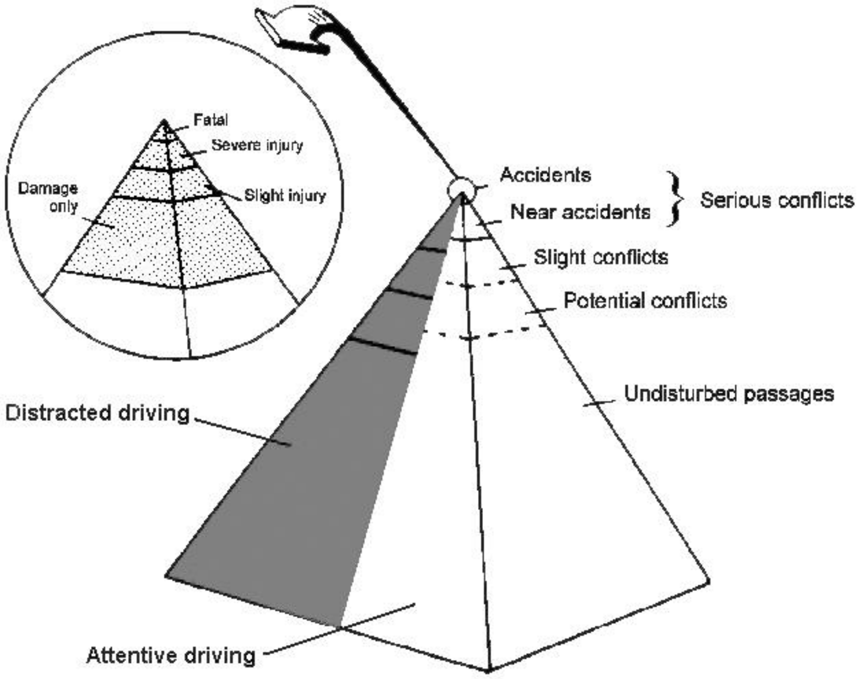

Figure 2.1: Interaction between road users adjusted to compare attentive vs. distracted driving (in grey) (adapted from (Hydén, 1987, p27). Note that this figure is not intended to indicate any relationship between numbers of accidents.

There have been many attempts over the past years to define the term 'distraction'. One definition put forward by a group of scientific experts that has gained currency is: *"the diversion of attention away from activities required for safe driving due to some event, activity, object or person, within or outside the vehicle"* (Basacik & Stevens, 2008). Lee, Young & Regan (2009) advanced a similar, more compact definition: *"A diversion of attention away from activities critical for safe driving toward a competing activity"*. In a European-American collaboration, Engström et al. (2013) developed a taxonomy that the Transport Research Laboratory (TRL), the Netherlands Organisation for Applied Scientific Research (TNO) and RAPP-Trans (2015) then used to further define distraction and the related concept of (in)attention:

- Driver inattention: occurs when the driver's allocation of resources to activities does not match the demands of the activities required for the control of safety margins (Engström et al., 2013, p38).
- Driver distraction: occurs when the driver allocates resources to a non-safety critical activity while the resources allocated to activities critical for safe driving do not match the demands of these activities (Engström et al., 2013, p35).
- Activities critical for safe driving: those activities required for the control of safety margins (Engström et al., 2013, p17).

This implies that tasks that are secondary to driving still play an important role in road safety. Enormous technological developments have seen drivers bring more and more portable devices into their vehicles, in addition to the increasing number of technologies that are built into the vehicles themselves.

There are a range of reasons why people use devices such as smartphones while driving, including economic reasons (e.g. making an efficient use of time) and sheer comfort (Brookhuis, De Waard, & Janssen, 2001). For instance, when time is scare it becomes very appealing to turn your car into a mobile office and use a smartphone while you drive. Likewise, using a navigation system may help to avoid a traffic jam and reduce your travel time by ten valuable minutes. Accessing route guidance advice also removes the need to actively think about which way to go, thereby saving cognitive resources. In a similar vein, making a phone call may relieve stress about a situation, saving energy and providing comfort.

Current phones and navigation systems are the most common screen devices that people bring into their vehicles (‘nomadic devices’), which is the reason why these are the focus of this study. There is some overlap in functionality between these two types of devices, since smartphones can be equipped with route guidance applications and mounted to the front window like a navigation system. Conversely, some navigation systems have Bluetooth and can be used as a hands-free phone device.

Efficiency – one of the key motives of device use in vehicles – may be regarded from both a driver and a road traffic perspective. Devices enable drivers to make efficient use of time by suggesting a shorter route or one that permits higher speeds, but also by enabling them to work while driving by talking on the phone. Efficient driving from a road traffic perspective is characterised by good speed adaptation and less traffic on the road, which can also reduce traffic jams. Societal gains from this kind of efficiency include increased travel time reliability due to more predictable behaviour, which is important for both the passenger and freight transport sectors (Warffemius, 2013). Moreover, since 1997, value of time (how highly people value an activity) spent on car travel has decreased by 16%. Warffemius (2013) suggests that this is due to the fact that car travel time can now also be spent working on smartphones.

This thesis focuses on the road safety and efficiency effects of the most common nomadic devices, mobile phones and navigation systems.

2.2.1. Mobile phones

Mobile phones have been in common usage for the past two to three decades. Since the arrival of the first iPhone in 2007, smartphones (i.e. mobile phones with extended computer functionality) have become extremely popular and sales are still increasing (GfK, 2016a). In this thesis, we will use the British English term *mobile phone* as opposed to *cell phone* in American English. There are important differences between current smartphones and older mobile phones; the most notable for our purposes is the user interface. The old 'dumb phones' or 'bricks' had buttons, whereas smartphones usually have a touchscreen. Touchscreens may not provide audio or tactile feedback confirming which buttons were pressed, which may increase visual distraction since the user may need to glance again to verify whether they pressed the intended button successfully. Furthermore, smartphones are equipped with numerous applications ('apps') over and above texting and calling, such as Facebook, e-mail, 'live' traffic information, and navigation apps. These may be responsible for peoples' increased urge to check and use their phone while driving.

Mobile phones are subject to extremely rapid change. Since entering common usage 20 to 30 years ago, texting via mobile phones soared in popularity in the 20th century (Arthur, 2012). The subsequent addition of features such as e-mail became particularly popular and widespread after the introduction of the iPhone. Since that time, touchscreens have become standard issue (cf. International Data Corporation, 2013), with smartphone sales accounting for up to 83% of total mobile phone sales in the Netherlands (Richards, 2015).
These days, the majority of people in Western countries own a mobile phone and have used it when driving. In most of these countries, (partial) laws have been passed against certain types or all phone use while driving (Burnett & Lee, 2005). For example, some countries require drivers to use 'handsfree' technology to talk on the phone. In the Netherlands, and in many other countries, drivers are not permitted to hold a mobile phone in their hand while driving, including dialling a number.

Mobile phones can be used in various ways while driving. The principle tasks that we address here are operating (e.g. texting, WhatsApp, gaming and number dialling) and conversing (handheld or handsfree). Other tasks not specifically covered in this thesis include dispatching for professional purposes, checking the time and streaming videos.

2.2.2. Navigation systems

Navigation systems are also referred to as route guidance systems and sometimes GPS (since they receive data from the Global Positioning System). They have become widespread over the last decade; in the Netherlands an estimated 91% of all households own some sort of navigation system, and two thirds of all households own a pnd in 2015 (KiM, 2015). Navigation systems became particularly useful and correspondingly popular after the turn of the century following the United States Government's decision to disable Selective Availability of the GPS signal, a deterioration generated by the US army (Ogle, Guensler, Bachman, Koutsak, & Wolf, 2002).

Navigation systems are designed to navigate drivers turn-by-turn to an unknown destination using audio or visual directions and often displaying the route on an animated map on a small screen. Navigation systems may be installed in vehicles by the OEM (Original Equipment Manufacturer i.e. the system is produced elsewhere but is branded with the automotive company logo) or 'aftermarket', i.e. by the car owner, or they can be brought into the vehicle each trip (i.e. a nomadic device). Smartphones with navigation software are also increasingly popular. Navigation systems are intended to provide a convenient alternative to a paper map while driving. They enable drivers to take the shortest (least distance) or fastest (fewest interruptions, fastest permitted speeds) route to a destination. Many navigation systems also provide information on traffic congestion and alternative routes, locate points of interest (e.g. petrol station, hotel, city centre) and even play music.

Navigation systems perform two main tasks: operating (programming destinations, selecting routes, setting speaker volume, etc.) and providing turn-by-turn route guidance. Drivers can operate navigation systems in several ways: joystick, push button, touchscreen keyboard or speech recognition. Route guidance instructions can be provided either visually or aurally, and some navigation system manufacturers have even explored tactile guidance (Van Erp & Van Veen, 2004; Kern, Marshall, Hornecker, Rogers, & Schmidt, 2009).

Based on Japanese accident data, entering destinations into navigation systems has been estimated to be responsible for a quarter up to a third of navigation system-related accidents (Oei, 2003). Although some manufacturers disable the ability for drivers to enter data or destinations into the navigation system while driving and most systems warn against it, nevertheless it is generally possible. However, using a navigation system may enable drivers to take shorter routes and decrease their exposure to traffic, which may be regarded as safer.

2.2.3. How do mobile phones and navigation systems distract drivers?

There are various categories of distraction that can have different effects on driving when using mobile phones and performing conversation tasks: visual, manual, cognitive and auditory (see e.g. Ranney, Mazzae, Garrott, & Goodman, 2000). Visual distractions, when drivers are not monitoring traffic, include looking at a phone or watching a bird next to the road, for example. Manual (or biomechanical) distractions include grabbing an item from the glove compartment. Examples of cognitive distraction include phone conversations and daydreaming. Auditory distractions may be caused by alerts such as an empty fuel tank warning or Facebook notifications that are difficult to ignore. These categories are closely connected. An empty fuel tank warning may prompt a driver to glance at the dashboard to identify the source and meaning of the sound. The types of distraction created by mobile phone or navigation system operation and tasks are set out in Table 2.1. This table demonstrates that, while devices and tasks create different visual, manual and auditory distractions, they all create a cognitive distraction. It also illustrates similarities in operating both types of device.

Table 2.1: Categories of distraction created by mobile phones and navigation systems.

Device	**Tasks**	**Examples**	**Distraction category (x = definite, (x) = possible)**			
			Visual	Cognitive	Manual	Auditory
Mobile phone	*Operation*	Texting, e-mail, games	x	x	x	
		Answering a call	(x)		x	x
	Conversation	Handheld		x	x	x
		Handsfree		x		x
Navigation system	*Operation*	Alternative route selection, destination entry	x	x	x	
		Volume change	x		x	x
	Use	Following route guidance	(x)	x		(x)
		Speed warnings, speed camera warnings	(x)	x		(x)

A discussion of methods for studying the effects of the different tasks identified in Table 2.1 and of the literature pertaining to both safety and efficiency of driving is presented in Chapter 3. The next section first relates these tasks to the driving task.

2.3. Describing the driving task

The secondary tasks identified in Table 2.1 distract drivers from their primary task of driving. The driving task itself has changed markedly over the past century and, during this time, various models, theories and classifications have been proposed to describe it.

An important distinction can be drawn between driver *behaviour* and driver *performance*, which Evans (2004) defines as: "*Driver behaviour is what the driver DOES do; driver performance is what the driver CAN do*". Driver behaviour refers to what the driver actually does where and when, whereas driver performance refers to how well the driver is able to deal with the various aspects of the driving task in terms of their knowledge, skill, perceptual and cognitive abilities (Evans, 2004).

Although many attempts have been made in the literature to describe the driving task, for instance, Vaa (2001), Summala (2005), Ranney (1994) and Evans (1991) note that as of yet there is no 'Grand Unified Theory'. This is primarily due to the lack of understanding of how drivers actually think and feel based on psychological and neurobiological evidence. The models that do exist in this regard are incomplete and only address certain aspects of the driving task (Vaa, 2001). In an overview of driving behaviour models, Ranney (1994) attributes the absence of a complete model to the complex nature of driving and to the fact that past research has focused more on hazardous driving behaviour than on everyday safe driving. The same observation is echoed by Hancock, Mouloua & Senders (2009), who suggest that accidents are too unpredictable to be able to reliably model which aspects of drivers' behaviour cause them. These behavioural aspects are extreme – mainly at the 'tail' of the overall distribution. Hancock, Mouloua & Senders (2009) argue that, while zero accidents should be the ultimate goal of driver safety research, there would be more use in a study focusing on "*a marriage of ecological and quantitative behavioural science*".

Nevertheless, there are a number of older and more recent models and theories that attempt to understand and explain driving behaviour. In this thesis, in addition to further defining the driving task, we aimed to address the questions: how do driver factors influence driving and why do drivers drive the way they do? In selecting which models and theories to consider in this thesis, we applied the following criteria:

- provides insight into cognitive, visual and visual-manual driver distraction;
- provides a conceptual/psychological framework to apply to experienced drivers;
- helps define the driving task or answer our other research questions.

We reviewed the models and theories selected via this process, along with others to flesh out the broader context, and developed a framework to answer our research questions. Our attempts to classify and describe these models and theories were guided by the work of Michon (1985) and Ranney (1994).

2.3.1. General driver behaviour models

One very early paper on driving behaviour is Gibson & Crooks' '*Theoretical field-analysis of automobile-driving*' (1938). The authors defined the concept of the 'field of safe travel' – a tongue-shaped area in front of the vehicle in which the trajectories along which the vehicle can safely travel are visible to the driver. In order to drive safely, the driver must strive to continually steer the vehicle in the middle of this field. The visible or invisible borders of the field of safe travel may be defined by natural boundaries (e.g. walls, trees, other vehicles, rain or fog), reduced handling at higher speeds (e.g. skidding or rolling), moving or stationary obstacles, potential obstacles (e.g. around a blind corner), and legal constraints (see Figure 2.2). Gibson & Crooks state that as drivers become more experienced, their ability to recognise and react to hazards improves and makes them safer drivers.

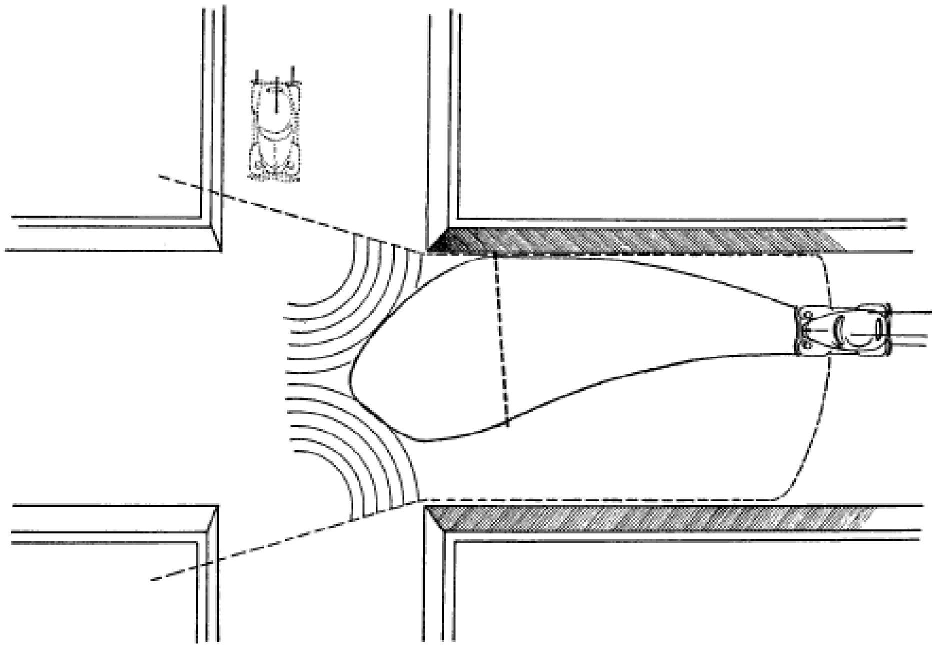

Figure 2.2: "A blind corner constituting a barrier to vision and its effect on the field of safe travel. At this moment the clearance-lines of potential obstacles cut off the field" (Gibson & Crooks, 1938).

Hancock et al. (2009) drew a connection between the safe field of travel and the concept of situation awareness, which refers to the extent to which drivers are aware of what is happening in their surroundings (Endsley, 2000). There are three levels of situational awareness. The first level involves perception of cues, e.g. drivers may be unable to see around a blind corner or may look in the wrong direction. The second level concerns comprehension, i.e. how drivers process those cues. An example of this is the looked-but-failed-to-see phenomenon (Hills, 1980), in which the driver did look in the direction of the danger, but was not able to process the information sufficiently to avoid a crash, since it may be beyond their visual or perceptive capabilities. The third level of situation awareness involves projection, i.e. forecasting future stations, which applies particularly to experienced drivers for whom many aspects of the driving task become automatic. It is widely accepted that automaticity leads to fewer errors (Reason, 1990) and faster, more accurate performance of the driving task, while drivers may not even be consciously aware of events that have taken place and their own reactions (Shiffrin & Schneider, 1977). The latter an example of *highway hypnosis* (Karrer, Briest, Vöhringer-Kuhnt, T., & Schleicher, 2005) which occurs when, after a period of monotonous driving, drivers suddenly become aware that they have no memory of a certain stretch of time or events within it. Automaticity is important in relation to driver distraction since driving automatically requires little attention (Gibson & Crooks, 1938; Shiffrin & Schneider, 1977) and enables the driver to direct attentional resources elsewhere.

Michon (1985) describes the driving task as a problem-solving task that is performed on strategic, tactical and operational levels. At the strategic level, the driver plans a trip in terms of trip goals, route, and cost/risk analysis. This includes choosing whether or not to use a navigation system, when to enter the destination, and whether to turn off a mobile phone before starting to drive. At the tactical level, the driver manoeuvres the vehicle to avoid obstacles longitudinally as well as laterally, to overtake other vehicles and to turn corners to fulfil the goals defined at the strategic level. This could include phoning and entering a destination while driving. At the operational level, the vehicle is controlled by shifting gears, braking, steering, etc. These operations may be influenced by tactical decisions, e.g. braking before a corner, and are often performed automatically.

Rasmussen's Skill-Rule-Knowledge model (Rasmussen, Duncan, & Leplat, 1988) follows similar lines (Wickens & Holland, 2000) and defines three levels of behaviour. Hale et al. (1990) elegantly combined the Michon and Rasmussen models into a matrix of exemplary tasks (see Table 2.2). They hypothesise that drivers operating at rule- or skill-based levels are more effective (i.e. more homogenous and predictable) than drivers operating at knowledge-based levels.

Table 2.2: Matrix of driving tasks (Hale et al., 1990).

	Planning	**Manoeuvre**	**Control**
Knowledge	Navigating in strange town	Controlling a skid on icy roads	Learner on first lesson
Rule	Choice between familiar routes	Passing other cars	Driving an unfamiliar car
Skill	Home/work travel	Negotiating familiar junctions	Road holding round corners

People may fail to act safely when driving for several reasons. Reason (1990) draws a distinction between *errors* and *violations*; violations are deliberate deviations from safe practice, whereas errors are 'slips' or 'lapses' (due to inattention) and mistakes (the consequence of a poor choice). Slips may occur when you perform a largely automatic task in familiar surroundings leading to absent-mindedness, and suddenly become aware that you committed an error e.g. while talking on the phone. Lapses relate to brief instances of memory failure (e.g. where was I going?). Mistakes may result from planning failure, often at the knowledge or rule level, when you have not achieved your objectives (e.g. you took the wrong way because the map was upside down). Clearly some distractions are also violations (e.g. texting). Figure 2.3 provides an overview of Reason's (1990) error taxonomy.

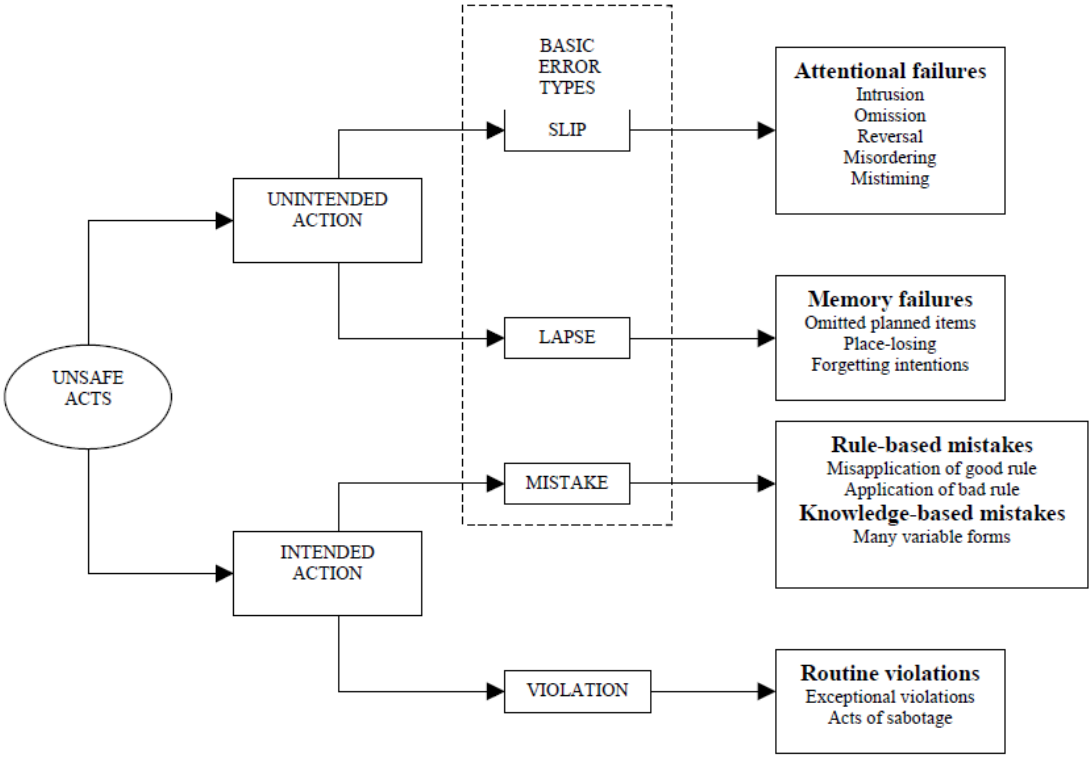

Figure 2.3: Error taxonomy (Reason, 1990 – sourced from Salmon, Regan & Johnston, (2005).

Reason argues that it takes multiple failures on multiple levels, often by multiple parties, to cause a road crash, illustrated in the 'Swiss cheese' model. Wegman & Aarts (2006, p31), depict all the required factors for a road crash as slices of Swiss cheese, and the holes in the slices as the chance of a crash occurring. The crash can only happen if the slices line up in such a way that the holes overlap. This implies that road safety requires drivers to pay attention to all slices and that safety may be improved by closing the holes.

These descriptive classification models have limited value as a means of predicting road safety effects (Salmon, Lenné, Stanton, Jenkins, & Walker, 2010). Nevertheless, they do clearly visualise the multiple levels and components of thinking, doing and erring, which helps to put driving behaviour into perspective and identify where driver distraction fits in.

2.3.2. How: Driver factors

A large body of research has been conducted into performing two tasks simultaneously. As early as 1890, William James recognised that, as a principle of psychology, humans are not easily able to perform two (or more) perception-requiring processes at the same time, unless the processes are highly *habitual* (cf. automaticity in later models). Kahneman (1973) similarly noted that people tend to break off conversations while driving when the demands of the driving activity become critical. These observations by James and Kahneman are important predecessors of the Multiple Resource Theory (MRT; Wickens, 2002; Wickens, 2008), which distinguishes four dimensions within which information processing resources vary, namely:

1. Stages of processing: perception vs. cognition (e.g. working memory) vs. response.
2. Codes of processing: verbal vs. spatial control.
3. Modalities: auditory vs. visual.
4. Visual processing channels: focal vs. ambient. This dimension was a later addition to the theory to help identify what drivers can see in their peripheral vision. This is where drivers perceive orientation and movement in particular (Wickens, 2008).

Wickens' model posits that driving performance is least hindered by two simultaneous tasks when they are performed at different levels within these dimensions. It predicts that people can time-share the driving task, which is primarily visual and spatial, reasonably well with speaking, which is auditory and language based.

The demand which two specific simultaneous tasks place on a driver's resources plays an important role. Although a driver may have the capacity to perform two particular tasks well separately, they may not be able to perform them simultaneously. The driver is distracted from the primary driving task due to their limited information processing capacity or high mental workload (De Waard, 1996; Wickens & Holland, 2000). De Waard's (1996) model (see Figure 2.4) illustrates the complex interaction between mental workload and task performance, and demonstrates that effort may compensate for high workload up to a certain level of performance. It is possible to compensate for a distracting secondary task by increasing effort, but only to a certain level, after which performance deteriorates.

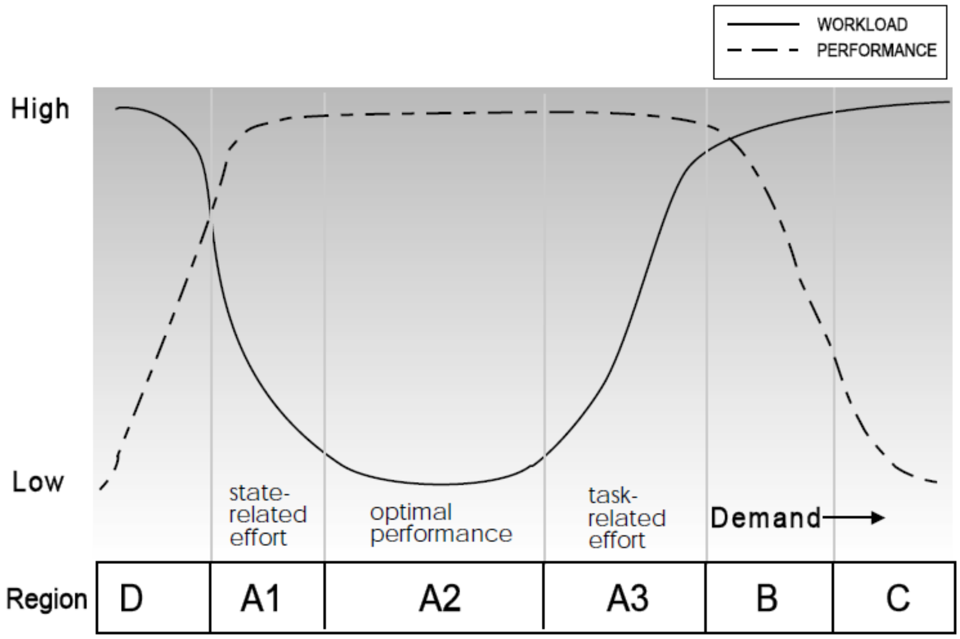

Figure 2.4: Relation between workload and performance (De Waard, 1996).

Another useful model for understanding driver distraction is the *SEEV* (salience, effort, expectancy, value) model (Wickens & Horrey, 2009), which was originally developed for airplane pilots (Wickens, Dixon, & Chang, 2003). This model presupposes four factors that are involved in acquiring visual information. The *salience* factor pertains to how well an event grabs a driver's attention, e.g. with loud noises or bright lights. *Effort* relates to how much effort it takes the driver to switch their attention to the new event. For example, when two visual tasks are spatially far apart, it either requires more effort to perform them, or more errors are committed or more time is taken. *Expectancy* refers to top-down attention, i.e. drivers know what to expect and consequently focus on that area. *Value, or expected value* denotes how important a source of information is and is related to expectancy. The SEEV model may be used to predict the target of a driver's attention, on the basis of the factors of value and expectancy.

Another major factor that influences driving performance is task difficulty, which refers to the demand a given task places on the driver. Experience decreases task difficulty, as do well-applied strategies and optimal driver state, by determining how much of the driver's processing resources should be allocated to the task. Task difficulty increases with task complexity. Task difficulty plays a central role in the Task-Capability Interface (TCI) model (Fuller, 2005). In this model (see Figure 2.5), task difficulty might be inferred by comparing capability and task demands. Capability refers to how well a driver is able to perform the driving task. A task is easy if a driver's capability exceeds the task demands, difficult if capability is equal to the demands, and too difficult where the demands exceed capability. Task demands depend on factors such as road context, vehicle, speed, and other road users, which together make up the objective complexity of the task. The driver's capability may depend on their experience and training, which set the upper limit of their level of competence. However, the driver's capability may be reduced by fatigue, drugs, stress, distraction (Fuller, 2000) and effort (Fuller, 2005). Drivers can influence task demand – and to a certain degree capability –on a strategic, tactical and operational level (Fuller, 2005).

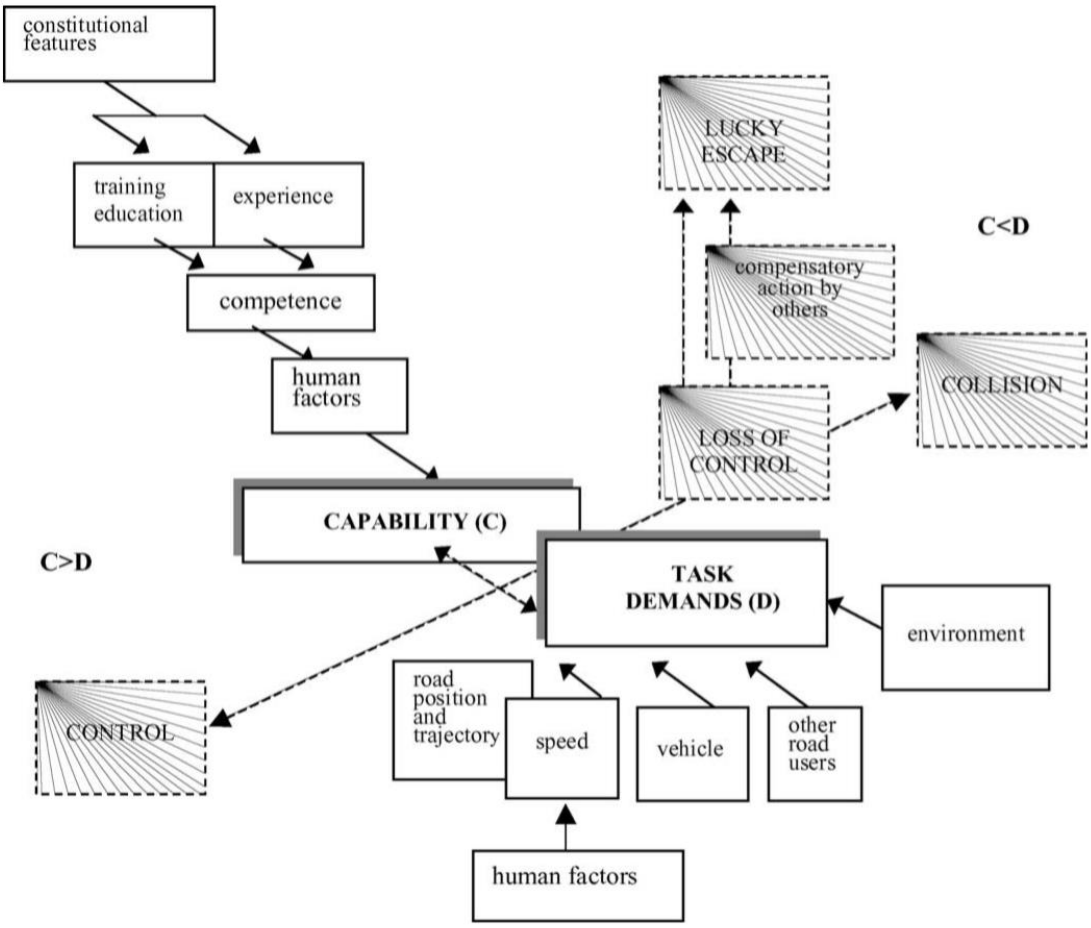

Figure 2.5: Task-Capability Interface model (Fuller, 2005).

When the TCI model is applied to driver distraction, we can infer that distraction decreases capability. The driver can compensate for this by decreasing speed and thereby task demands. Or, the combined tasks may become too difficult for the driver to perform and, as a result, the driver experiences loss of control with all the associated consequences. Furthermore, following an instance of high workload, it may take some time before the driver recovers to a state of feeling under low demand – also known as 'hysteresis' (Morgan, 2008). The overlap between distraction and workload, on the other hand, is more complex, since drivers might use distracting activities to prevent themselves from falling asleep due to low workload (Sheridan, 2004). Lansdown et al. (2015) proposed expanding the TCI model with a further set of perspectives to create a systemic driver distraction model (see Figure 2.6). This model tracks driver, vehicle, primary and non-primary tasks, and environmental factors, and the interactions between them through time. These factors are all subject to their own traits (stable) and states (variable through time). Task demands are influenced by all these factors at different points in time, not only the driving task and any secondary task.

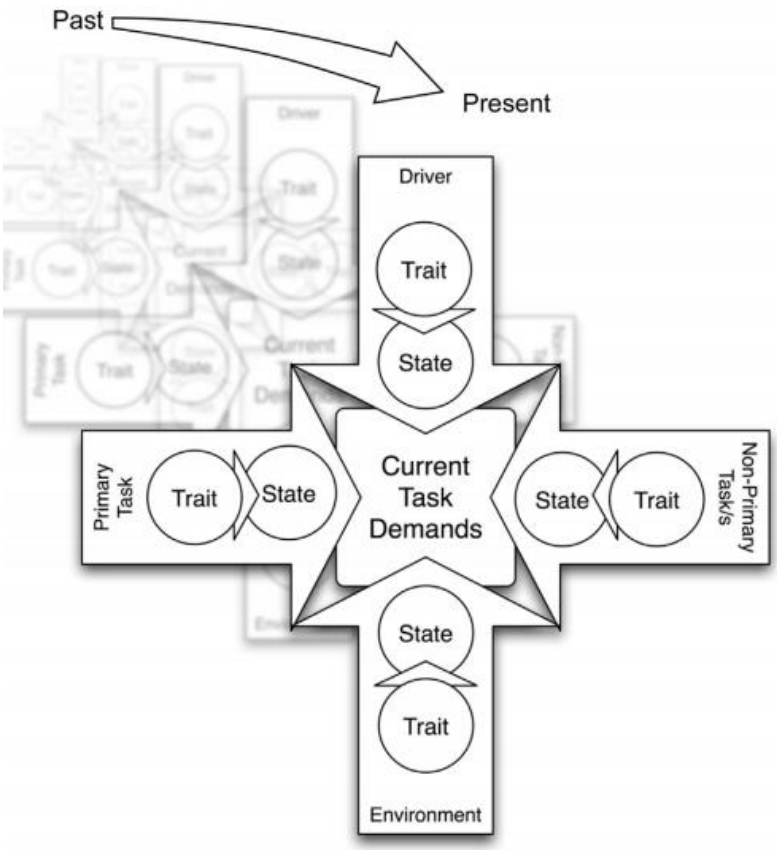

Figure 2.6: Systemic driver task demand model (Lansdown et al., 2015).

Interestingly, on the basis of literature reviews and original research articles regarding phone use while driving (using the 'grounded theory approach'), Parnell, Stanton & Plant (2016) identified the main factors of distraction and how these interrelate to each other. They developed the PARRC (priority, adapt, resource, regulate, conflict) model, which accounts for the mechanisms of distraction (from Wickens' MRT model, 2002), the environment, Fuller's notion of capability versus demand, and how drivers prioritise their goals. The PARRC model is useful for case study analysis to help understand how systemic factors impact on distracted driving and which stakeholders are involved (e.g. driver, policy makers, automobile and in-vehicle device manufacturers). It demonstrates that the driver's presumed ultimate goal (i.e. arriving safely at their destination) is not necessarily prioritised in all situations.

The driver (attention) resources theories described above are complemented by Lee's (2014) reflections on distraction dynamics. Distraction dynamics involve how drivers engage with and disengage from distracting tasks and the driving task. Lee's line of thinking is about how managing interruptions to the driving task contributes to distraction in terms of timing, switching and prioritisation. This alternative viewpoint supports the view that secondary tasks can help drivers disengage from drowsy mind-wandering and re-engage with the driving task (Lee, 2014).

2.3.3. Why: Driver motivations

People's main motivation to drive is usually to go somewhere in a safe and comfortable fashion. However, different drivers make different choices while driving, e.g. car make and model, speed, and using in-vehicle technology. Gibson & Crooks assert that a driver "*does all these things because he has learned to do them, not because he is frightened into a continual state of strained attention*".

Taylor (1964) demonstrated that drivers accept a certain level of risk (or anxiety), measuring subjective risk by means of galvanic skin responses to small hazards. He theorised that increasing subjective risk may lead drivers to increase their concentration levels and give more attention to hazards, thus decreasing objective risk in order to reduce their level of anxiety.

This led Näätänen & Summala (1974) and later Summala (Summala, 1988) to advance their zero-risk model, in which they claimed that drivers aim to keep subjective risk as low as possible. Therefore, increased subjective risk should indeed lead to safer driving, as drivers adopt strategies to decrease their risk.

This claim was further developed in the Risk Homeostasis Theory (Wilde, 1982, 1988, 1994), which essentially argues that drivers attempt to maintain a constant target level of subjective risk in relation to statistical risk. Over time, this should mean that drivers increase subjective risk in response to safety measures. Although this model was heavily criticised for incorporating statistical risk (McKenna, 1988; Evans, 1991, p299), the Risk Homeostasis Theory made a useful contribution to introducing the homeostasis mechanism (cf. Cnossen, Rothengatter, & Meijman, 2000) and the term 'behavioural adaptation', which refers to the phenomenon of drivers adapting their behaviour to circumstances, including safety measures (Young & Regan, 2013).

In response to the zero risk model and the Risk Homeostasis Theory, Fuller (1984) conducted a behavioural analysis of driving and developed a threat-avoidance model based less on subjective risk (i.e. the subjective probability of having an accident) and more on the likelihood of a *potential* threat. Fuller also argued that driver behaviour is not motivated by maintaining a certain level of risk, but by avoiding threats in a more general sense and trying to stay within certain margins of safety (Fuller, 1984, 2005). He then developed his Task-Capability Interface model (Fuller, 2000, 2005) which posits that drivers strive to maintain a certain level of task difficulty rather than risk.

Other authors have noted that risk alone cannot account for all driver behaviour (Evans, 1991), e.g. pleasure can motivate speed choice (Rothengatter, 1988). Drivers may also seek a sense of excitement or relaxation, or be fixated on vigilance (Vaa, 2001).

Vaa (2007) later adapted this into his Risk Monitor Model, which also accounts for a driver's conscious experience of their body's emotional response to events. This is based on Damasio's (1994) somatic marker theory which contends that bodily reactions, such as sweaty hands and muscular contractions, influence our decisions. The Risk Monitor Model describes driving as a continuously-changing environment in which the driver aims to achieve an optimal feeling (Vaa, 2007), including level of risk, arousal, joy and relaxation.

Fuller (2011) notes that some of these feelings extend beyond driving safety motivation. He went on to propose the Risk Allostasis Theory (RAT), which specifies the task difficulty component of the TCI model, focusing on safety. The theory was based on evidence that perceived task difficulty is related to feelings of risk (see Mesken, Hagenzieker, Rothengatter, & De Waard, 2007; Stradling et al., 2008; Fuller, 2011), and predicted that drivers keep their feelings of risk within certain limits by attuning their behaviour.

Threshold theories suggest that task difficulty and feelings of risk ratings remain stable until the driver reaches a certain speed, specifically around 50 km/h on residential roads and 110 km/h on the motorway (Lewis-Evans, De Waard, & Brookhuis, 2011). The theories and models described above could potentially be updated to account for this phenomenon (Lewis-Evans, De Waard, & Brookhuis, 2010).

It is unlikely that drivers are motivated exclusively by fear. Hancock et al. (2009) distinguish two forms of distraction: the first is dependent on the driver's social role which distracts their attention from the primary driving task e.g. a parent who turns around to reseat an unrestrained child, or a business person making a phone call. The second form of distraction is the driver simply not focusing on the right aspect of the driving task at the right moment.

From the discussion above, it seems plausible that driver distraction is sometimes planned when the driver is experiencing low feelings of risk. In view of the threshold effects, this may indicate that drivers are more likely to increase task demands by engaging in distracting activities when traveling at relatively low speeds, and perhaps even more so when stationary. On the other hand, drivers are also confronted with unplanned distractions, such as incoming phone calls or navigation system warnings, which may be hard to ignore.

2.4. Implications of theories of driver behaviour for distraction

Young, Regan, & Lee (2009a) put together an overview of various factors in distraction effects (see Figure 2.7; page 34). This clearly demonstrates that distraction can be dealt with on many levels of driving task performance, and the list is hardly exhaustive. It is useful to note that drivers' awareness of what is going on around them may deteriorate when they are distracted. They may miss events, forget where they were going, and be less able to predict what might happen. The automatic nature of many aspects of the driving task supports the assertion that experienced drivers could be less hampered by distracting activities.

This overview underlines the value of describing driver behaviour at multiple levels. Effects could be described in terms of simple operational effects, or in terms of higher level distractions as well, relating performance to timing or planning to avoid distracting activities. Similarly, the decision to describe an error as a lapse or a mistake may have important implications for recommendations to change certain practices. Having a conversation on a mobile phone may distract drivers (cognitive, auditory, perhaps manual) in a markedly different way to texting (visual, manual, perhaps cognitive). Texting is similar in turn to operating a navigation system (visual, biomechanical) but is dissimilar to following route guidance instructions. It also seems useful to take account of driver dynamics, i.e. measuring how much effort it takes drivers to engage with and disengage from tasks, and how both engaging and disengaging can have positive and negative consequences. The Multiple Resource Theory provides interesting opportunities for predicting whether some distractions have worse effects on driving performance because they are similar or dissimilar to the visual-spatial driving task. The SEEV model draws key inferences regarding how drivers process the visual information they receive.

The motivational models developed to date demonstrate that drivers can be motivated to some extent by both fear and risk, but also that they are capable of regulating those feelings. The demands of the driving task are considerably influenced by secondary tasks; therefore drivers may tend to slow down in order to decrease the difficulty of the simultaneous tasks.

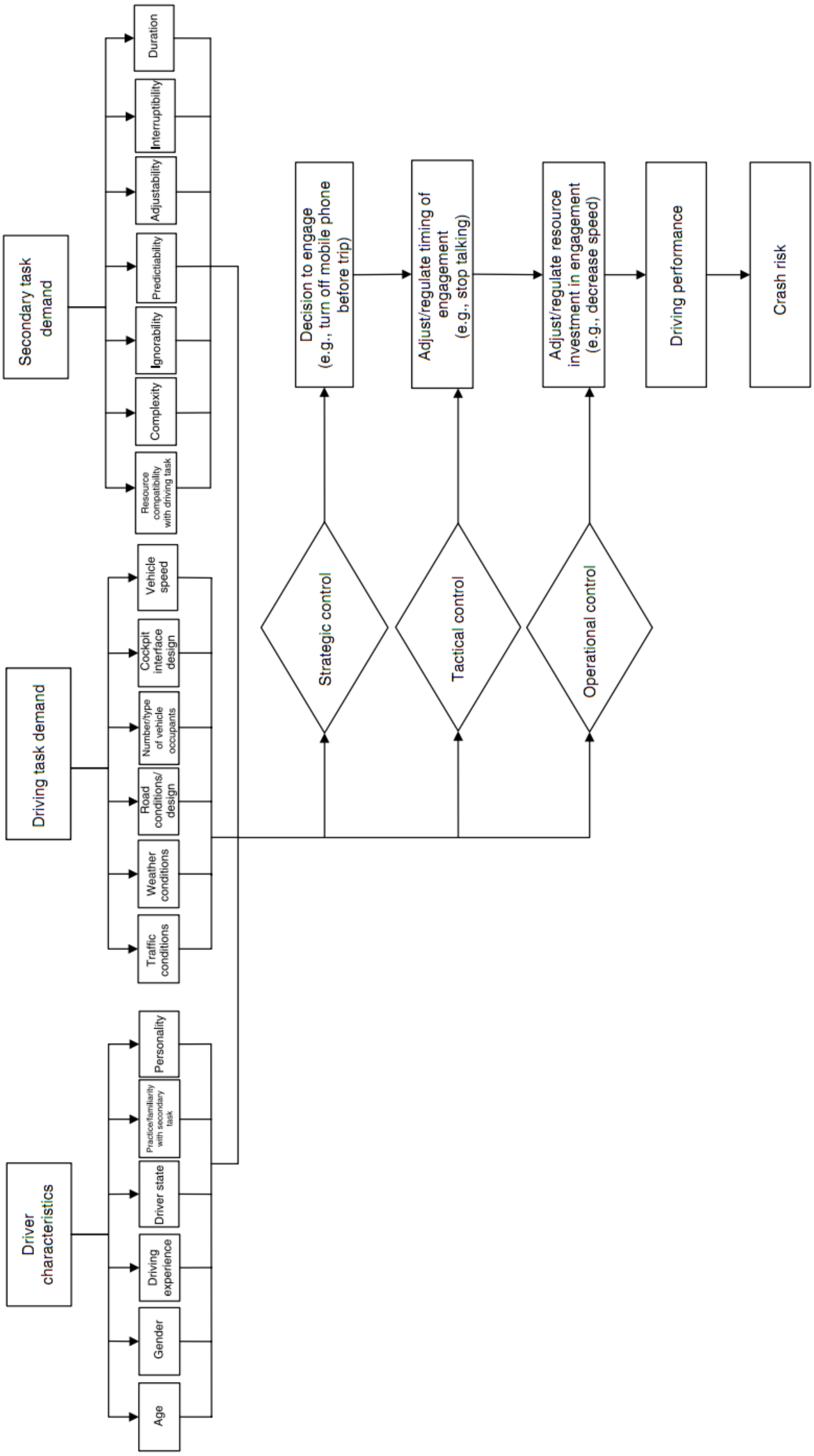

Figure 2.7: Factors in the effects of distraction on driving performance (Young et al., 2009a).

2.5. Conclusions

In this chapter, we have set out a framework of definitions of driver distraction, tasks under investigation, and underlying driving theories for this thesis. The models and theories relating to driving described in this chapter are fairly diverse, ranging from simple taxonomies to addressing vast numbers of possible factors that influence driving. Naturally we have only been able to review a selection of models and theories from the literature. We have not covered mathematical models, nor factors such as age and gender differences. It is striking that, despite the enormous number of models available, broad gaps remain in our understanding of how distraction works and why.

It is clear that the driving task is predicated on guiding the vehicle to a destination without any collisions. It involves a set of behaviours that at first attempts demand every ounce of beginner drivers' attention, but that quickly becomes increasingly automatic as the driver gains experience, requiring less attention and leading to faster reaction times and fewer errors. This may indicate that distraction is related to the limitations of drivers' attentional resources, since it does not immediately result in decreased task performance. Engaging in a distracting task can even prevent drivers from falling asleep. Yet when traffic demands are higher, which may occur at any time, engaging with distracting tasks may quickly lead to overload, decreasing the driver's capability and driving performance. One strategy drivers use to reduce demand on their attentional resources in such cases is slowing down, but this may not always be possible or sufficient.

Furthermore, the driving task is heavily dependent on the driver's visual performance, and drivers can only properly visually attend to one thing at a time. They cannot, for example, check a screen and keep a firm eye on the road simultaneously.

Lastly, in our view it is insufficient to focus exclusively on the driver and the driving task. Both exist within a complex system that includes policy makers, road maintenance workers, road designers, vehicle manufacturers, manufacturers of distracting devices, etc. which can all distract drivers (see Parnell, Stanton & Plant, 2016).

This chapter attempted to describe the rich tapestry of factors, levels and interactions that make up a task performed by a large number of people every day. In the following chapter, a review of empirical studies is presented on the effects of mobile phone and navigation system use on road safety and efficiency to bring these theories and taxonomies to life.

3. How have usage of mobile phones and navigation systems and their effects on driving been studied to date?

3.1. Introduction: Methods applied[1]

In this chapter, the various data collection methods (3.2) and measures (3.3) are described that have been employed to investigate the effects of navigation systems and mobile phones on driving and driving safety in order to determine the soundest approach. Together with Chapter 2, this chapter provides a solid base for interpreting the results of our literature review, which are set out in Chapter 4.

3.2. Data collection methods

3.2.1. Lab testing

Driving consists of many different subtasks (see also 3.3) which can be tested separately in a laboratory setting. For instance, people are tested on their reaction to an unexpected event when affected by a distractor such as adding a simple secondary computer task. The major advantage of such an approach is the considerable experimental control and the ability to study causal effects under proper experimental conditions. Furthermore, lab testing is generally safe and often relatively cheap as it requires relatively few resources.

However, the principle drawback of lab testing is that often only a few subtasks of the driving task are assessed at a time and therefore the results may not hold when drivers are performing the full range of subtasks in real driving. Sometimes the effects tested in the lab are not realistic and may not transfer to real life driving. Furthermore, participants are aware that their behaviour is being scrutinised by researchers and they may adjust it accordingly, i.e. by behaving in the way they believe is expected of them – the so-called Hawthorne effect (Jones, 1992).

[1] This Chapter is partly based on Knapper, Hagenzieker, and Brookhuis (2010).

A specific form of lab testing to study device use is usability testing. This involves testing how well people are able to operate a system and identifying any difficulties they encounter (i.e., Nowakowski, Green, & Tsimhoni, 2003). Assuming that an easy-to-use system is less distracting, this should help decrease driver distraction. It may involve expert testing. See also 3.3.6.4 for further detail on usability and how navigation systems' usability is assessed in the literature.

Another useful form of lab testing is the Lane Change Task (LCT) (Mattes, 2003), in which participants complete a simple driving task on a PC in a dual task situation. LCT was developed specifically to assess driving distraction in a simple, low-cost manner. While driving at a constant speed of 60 km/h, participants are requested to change lane following a sign displayed on the computer screen. While performing this task, participants may be requested to perform a secondary distracting task, enabling comparison between distracted LCT performance and simple LCT performance with no secondary task. Since the LCT is combined with other components of the driving task, it can be considered a very simplified form of a driving simulator.

3.2.2. Driving simulator experiments[2]

In a driving simulator, most components of the driving task can be performed simultaneously. Driving simulators are available in several versions, with various levels of sophistication: high-level simulators are usually equipped with a 3-DoF moving base, realistic cabin and controls, and a full field of view; mid-level simulators are basically stationary or equipped with a 2-DoF moving base; and low-level simulators usually comprise simply a (fast) PC with a gaming steering wheel (Young, Regan, & Lee, 2009b), similar to that used in lab testing.

Driving simulators re-create the real-life driving experience better than lab tests due to their high face validity (Blana, 1997), depending on their level. They generally provide an acceptable level of experimental control and both the environment and each individual robot-traffic-participant can be altered with relative ease (depending on the software). Driving simulators are also safe (Caird & Horrey, 2011) for the participant, the researcher, and other traffic. Simple driving simulators tend to be low-cost, but even those may take a significant time investment to programme.

[2] Chapter 5 describes a driving simulator experiment and Chapter 6 details a validation study on the same driving simulator.

However, driving simulators lack content validity, i.e. they do not adequately re-create the real driving experience (Blana, 1997). Most simulators do not provide kinaesthetic information and therefore do not re-create the feeling of tyres moving on the road's surface, engine performance or cornering (Alm, 1995; Carsten & Gallimore, 1996). Furthermore, participants may feel under scrutiny, which makes it difficult to determine whether a distraction is realistic (Young et al., 2009b). Another problematic issue is that driving in a simulator makes approximately 10% of participants car sick, because the motions they see are not the motions they feel. Specifically people older than 50 years are among this group. This is referred to as *simulator sickness* (Young et al., 2009b; Stoner, Fisher, & Mollenhauer, 2011) and occurs more frequently in poorly-designed simulators (Andersen, 2011). It also takes time to get used to driving in a simulator as they can sometimes be more difficult to operate than a real vehicle. Finally, people driving in simulators experience very low feelings of risk (Young et al., 2009b) which means it may not be possible to generalise the effects identified across real driving. As a general rule it is difficult to translate the effects of risk, or lack of risk, identified in a driving simulator to real driving risk (Carsten & Brookhuis, 2005).

3.2.3. Field experiments

Field experiments are performed using either normal or instrumented vehicles. They can be conducted on a closed test track or on the public road. Each set-up has pros and cons, but at least testing drivers in real vehicles does improve generalisability, i.e. field experiments have high external validity (Blana, 1997). In general, driving a real vehicle avoids many of the drawbacks of driving simulators in terms of sensory feedback, feelings of risk (although risk is generally minimal on a closed test track), and interaction with other road users which increases external validity.

Nevertheless, drivers may still feel under scrutiny and change their behaviour accordingly (Carsten et al., 2013). There are also ethical questions in relation to requesting participants to perform hazardous tasks while driving that make it difficult to research certain types of distraction. With field experiments the level of experimental control is lower since neither traffic nor the weather – which both affect driving – can be controlled (Hoogendoorn, 2012). Furthermore, it is not certain to what extent the specific track selected for testing purposes affects driving.

One frequently applied methodology for field experiments is the *Wiener Fahrprobe*, the Viennese driving test (Chaloupka & Risser, 1995). Following a standardised route, two researchers ride in the vehicle with the participant, one observing and grading the driver in relation to a standardised set of variables and the other observing and grading the driver's interaction with other road users and their driving in general. Drivers often become less cognizant of being under observation after 15 minutes (Turetschek, 2009, p. 42). This method requires extensive training for the observers on the standardised metrics.

3.2.4. Naturalistic driving studies[3]

Naturalistic driving involves observing drivers in their natural environment. This is sometimes done in roadside studies, observing what passing drivers are doing e.g. texting, phoning (or both) (Young, Rudin-Brown, & Lenné, 2010; Savolainen, Das, Gates, & Datta, 2011; Vera-López et al., 2013), or engaging with other distractions (Sullman, 2012).

Naturalistic observations can also be conducted inside a vehicle using small cameras and unobtrusive sensors to simultaneously observe the driver, the vehicle, the cockpit and the surrounding environment. These techniques have improved considerably over time and have become more widely available in recent years. This type of testing used to require an instrumented vehicle containing bulky and expensive equipment that was so unlike a normal vehicle that it could hardly be claimed to be 'naturalistic'. Nowadays, cameras, sensors and computers have become more affordable and available in ever smaller formats and form factors, and can be installed in vehicles less obtrusively. This equipment can be built into many different makes and models so that participants can even drive their own vehicle – the ultimate form of naturalistic driving. Alternatively, researchers can fit out a fleet of rented vehicles to be distributed among a sample of participants, although drivers may then require some time to get accustomed to the vehicle.

Naturalistic driving studies that have sufficient 'body' (i.e. duration of study, sample size, number of kilometres driven) can reveal useful information regarding exposure to certain events (McEvoy & Stevenson, 2009). For instance, how often drivers encounter hazardous events is easily inferred, or drivers may engage in behaviours that distract them from driving. Large scale naturalistic driving studies even enable estimations of the crash risk for different types of distraction (Dingus et al., 2006a). Naturalistic driving data can inform theory building and deliver up some basic ideas that may be

[3] Chapter 7 describes a naturalistic driving study and its results.

tested more accurately under experimental conditions (Carsten & Brookhuis, 2005). Another major advantage is the assessment of what drivers decide to do, when, where, how often, and under which circumstances, and the drivers themselves are not significantly influenced by the researchers or other non-natural circumstances.

Although naturalistic driving is subject to certain limitations, it has been referred to by some as the gold standard of driver studies. Carsten et al. (2013) argue that no single method answers all of our questions. Researchers still need to analyse and interpret a lot of data. In order to ensure that such studies are repeatable, we need to take account of interrater reliability, i.e. the extent to which the analysts apply equivalent scores (McEvoy & Stevenson, 2009). This is never perfect and involves high time and costs relative to the small sample size used (McEvoy & Stevenson, 2009). Long-time recording may be necessary to investigate long-term drivers behaviours (Carsten et al., 2013). Furthermore, analysing video data requires clear definitions, and it is still impossible to infer from video what drivers are really thinking. The fact that samples are often biased, i.e. the participants volunteered for these studies are not randomly sampled, may imply that these individuals do not mind being observed. It is open to question therefore whether any sample can be generalised across the entire driver population (Bonnard & Brusque, 2008). It is virtually impossible to isolate a clear single cause of a particular effect since many variables that may influence the effect cannot be controlled.

3.2.5. Crash/accident studies

Crash studies focus exclusively on crashes and attempt to diagnose the cause. They are most often based on police data concerning real traffic crashes, which may be combined with phone company data, vehicle and site information, and witness reports (Stelling & Hagenzieker, 2015).

The limitations of this kind of study include the fact that police-reported crashes are only a subset of all crashes, and therefore a biased sample. Furthermore, the information pertaining to driver distraction is gathered after the crash has occurred, and often not in a systematic manner. Since investigators, police and witnesses all tend to interpret the information in their own way, the data is also subjective to a certain extent. Finally, crash studies provide no information regarding the prevalence of distractions. Although we can determine how often distractions are a contributing factor to crashes, we cannot estimate crash frequency due to distraction (Gordon, 2009). See Section 4.3.2 for further details on crash studies and risk estimates.

In summary, it is best to approach a problem from different angles and to design studies that combine multiple methods in complementary fashion (Carsten et al., 2013). Figure 3.1 graphically represents the relationship between the levels of experimental control and realism of the different testing methods.

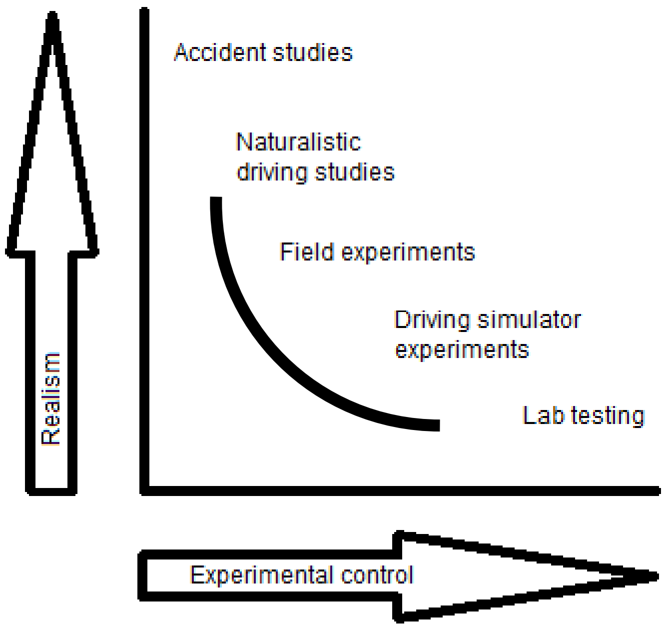

Figure 3.1: Graphical representation of method scores on realism and experimental control.

The relationship between crashes and driver behaviour is complex. Driver behaviour may generally be regarded as a crash risk factor, along with weather and road conditions. When drivers behave in ways that distract them from the driving task, their driving performance deteriorates, increasing crash risk. Crashes may therefore be regarded a consequence of both behaviour and performance.

3.3. Measures

It is certainly possible to measure driving performance using the methods described above. Longitudinal control, lateral control, events, subjective measures have been registered (Young et al., 2009b) as well as physiological measures such as heart rates and eye motions. The series of measures described below is by no means exhaustive. It should also be stressed that not all variables can be combined with all methods under all circumstances.

For instance, requesting participants in a naturalistic driving study to complete subjective measures before, during or after each trip would seriously affect the realism of their driving behaviour. Some measures also require specific and often expensive equipment that is not always available or affordable.

3.3.1. Longitudinal control

One major component of the driving task is maintaining longitudinal control, i.e. keeping a safe distance from the vehicle ahead. Crucial measures in this regard include speed, headway distance, and derivations such as the mean or standard deviation of speed. Not only is it the law of physics that the faster a vehicle travels, the more serious a crash, but also there is a well-established positive link between driving speed and crash risk as well (Aarts & Van Schagen, 2006).

3.3.2. Lateral control

Another important component is keeping the vehicle on the right track, i.e. maintaining lateral control. This can be measured by means of steering wheel angle and acceleration, but the main way this measure is used is the form of the outcome – the lateral position of the vehicle –and the standard deviation thereof. A common way of expressing this is to take the centre of the lane as zero and measuring the SDLP (standard deviation of lateral position), which increases as lateral control decreases. An example of a lateral control task is the Lane Change Task (LCT, Mattes, 2003), which we discussed in Section 3.2.1.

3.3.3. Event detection and reaction time

Other useful measures that are not related to vehicle control include event detection and reaction time to events. These measures demonstrate how well a driver is attending to the traffic situation. This is often measured in a driving simulator due to the need to control the timing of the event. For example, the driver encounters a series of sudden, unexpected events (e.g. brake lights of the vehicle in front), and the driver's reaction time is measured thereupon (e.g. the time it takes to hit the brake) or whether the driver reacts at all.

A broadly applicable task in this respect is the Peripheral Detection Task (PDT). The participant is asked to press a switch in response to a small red light as soon as possible, inserted as a secondary task in addition to the driving task. The participant's response time and any red lights they fail to respond to enable us to accurately measure the amount and timing of a visual distraction and workload (Harms & Patten, 2003).

3.3.4. Subjective workload measures

As described in Section 2.3.2, workload has an important effect on human performance during driving. Human beings can only do so much at one time, but are capable of doing more by increasing effort expended. One means of measuring workload is to ask a participant how much effort they (feel to) put into performing certain tasks (De Waard, 1996). Two well-known measures have been developed and validated in this respect, the Rating Scale Mental Effort (RSME) and the NASA Task Load Index (NASA-TLX). The RSME is the simplest, one-dimensional approach in this respect, which requires participants to rate *ex ante* how much effort they put into performing a (series of) task(s) by drawing a line on a paper scale (Zijlstra & Van Doorn, 1985). The NASA-TLX is a multi-dimensional scale that can be administered using either a PC or pencil and paper. It is used to distinguish between mental and physical demand, temporal demand, performance, effort and frustration levels (Hart & Staveland, 1988).

3.3.5. Physiological workload measures

Heart rate measures, specifically Heart Rate Variability (HRV), have also been used to measure workload, especially when task demand is high and the driver has to expend considerable effort to complete a particular task (see De Waard, 1996). Galvanic skin responses have been used to measure feelings of risk (Taylor, 1964) (see also Section 2.3.3).

3.3.6. Eyes

Safe driving involves watching the road and other traffic. Tracking eye movements, i.e. where people look and do not look, provides information on how well a driver is performing the driving task in that sense. An important measure is the length of time during which the driver is not watching the road (Time Eyes Off Road, TEOR), which includes both glance direction and duration. Monitoring glancing behaviour and eye movements requires specific equipment, including high-resolution cameras and applied software. These techniques can be applied in real driving situations, but are most often used in driving simulators (Fisher, Pollatsek, & Horrey, 2011). The duration of a driver's glance towards a task is an indication of task difficulty (Fisher et al., 2011). Victor et al. (2015) assessed how glancing relates to rear-end crashes and demonstrated that glance behaviour in response to a distractor is more predictive of crash risk than distracting activities themselves.

Another technique that measures eye behaviour is the occlusion technique. This was developed to determine how much visual information drivers minimally require to perform tasks involving an in-vehicle human-machine interface such as a navigation system (Godthelp, Milgram, & Blaauw, 1984). This technique can be used without requiring participants to actually drive. Participants wear glasses that can be occluded or transparent while conducting a navigation task. The occlusion represents time spent watching the road (i.e. not looking at the device) and transparency time spent operating the device. This enables the measurement of the duration of viewing time required to perform a task (Pettitt, Burnett, Bayer, & Stevens, 2006).

3.4. Conclusion

A wide variety of methods and types of measurements have been used to study driver distraction and driver behaviour regarding phone and navigation system use while driving. Each method represents a set of pros and cons, and the consensus is that no perfect method has been developed yet. The measurements that researchers record depend heavily on the selected method and the resources available. Unfortunately, we still have no reliable means of reading drivers' minds.

4. Literature review of effects of mobile phone and navigation system use on road safety and efficiency

4.1. Introduction

In this chapter, the scientific literature relating to driving while using mobile phones and navigation systems is assessed, specifically with respect to the impact on driving safety and efficiency. The tasks people perform on their mobile phones (see also Section 2.2.3) include having conversations and operating the phone (e.g. texting, messaging, socialising and gaming). Drivers operate navigation systems which then provide route guidance to assist drivers with wayfinding. Drivers may also perform other operations, e.g. change the volume. The task framework proposed in Table 2.1 in this chapter will be used again to discuss the relationship between the various tasks listed there with driver safety and efficiency on the basis of our review of the literature.

First the current body of knowledge is summarised, recent changes, potential adjustments and current debates regarding the effects of drivers using mobile phones and navigation systems. Then the following research questions will be dealt with:

1. Which impacts on safety are the result of drivers using mobile phones and navigation systems (Section 4.4)?
2. How do these safety impacts relate to efficiency (Section 4.5)?
3. How comparable are these impacts across the two types of devices (Section 4.6)?
4. What knowledge gaps are there in the current body of research (Section 4.6)?

In the previous chapters we focused on theories and methodologies and we now turn our attention to the effects of performing tasks on mobile phones and navigation systems while driving. Four main tasks were identified in Table 2.1 and the reviewed literature is investigated on how they affect driving and the extent to which this affects safety and efficiency. Some components of tasks performed on mobile phones and navigation systems while driving are comparable in terms of distraction. This may also be the case for the effects they have, which may in turn affect efficiency gains or losses.

Although a number of extended literature reviews on mobile phone use have been published to date (e.g. McCartt, Hellinga, & Bratiman, 2006; Collet, Guillot, & Petit, 2010a, 2010b; Kircher, Patten, & Ahlström, 2011; Llerena et al., 2015), our review is distinctive for four reasons. Firstly, the literature results pertaining to two in-vehicle devices is compared, whereas most older reviews assess only a single device or task, in the anticipation that reviewing these two devices in tandem will provide insight into driver distraction caused by nomadic devices from a broader scope. Secondly, it is likely that the rapid technological developments in both types of devices continue to change and affect driver behaviour and performance in new ways, therefore this study may be regarded as a comprehensive update. Thirdly, recent research results – especially with regard to phone conversations while driving – have markedly changed the scientific debate; therefore, the aim is to help summarise and interpret recent claims. Finally, certain potential positive efficiency effects are suggested to counterbalance some potential negative safety effects and seek to provide a balanced view.

4.2. Literature review methodology[4]

Four large scientific databases and search engines (Web of Science, Scopus, TRID and Google Scholar) were used to pull up as many publications as possible. The body of information considered in phone conversation literature reviews up to 2010 is already well known so only reviews and meta-analyses to produce a summary were used. Only publications on the effects of phone conversations on driving from 2010 up to and including 2013 were selected for our review. Literature relating to texting was scarcer – possibly because texting gained popularity during a later period – so literature from as early as 2000 up to and including 2013 as well was selected. Since the year 2000 also signalled the rise in popularity of navigation systems (see Section 2.2.2) this was used as the start date for a search for literature on route guidance and navigation system programming tasks. The keywords used for inclusion criteria are set out in Table 4.1. Several papers fell under more than one heading. The total number unique papers in the database came to 651. After an initial search conducted in 2013, more publications

[4] This Chapter is based on a review conducted in 2013; this review was updated in 2016, at the final phase of the PhD research period.

were found by scanning reference lists and regularly searching for new literature.

Table 4.1: Keywords and search combinations used in 2013 literature search.

Mobile phone, cell phone		Navigation systems, PND, portable navigat*, GPS, nomadic device	
Texting, SMS, text message	Conversation	Operating	Wayfinding
Touch screen	Review, meta-analysis	Destination entry, visual, manual	Route guidance
Safety effects, driving, road, traffic, behaviour, performance			

The results of the literature review are described below, starting with the literature on phone conversations while driving (Section 4.3), including a summary of effects identified in earlier literature reviews and meta analyses. The recent controversy regarding the risks of having phone conversations while driving is discussed as well, followed by the literature published since 2010, divided into several distinctive topics. The literature concerning the effects of operating phones while driving is treated (Section 4.4), addressing topics such as the effects of different phone interfaces, how different groups of people are affected and how much time drivers actually spend operating their phones while driving. In Section 4.5, the literature regarding wayfinding using route guidance from a navigation system is assessed. How is route guidance information best presented, and how are drivers affected by using navigation systems. In Section 4.6, the literature regarding operating navigation systems while driving is covered, looking at various design options and possible improvements. Subsequently, in Section 4.7, the literature on the efficiency effects of each of the four tasks is examined. Finally, all findings are summarised and an attempt is made to answer the four research questions.

4.3. Phone conversations

4.3.1. Meta-analyses and other literature reviews

Three relevant meta-analytic studies were found (Horrey & Wickens, 2006; Caird, Willness, Steel, & Scialfa, 2008; Elvik, 2011). Horrey & Wickens included 23 studies in their analysis, whilst the main conclusion was that phone conversations while driving only seem to have a significant effect on drivers' reaction times (0.13 seconds) and hardly any effect on lateral performance. The authors attributed the low impact to the different resources that are required, i.e. lane-keeping requires ambient resources, and response to danger requires focal vision (see Section 2.3.2). The analysis by Caird et al. (2008) involved 33 different studies, rendering a total of 94 effect-size estimates for a total of approximately 2,000 participants. They observed that reaction time consistently increases as a result of phone conversations while driving. Neither headway nor lateral control measures appeared to have significant effects. The results relating to lateral control were particularly variable across the studies. Speed reductions occurred somewhat more frequently with handheld phoning than handsfree phoning. Elvik (2011) assessed the combined results of several papers on the risk of being involved in an accident while using a mobile phone. In spite of concerns surrounding information accuracy, he estimated a 2.86 odds ratio of risk of being involved in an accident while using a mobile phone. That is, the odds of being involved in a crash are 2.86 times higher when using a phone as compared to normal driving. However, Elvik identified evidence of publication bias and reasoned that the risk estimate is unlikely to be correct. He provided no suggestions for alternative research directions.

More recently, a number of recent literature reviews were published (Dragutinovic & Twisk, 2005; Svenson & Patten, 2005; McCartt et al., 2006; Brace, Young, & Regan, 2007; Buckwalter Jr, 2010; Collet et al., 2010a, 2010b; NSC, 2010; Kircher et al., 2011). These reviews pointed to several effects that conversations have on driving, which are set out in Table 4.2.

Table 4.2: Measures affected by phone conversations while driving in the literature reviews.

Topic	Measure	Effect[1] (source[2])	Remarks
Performance	Speed keeping	↓ (1, 2)	
	Lateral control	↓ (2, 3) - (1, 4, 5)	
	Throttle control	↓ (1)	
	Headway distance	↑ (2, 6, 7)	
	Driving speed	↓ (6, 7, 9)	
	Remembering and interpreting objects	↓ (6)	'Looked but failed to see'
	Visual search patterns	↓ (1, 6)	Specifically when answering/ initiating a call (1). During phoning: more straight ahead looking (less to mirrors, periphery). Also known as a diminished field of attention (3) or reduced general awareness (4)
	Reaction times	↓ (1, 2, 3, 4, 5, 6, 7, 8)	
	Decision making processes	↓ (1)	
	Detection of driving related events	↓ (2, 6)	Also referred to as hazard detection
Risk	Crash risk	↑x4 (1, 7); ↑x2 to 4 (3)	*No reliable estimate of the proportion of crashes in which phone use was a factor (7)*
Behaviour	Risk taking in decision making	↑ (4)	
Group differences	Differences male /female?	No (7)	
	Age	No (7)	Negative effects may be greater among older drivers (50-80) (7)
Comparison to other distractions	Compared to talking to passenger?	↑ (7)	
	Practice	- (6)	Practice does not help
	Difference HH vs HF	- (all)	
	Conversation complexity	↓ (3,9)	Negatively impacts driving performance
Inattention blindness		↑ (5)	

[1] While phoning, as compared to 'normal' driving (↓ = negative, - = neutral, and ↑ positive effect)

[2] 1: Brace et al. (2007), 2: Collet et al. (2010a), 3: Svenson & Patten (2005), 4: Dragutinovic &Twisk (2005), 5: NSC (2010), 6: Kircher et al. (2011), 7: McCartt et al. (2005), 8: Buckwalter Jr (2010), 9: Young & Regan (2007)

4.3.2. The current debate on risk

The aforementioned study by Elvik (2011) exemplifies part of the current debate regarding phone conversations with its critical assessment of methodologies and risk estimates. The debate centres on three related notions:

- In large-scale naturalistic driving studies, risk during phone conversations has, through large scale naturalistic driving studies, not been found to be substantially higher than during normal driving.
- Phone billing data studies (McEvoy et al., 2005, Redelmeier & Tibshirani 1997) may well be confounded, but probably alternative studies are too.
- In naturalistic driving studies, it is difficult to determine whether a given event is genuinely safety critical; is it therefore appropriate to use them as a safety indicator alongside actual crashes?

The problems in this regard relate principally to the methodologies used. The discussion mainly focuses on the risk of drivers being involved in crashes due to mobile phone use. Redelmeier & Tibshirani (1997) were the first to provide an empirical risk estimate, based on a combination of car crashes and mobile phone billing data from the day on which the crashes occurred and the previous day. The authors found that the risk of being involved in a crash while using a mobile phone was four times higher (95% confidence interval: 3.0 to 6.5) than when not using a phone, based on a case-crossover research design[5]. The accompanying editorial commentary (Maclure & Mittleman, 1997) was more conservative in its assessment, but confirmed that the risk minimally more than doubled on the basis of the data provided. Redelmeier & Tibshirani's conclusions from Canada were more or less replicated in Australia by McEvoy et al. (2005), who used a similar research design and achieved comparable results. Although these studies appear to have been conducted with extreme care and the results take account of critical uncertainties, their limitations may in fact be substantial. The imprecise recording of crash times (often rounded by five or even fifteen minutes), the inexact nature of baseline driving and the quality of the estimates, and the fact that it only involved drivers who crashed while using their phone are some reasons for concern that potentially introduce bias (Young & Schreiner, 2009a). Furthermore, the reasons drivers gave for making a phone call while driving, e.g. being lost or in a hurry, may also

[5] In a case-crossover design, each case of phone use while driving is matched with the time window of non-use (control) for the same driver. Risk during the case window is then compared to risk during the control period.

change the estimates of how much the phone was in use in the experimental or control groups (Farmer, Braitman, & Lund, 2010). Although adjustments to those estimates have been proposed (Young & Schreiner, 2009a; Young, 2012b), these were subject to criticism as well (Braver, Lund, & McCartt, 2009; but also Young & Schreiner, 2009b; see Kidd & McCartt, 2012; Mittleman, Maclure, & Mostofsky, 2012; and Young, 2012a). Furthermore, the phone billing data in the 2005 McEvoy et al. study could not exclude other behaviours apart from the conversation itself (e.g. dialling), which may have inflated the number of phone use instances to some extent as this turned out riskier than having the phone conversations that were billed (McEvoy, Stevenson, & Woodward, 2012).

Another Canadian risk study (Asbridge, Brubacher, & Chan, 2013) compared 312 drivers who crashed, of whom the police reported to have been using their phone while driving to 936 other drivers who crashed of the same age, gender, alleged drug/alcohol use, crash type, date of crash, time of day and geographic location. The drivers' culpability (i.e. whether the driver did anything wrong or whether the crash was due to an external cause, cf. Sanghavi, 2012) was then estimated from the police reports of all the crashes. The data indicated that the chance of phone users being culpable was higher than non-phone users, and the authors concluded that *"cell phone use increased the odds of a culpable crash by 70%"*. The study was criticised (Sanghavi, 2013a) because a relationship between phone use and culpability does not provide information about crash risk. Sanghavi reasoned that if phone use might lead to lower crash risk and this effect is stronger in non-culpable conditions, this could have produced the same results. There may also be a correlation between culpability estimates and phone use, since police officers were more likely to deem the driver culpable if they were using their phone (Sanghavi, 2013b). This may have inflated the odds ratio.

This debate arose when several large-scale naturalistic driving studies in the United States presented odds ratios for the risk of handsfree phone conversations while driving of *less than one* (and later equal to one), that is, a decrease in risk of (nearly) crashing due to phoning while driving (Olson, Hanowski, Hickman, & Bocanegra, 2009; Hickman, Hanowski, & Bocanegra, 2010; Fitch et al., 2013). Those studies revealed no substantial decrease or increase in the risk of a (near) crash due to handheld phoning. A similar study by Klauer et al. (2014) showed that talking on a phone did not increase (near) crash risk in a sample of experienced drivers or in a sample of novice drivers.

This evidence was contrary to the widely accepted view that making a phone call while driving increases crash risk approximately fourfold (Redelmeier & Tibshirani, 1997; McEvoy et al., 2005). For instance, a Canadian study conducted by Laberge-Nadeau et al. (2003) concluded that phone users run a 38% higher relative risk of having either injury or non-injury crashes than non-phone users. This study used a combination of questionnaire data (to discriminate between phone users and non-users) and phone users' billing data, and their accident record. It was unclear, however, whether the drivers were using their phone before or during the accidents and whether this usage was a factor in the accident. Another study (Backer-Grøndahl & Sagberg, 2011) assessed the relationship between phone use while driving and crash risk for handheld versus handsfree phoning in two Norwegian questionnaire datasets (1997 and 2007), completed by people reporting accidents to an insurance company. Overall, the relative risk increased significantly (1.06-3.16), but not in the 2007 dataset separately (0.73-3.14) for neither handheld or handsfree phoning. The authors concluded that phoning while driving is associated with increased crash risk, but that there are no significant differences in risk between handheld and handsfree phoning. These outcomes should be treated with caution due to the low response rate and potential self-reporting bias. Self-reporting bias, for instance, could lead to underreporting of crashes (Hanley & Sikka, 2012) and we could therefore assume that the relative risk is in fact higher. According to a study into whether drivers adjust other components of the driving task to compensate for talking on the phone (Fitch, Grove, Hanowski, & Perez, 2014), drivers tend to watch the road ahead for longer periods, but do not slow down or significantly increase their headway distances.

The large scale naturalistic driving studies had their own disadvantages. The US National Safety Council (NSC, 2010) noted several important ones. Firstly, even large-scale naturalistic driving studies only consider a small number of crashes. They bolster this number by including near-crash data in crash risk calculations. It is not known whether all near-crash instances are recorded. Furthermore, the correlation between phone use and increased risk is not necessarily causation. According to Zhao et al. (2013), drivers who say they often use their phone while driving were also more prone to engaging in other risky behaviours, such as speeding and overtaking. The NSC also claimed that neither cognitive distraction is measured nor observed as such, and even hands-free phone use is difficult to measure. The NSC decided to continue to use the statistic that the risk of crashing while engaged in a handsfree phone conversation is four times higher than no phone use.

Interestingly, the most recent large-scale naturalistic driving study does reveal a statistically significant increase in risk, however, with an odds-ratio of 2.2 (Dingus et al., 2016), based only on actual crashes. The authors also report that 68% of the crashes involved some form of observable distraction.

It is difficult to investigate changes in driving risk due to phone use for several reasons (Stelling & Hagenzieker, 2015): 1. Police reports are not filed for all crashes; 2. The extent of distraction is difficult to assess reliably and objectively following a crash; 3. Police are unable to determine the source and type of distraction, nor whether it was the sole cause of the crash; 4. Crash studies do not typically include the prevalence of different types of distraction. Crash studies therefore merely provide an estimate of crash risk due to driver distraction. More recent experiments assessing the influence of phone conversations on driving performance may help us understand *how* such conversations affect people's driving performance.

4.3.3. Driver behaviour and effects on performance in recent publications

In spite of recent findings that phone conversations may pose less risk to drivers than indicated in earlier studies, or perhaps due to the controversy surrounding these results, numerous studies have attempted to gain more insight into how phone conversation impact on driving performance. For example, technological advances have enabled researchers to examine drivers' brains while performing phone-related tasks. Some studies have recently been replicated, revealing new insights into underlying factors.

Effects of phone conversations on driving performance in publications post 2010

When talking on the phone, drivers often slow down. In a study conducted by Strayer, Cooper & Drews (2011), participants were asked to perform a car-following task in a driving simulator while holding a conversation (observing handheld, handsfree and baseline driving). The participants tended to compensate for the distraction of the conversation by slowing down and increasing headway distance. The authors claim, however, that this does not sufficiently compensate for their decreased reaction time.

In a study on naturalistic driving data by Sayer, Bao & Funkhouser (2013), phone conversations did not appear to affect lateral driving performance but only following behaviour (distance and distance variation) in older drivers (aged 60-70) but not middle-aged and younger drivers. Reimer et al. (2008)

found that older participants (aged 51-66) slowed down more in the driving simulator when having a phone conversation than younger drivers (aged 19-23), with similar speed control performance in both age groups. It appears that older drivers are equally capable as younger drivers of dealing with the additional workload created by a phone conversation (Reimer, Mehler, Coughlin, Roy, & Dusek, 2011).

Phone conversations do require a share of drivers' attentional resources. Brain research that used an fMRI in a driving simulator study (Schweizer et al., 2013) revealed that driving activates several brain areas in the posterior region, depending on the complexity of the driving task. When distracted by a cognitively distracting verbal task, drivers' brain activity shifted towards the anterior brain, activating not only auditory areas but also the prefrontal cortex while the posterior brain regions became less active. This result implies that brain capacity allocated to driving decreases during a cognitive distraction. Garrison & Williams (2013) asked 20 drivers to hold a handsfree conversation in a simulator, in which they passed driving-related objects (e.g. hazards, parked vehicles) and non-driving related objects (e.g. billboards). Although drivers glanced at both types of objects less often in the distracted than in the baseline conditions, driving-related objects did receive more attention than non-driving related ones. This result demonstrates that drivers do still pay attention to hazards even when distracted by a handsfree phone conversation (Garrison & Williams, 2013). Gherri & Eimer (2011) used ERP in a laboratory setting to show that visual processing, similar to driving related processing, is less efficient when participants are requested to process verbal messages at the same time. Therefore, active listening to a phone conversation while driving may also affect visual aspects of driving performance. This may provide some evidence against strict Wickens' MRT (see Chapter 2), which asserts that different modalities (auditory and visual) can be used simultaneously without detrimental effect to either. Truck drivers holding a phone conversation (N=50) in a truck driving simulator decreased their number of off-road glances and increased the duration of riding the clutch (i.e. not fully releasing the clutch) compared to baseline driving (Fine et al., 2012).

The mere presence of a phone in a vehicle can affect drivers. O' Connor et al. (2013) assessed the factor structure of a mobile phone overuse scale (CPOS) intended to assess the addictive nature of mobile phone use, based on DSM IV-related measures. They linked the outcome to other scales and to previous motor vehicle crashes. One CPOS subscale 'Anticipation' (often think about calls/messages you may receive, think about your phone when it is turned off) was significantly associated with motor vehicle crashes (self-reporting). The authors suggest that crash risk may increase due to more frequent phone checking while driving (gaze directed away from the road) or due to the increased cognitive load (processing speed affected).

Answering or initiating phone calls

One of the main reasons drivers answer their phone even when they know it may be dangerous is that it is not so much a conscious action as an automatic one which they struggle to resist, and because it is subject to a time constraint: it will soon stop ringing (Haddington & Rauniomaa, 2011; Rauniomaa & Haddington, 2012). Haddington & Rauniomaa (2011) identify three steps: orienting to the ringing phone, locating the phone and handling the phone. They claim that this is much more dangerous than planning an outgoing phone call because drivers move their gaze away from the road when the phone rings, take a hand off the wheel to grab the phone, or instruct other passengers how to use the phone. In a survey of 181 drivers in Australia, the majority said they answer calls more often than they make them. The authors suggest this may be evidence of social pressure to respond (Waddell & Wiener, 2014).

Other studies have found that even a ringing phone increases driver reaction times (Zajdel et al., 2012; Zajdel, Zajdel, Śmigielski, & Nowak, 2013). There could be a corresponding difference between drivers either answering or initiating a phone call. In a study by Tractinsky et al. (2013), drivers in a simulator were more likely to answer a phone call than to initiate one, waiting for the right driving demand circumstances. However, younger drivers were less likely than older drivers to take account of the driving environment when deciding whether to pick up a phone or not, evidence of the distracting effects of a ringing phone. Another study found that especially young participants who said they rarely ignore a ringing phone were more prone to speeding or being involved in collisions (Holland & Rathod, 2013).

Hislop (2012) surveyed 149 UK drivers at a motorway service station and subsequently interviewed 15 of them over the phone. This subsample of 15 subjects consisted of professional drivers who either used a phone while driving very frequently ('serial users') or hardly ever. Interestingly, the drivers whose cars were equipped with handsfree phoning facilities were more likely to use their phone frequently while driving, although as many as

45% of handheld phone owners used their phone while driving on occasion. Most participants (11) did self-regulate by more often choosing not to engage in or answer more complicated phone calls, e.g. with clients from unknown numbers.

Conversation partner and content

Several studies addressed the question of whether the content of a conversation affects driver distraction. Some suggest that even the simplest conversations, e.g. hearing a word and responding 'yes' or 'no' whether or not it concerns an animal, is enough to increase brake reaction time in a simulated car-following task by approximately 300 ms (Rossi, Gastaldi, Biondi, & Mulatti, 2012). Another study (Cao & Liu, 2013) involved a simple sentence comparing task in which drivers pressed a button to indicate whether or not two sentences were similar. The results showed that this task had no effect on lane-keeping but did increase mental workload. In this study it was only possible to measure lateral performance in the driving task, but it did indicate that drivers expended effort and therefore brain capacity to complete the conversation. Emberson et al. (2010) used a tracking task to demonstrate that participants react more slowly and with a greater margin of error when overhearing one other person having a phone conversation compared to overhearing two people having a conversation. Thus, even when drivers are not personally involved in a conversation it can still distract them, and one-sided conversations even more so.

This may be related to the results obtained by Maciej et al. (2011) showing that vehicle passengers observing the surrounding driving situation change their speaking rhythm to talk more often but in shorter chunks compared to their conversation partner on the phone. The literature confirms that passenger conversations are less distracting than driver's own phone conversations. Surprisingly, Lansdown & Stephens (2013) found that a couple quarrelling in a vehicle as passengers had a worse effect on the driver's performance (lateral and longitudinal performance) than when only one of them was present in the vehicle and the fight took place over the phone. Lansdown & Stephens suggest that the physical presence of passengers and interest in romantic relationships may draw more glances from drivers. Furthermore, they contend that passengers are less able to regulate the conversation when they are romantically involved with the driver.

When arachnophobes are emotionally involved in discussing spiders while driving in a simulator, their workload was higher and they committed more errors than non-arachnophobes (Briggs, Hole, & Land, 2011). Participants were requested to drive at 50 mph while holding either a phobia-related conversation (to simulate an involving conversation), a normal conversation or not speaking at all. Participants adapted their speed less often particularly during phobia-related conversations, but also during normal conversations, which led to more speed deviations. This is evidence that the content of a conversation does affect driving performance. Dula et al. (2011) reported an increase in speeding, collisions and centreline crossings during emotionally-charged phone conversations compared to mundane conversations or no conversation at all. However, this study should be interpreted with care; all the participants were students and they did not report whether these conversations were on the phone or with a passenger, and the two groups that were compared consisted of different participants. According to another study involving ERP and fMRI brain assessments, an angry tone of voice was less distracting in terms of cognitive load, attention distribution and reaction time than a neutral one (Hsieh, Seaman, & Young, 2010).

A final study of interest by (Becic et al., 2010) reversed this perspective and investigated what effect driving has on the quality of phone conversations. The authors found that driving negatively impacts on people's ability to hold a conversation; talking on the phone while driving in a simulator affected participants' recall ability, level of comprehension and long-term memory storage of the conversation. The more demanding the driving task, the greater the effect on the conversation. The authors concluded that when engaged in a demanding conversation, either our conversation or driving performance suffers.

Using the phone while driving: Who does it and how often?

Willingness to use a phone while driving is influenced by drivers' attitudes towards that behaviour, and by perceived behavioural control, i.e. drivers who are confident in their ability to perform a phone task while driving are more inclined to do so (Rozario, Lewis, & Kartherine White, 2010). This is confirmed by a study by Schlehofer et al. (2010), which demonstrated that drivers who frequently use a phone while driving believe themselves to be more in control of the vehicle and more skilled than other drivers, regardless of whether this is true. What is more, they tend to overestimate their own (simulated) driving performance. According to Schlehofer et al. (2010), drivers who use their phone frequently while driving have an illusion of skill and control and are often younger adults.

A survey of 1,500 European drivers (Jamson, 2013) revealed that well over 90% of drivers own a mobile phone. Among American drivers (Braitman & McCartt, 2010) 40% of all drivers report that they talk on the phone while driving at least a few times per week, increasing to 66% of young male drivers. In Australia, 43% of drivers surveyed reported that they answer phone calls while driving on a daily basis (White, Hyde, Walsh, & Watson, 2010). An Australian roadside observation study by Glendon (2007) observed 1.2% of drivers using a handheld mobile phone. Further Australian road side observations performed by Young et al. (2010) spotted 195 out of 5,813 drivers using a handheld phone (3.4%). According to the 2010 US National Occupant Protection Use Survey (NOPUS), 5% of drivers use a handheld cell phone (NHTSA, 2011). A study by Farmer et al. (2010) indicated that drivers talk on the phone approximately 7% of the time while driving. Sullman (2012) observed 2.2% of drivers holding a mobile phone to their ear in southern England in peak, off-peak and free-flowing traffic. When measuring handheld phone use in Minnesota in 2011, Eby & Vivoda (2010) found that 4.7% of drivers engaged in a phone conversation in August, compared to 6.8% in June. A comparison with earlier years shows the phone use rate among drivers is increasing. Taken together, one probably could safely estimate that 1-11 % of drivers use a phone while driving (WHO, 2011).

The question then is, what effect does mobile phone use have on road safety? A naturalistic driving study by Funkhouser & Sayer (2012) involving 108 participants over four weeks revealed that 6.7% of driving time is spent holding phone conversations; the rate is higher among younger drivers at 8.8%. However, drivers did demonstrate some ability to self-regulate their phone use in that they were more likely to use the phone when stationary. Beanland et al. (2013) argued that the fact that few crashes are attributed to phone use is due to drivers regulating and restricting their phone use to non-demanding situations.

Neutral or potentially positive effects?

It appears that phoning while driving is relatively safe when performed by experienced drivers, on the motorway, in good weather and in light traffic (Collet et al., 2010b). The fact that phone conversations may help drivers avoid drowsiness and enable them to swiftly alert the emergency services in the event of a crash may even be considered positive effects of phone use in vehicles (Collet et al., 2010a; ETSC, 2010) – although the mandatory roll-out of the eCall rapid assistance initiative may make this function redundant in the EU in future.

There are some indications that driving is minimally affected by phone conversations on simple routes with little traffic (Iqbal, Ju, & Horvitz, 2010). Benedetto et al. (2012) only identified a significant negative effect on reaction time in urban areas, and not when driving in rural areas or on the motorway. The minimal effect may imply that well-planned phone conversations have a minimal impact on safety. Furthermore, it appears that a proportion of the population (2.5% in a sample of 200 participants) is able to perform cognitively distracting tasks with no impact on their driving at all(Watson & Strayer, 2010).

There is some evidence that commercial vehicle drivers can successfully use phone conversations to overcome drowsiness (Toole, Hanowski, Smith-Jackson, & Winchester, 2013). A driving simulator study by Atchley & Chan (2011) revealed that conducting a secondary verbal task may enhance drivers' performance when the driving task itself is highly monotonous. The results of this study showed improved lateral performance during the secondary task compared to monotonous driving with no secondary task. Similar results were obtained by Jellentrup et al. (2011), who performed a field test with 18 participants who were asked to drive on a monotonous test track following two trucks. During the drive, they also answered regular phone calls. EEG, eyelid measures, and reaction time measures revealed that the drivers were more alert during the phone conversations up to 20 minutes afterwards, than during normal monotonous driving.

4.4. Operating mobile phones

A number of more recent papers (post-2010) sought to gain more insight into how operating a phone (as opposed to talking on the phone) affects driving performance. Prior to 2010, texting while driving received little recognition as a research area in its own right, but texting rapidly became much more common after 2010 (NHTSA, 2011). Recent technological advances have changed the way mobile phones are operated. Since the introduction of the iPhone in 2007, mobile phone technology has continued to advance rapidly and touchscreen smartphones are now the rule. Operating a touchscreen is significantly different from operating the buttons on an old 'dumb phone' and this may also have changed the way people operate phones while driving. Voice control has also improved, enabling more people to operate a phone in this way, in some cases via in-car computers. Last but not least, these advances may have changed drivers' attitudes towards operating their phone as well. There is therefore ample reason to continue to study phone operating while driving.

We use the term operating to include all behaviour surrounding touching and looking at mobile phones, including texting, Facebooking, gaming, e-mailing and dialling. However, that does not imply that effects of these different operational tasks are identical. For a long period, the volume of research into texting paled in comparison to calling, as observed by Reed & Robbins (2008), Benden et al. (2012) and others. But as early as 2008, Caird et al. (2008) noticed that texting has different, more lateral effects on driving performance than calling. We will now consider some relevant studies, commencing with a meta-analysis on the topic.

Caird et al. (Caird, Johnston, Willness, Asbridge, & Steel, 2014) performed a meta-analysis of the effects of texting on driving. They included a total of 28 experimental studies, yielding a sample of 977 participants and producing 234 estimates of effect sizes. Their results revealed that:

- Both typing and reading texts while driving affected eye movements, stimulus detection, reaction time, collisions, lane positioning, speed variance and headway. Speed generally was reduced during texting.
- Reading texts led to somewhat lower decrements than typing them, although the effects were still adverse.

The authors noted that these studies did not take account of drivers' strategies relating to texting, such as refraining from texting during difficult driving circumstances.

4.4.1. Effects of phone operating on driving performance

Operating a phone can have numerous effects on driving performance. Reed & Robbins (2008) asked 17 participants between 17-24 years of age who were regular texters to drive in a driving simulator. They found an increase in missed signs and reaction time to an unrelated visual reaction time task while texting compared to normal driving. Although average speed was reduced while texting, this was not sufficient to compensate for increased reaction time. Car following performance (maintaining a constant following distance from a lead vehicle) was also impaired. The texting task had the greatest impact on lane position variability.

Cooper, Yager & Chrysler (2011) asked 42 participants to perform text reading and text typing tasks while driving an instrumented vehicle on a closed test track. The results showed an increase in reaction time, missed events and SDLP as well as a reduction in speed and the number of glances towards the road when both reading and typing texts. There was little difference between the two types of task. The authors recommend that drivers should never text while driving, and that more research is required to better understand when drivers text in the real world.

Hosking et al. (2009) asked 20 young and novice drivers to perform text reading and typing tasks on a phone provided by the researchers while performing a lane change task in a driving simulator. They found that participants directed more and longer glances within the vehicle (i.e. not on the road) while texting compared to baseline driving. Once again, there was little difference between the reading and typing tasks. The participants' performance on the car-following task in terms of mean and variability of time headway, and on the lane change task in terms of maintaining a constant lane position and responding correctly to lane change assignments deteriorated while texting. The authors reported no effect on speed or on speed variability.

Ranney et al. (2011) carried out a low fidelity driving simulator experiment in which 100 participants performed a range of phone tasks in a simulator, comparing touchscreen (iPhone) and button phone (Blackberry) usage. The phone tasks included dialling a ten-digit phone number, selecting contacts and text messaging. Text messaging was associated with the highest level of potential distraction according to several indicators, including reaction time to a response task and correctness of response, SD lane position, and task duration. The touchscreen phone appeared to be somewhat more distracting. These results could differ in real life, however, as none of the participants were using their own phone.

Crisler et al. (2008) assessed the effects of several tasks, including texting and operating an iPod, on simulated driving performance among 14 student drivers. The authors reported reduced lane keeping performance and increased speed variability.

Alosco et al. (2012) compared the effects of texting (n=45) to eating (N=45) and normal driving (N=90) in a simulator. They found that both eating and texting led to more crashes and centre line crossing than normal driving. The effects of eating and texting were approximately equal. It should be noted that the drivers in this study were relatively young (aged 20).

Choi et al. (2013) recorded the effects of text messaging and destination entry on both driving performance and smoothness of movement among 55 participants. When operating either device, the participants' performance in maintaining a constant speed and a constant distance to the headway vehicle was worse than baseline driving and their lateral performance also deteriorated. The largest reductions in smoothness of movement occurred during destination entry, although texting also deteriorated smoothness of movement compared to baseline driving. This study suggests that car handling also deteriorates in line with drivers' driving control movements.

In a study by Libby & Chaparro (2009), 32 participants responded to billboards by phoning, texting (on the researchers' phone) or talking out loud while driving in a simulator. When texting, drivers reacted more slowly to a tertiary reaction task, drove more slowly, exhibited more lane position variance, and took their eyes off the road more often than when phoning or talking.

Burge & Chaparro (2012) assessed the situational awareness of hazards of 20 participants when texting while driving in a PC driving simulator. The participants drove through scenarios both with and without hazards, while either texting short strings of letters or not using a phone. Sometimes they were asked to copy the string of letters and other times to alphabetise it, which is more demanding. The participants missed more hazards and reacted to them more slowly when texting than during baseline driving. There were fewer misses when copying text, but more false alarms, compared to alphabetising. The authors recommended a better-safe-than-sorry approach.

A study by Park et al. (2013) demonstrated that even a simple reaction time task is affected by the addition of a texting task. The results showed slower reaction times and increased heartrate and respiration rate.

Mouloua et al. (2010) asked 30 participants to text and drive in a driving simulator, in light or heavy traffic. The measurements taken included an EEG. The results showed that texting had a significant effect on theta activity, indicating increased inattention. The participants also committed more driving errors, such as lane deviations and crashing, while texting.

In addition to texting, other common phone operations include Facebooking and e-mailing. Basacik et al. (2012) asked 28 young participants (aged 18-25) to drive in a simulator while posting messages on the Facebook app installed on their own smartphones and not using a phone. They found that Facebooking increased reaction times to secondary task stimuli, deteriorated lateral position performance, and decreased time spent watching the road (50% during reading/typing vs 10% during baseline driving). The participants compensated for their poorer performance by reducing speed, but not to a sufficient degree. Three of the 28 participants indicated that they use Facebook during real-life driving.

In another driving simulator study (Eder, Lu, & Chen, 2009), 14 participants (aged 18-41) read an email, listened to an email being read aloud, or both, and dialled a phone number contained in the email while performing a lane change task. The secondary task information was provided either aurally or visually, or a combination of both. Receiving the information visually and both visually and aurally changed the participants' heartrate and heartrate variability, suggesting increased workload. Receiving the information aurally alone appeared to be less demanding.

The effects of texting on driving performance in a tunnel proved similar, but the potential consequences are even more harmful as the road is less forgiving (Rudin-Brown, Young, Patten, Lenné, & Ceci, 2012).

There appears to be a clear consensus that operating a phone impairs reaction times and hazard detection, distance and speed keeping, lane keeping, and glancing behaviour; increases crash risk; and may also reduce speed.

Touchscreen vs button phones, auto lock, and speech-to-text

Different models of phones vary widely in terms of properties, operating modalities and settings. Touchscreen smartphones have rapidly overtaken 'dumb phones' in recent years. We now turn to the literature dealing with the relative differences between phones and the corresponding effects on driving performance.

Brumby & Seyedi (2012) demonstrated that the type of lock-screen setting and period of inactivity before the phone locks may affect driving performance. They recommend drivers who text to set a longer auto-lock threshold to avoid feeling pressured to finish text messages more quickly, although this pressure in itself may discourage drivers from texting.

It has been demonstrated that entering text on both a touchscreen and a physical keyboard affects performance on a lane change task, but that operating a touchscreen increases workload. Furthermore, we are more prone to making typographical errors on touchscreens (Crandall & Chaparro, 2012). Experienced phone users perform worse on touchscreens than on phones with tactile buttons in terms of text typing speed and eyes-off-road time (Reimer, Mehler, Donmez, et al., 2012).

When comparing handheld typing to text-to-speech functionalities, text-to-speech appears to improve driving performance to some degree but nowhere near baseline driving levels in terms of off-road glance time and mental workload (Owens, McLaughlin, & Sudweeks, 2011). Mobile phone manufacturers expend considerable effort on improving display usability but not always with the aim of minimising distraction (cf. Cuřín et al., 2011).

Neurater et al. (2012) evaluated one particular speech-to-text system, comparing the performance of 24 participants using that system versus a touchscreen device while driving on a closed test track. The participants performed operating tasks on the researchers' touchscreen smartphone or using an aftermarket handsfree kit. When manually operating the smartphone, the participants exhibited reduced lateral control (lane deviation and time out-of-lane), as well as longer (10% of glances over 2 seconds) and more frequent off-road glances, and increased workload compared to the handsfree device. A recent study assessing the voice assistants available on most smartphones (Apple's Siri, Microsoft's Cortana and Android's Google Now) found that these voice assistants still take up considerable mental workload, and advise caution with use while driving (Strayer, Cooper, Turril, Coleman, & Hopman, 2015).

Differences between drivers

Westlake and Boyle (2012) demonstrated that teenage drivers who frequently engage in distracting texting behaviours are more likely to be involved in crashes than adults. This makes them a more likely target for policymakers and other interventionists than those who text less frequently.

Samuel, Pollatsek & Fisher (2011) compared the effect on glancing performance while driving among frequent and infrequent texters, and button (Blackberry) and touchscreen (iPhone) texters. This driving simulator study involved 18 teenage participants. Frequent texters texted at least 20 times per day and infrequent texters 1-5 times per day. Infrequent texters were more likely to keep their gaze within the vehicle (i.e., not on the road) for longer than frequent texters. Blackberry users were somewhat less likely than iPhone users to keep their gaze inside the vehicle. Unfortunately, due to low power, none of these results were statistically significant.

Young drivers are the main group that reports texting frequently while driving (Braitman & McCartt, 2010). Pradhan et al. (2011) studied the effects of 12 months' driving experience among 42 teenage drivers. The study focused on a range of tasks while driving over time included texting, which was assessed on a closed test track. While driving, participants would pass a road worker and it was recorded whether they displayed behaviours indicating caution and whether they suspended the texting task at this point. The results showed that, after 12 months, the participants paid more attention to the road worker, but fewer suspended the texting task. In another study, young drivers (N=20) spent less time watching the road, and displayed less lateral and longitudinal stability while texting compared to normal driving (Hosking et al., 2009).

Professional truck drivers' performance in a truck simulator (N=50) also suffered due to texting/operating their phone. There were more collisions, lane deviations, and glances off road than in baseline driving (Fine et al., 2012).

4.4.2. Behaviour: When do drivers text and how often?

While it is clear that texting and other visual manual tasks have a significant impact on driving performance, they may or may not be considered harmful depending on precisely when drivers perform those tasks. This question has been investigated through a series of questionnaires and, more recently, naturalistic driving observations.

In 2012, Cooper et al. (2013) observed 5,664 vehicles at 129 sites to assess mobile phone use and compared this dataset to a similar one they collected in 2011 (Cooper, Ragland, Ewald, Wasserman, & Murphy, 2012). Over the year, mobile device operation increased substantially, most notably among younger drivers (aged 16-24), from 1.9% in 2011 to 6.3% in 2012. The percentage of overall use almost doubled from 1.7 to 3.3%. The percentage of phone-to-ear was also somewhat higher (from 2.1% in 2011 to 2.4% in 2012); the authors suggest this may relate to rates of smartphone ownership.

Cook & Jones (2011) surveyed 274 college students aged 17-29 and found that more than half texted while driving on a weekly basis, and that 17% accessed the internet while driving. In an Australian questionnaire study of 169 university students (aged 17-24), Nemme & White (2010) reported that attitude, subjective norm and perceived behavioural control were predictive of drivers' intention to text while driving. Students who had a positive attitude towards texting while driving were more likely to do so in practice, and students who had previously read texts while driving were twice as likely to do so again in future. Moreover, students who believed that their peers do not disapprove of texting while driving texted more often.

Half of the 1,057 respondents surveyed by Hallett, Lambert, & Regan (2012) reported sending or reading 1-5 text messages while driving in a typical week despite 89% of participants agreeing that texting while driving impairs general driving performance. It is apparent that people are not aware of the extent of the impairment. Nevertheless, many drivers agreed that reading and typing are 'very distracting' (Lansdown, 2012).

Harrison (2011) also used an online questionnaire to survey 91 students who drove at least once a week. 91% reported that they have texted while driving, with approximately half doing so at least 'fairly often' even though most also believed that texting while driving is dangerous and should be illegal. The majority had not experienced negative consequences when texting while driving (e.g. injuring themselves or others, damaging a vehicle), although 2-4% had done. The majority of respondents also admitted that they themselves noticed the negative effects of texting on driving performance, such as drifting into another lane.

It seems that people generally struggle to ignore incoming text messages. Atchley & Warden (2012) presented a hypothetical choice task to 35 students, which revealed that information in text messages often has immediate value, for only a short period of time. This value also depended on who sent the text. The authors suggested that the urge to text does not necessarily signal an addiction, and it may be effective to recommend that people postpone sending a text while driving. Bayer & Campbell (2012), on the other hand, contended that for some people reading or typing a text is an unconscious or automatic action rather than a rational decision.

In a questionnaire survey of 537 high school students conducted by O'Brien, Goodwin & Foss (2010), 45% reported that they used a phone the last time they drove; 4% said they often initiated a text exchange themselves; 11% replied to texts often; and 23% read text messages often. Risk reduction strategies employed by the respondents included waiting until it feels safe (approximately 50%), although approximately 10% reported that they read texts and reply right away. Most considered texting while driving to be more dangerous than talking on a phone during a trip. Another study (Atchley, Atwood, & Boulton, 2011) surveyed 348 undergraduate students in Lawrence, Kansas, where it was not prohibited to use phones while driving at the time. About 70% reported that they had initiated a text exchange; 81% had replied to a text; and 92% had read a text. Although the respondents did consider these texting behaviours risky, this was not predictive of their behaviour. They also waited until road conditions seemed safer before typing a text than before reading or replying, suggesting some form of cognitive dissonance avoidance, where drivers change their attitude in accordance with their behaviour.

It is possible to argue that whether texting while driving is detrimental to safety depends on the circumstances. Funkhouser & Sayer (2012), for instance, studied naturalistic driving behaviour in 108 participants over a one week period. The participants performed visual-manual tasks on the phone for 2.3% of the driving time, and proved more likely to perform the tasks when stationary than when travelling at higher speeds. The authors argue that this is evidence of some degree of self-regulation.

In 1,432 trips as part of a naturalistic driving study, participants were asked to complete 374 visual-manual phone tasks to assess whether the driving context influences participants' decision to use a phone while driving (Tivesten & Dozza, 2015). The study revealed that participants initiated most of the tasks while stationary, and very few of them while driving at high speeds. They also waited longer to initiate the tasks after completing sharp turns and lane changes. They did not appear to slow down to complete any of the tasks. The authors conclude that drivers do take the driving circumstances into account when deciding to use a phone, but not always to a sufficient extent.

According to a study by Janssen et al. (2010), drivers often use the time a phone takes to load or execute an instruction to switch between a driving and a phone operating task. This behaviour was more common when drivers were asked to prioritise the driving task. It therefore seems worthwhile to continue to promote safe driving and to assess whether phones can be programmed to pause operating tasks regularly. Christoph et al. (2013) studied naturalistic driving data obtained from 21 participants operating their phone approximately 4% of the driving time; 4% of these interactions took longer than 15 seconds. The participants did not appear to slow down while operating.

4.4.3. Texting and crash risk

It seems likely that texting leads to crashes. Drews et al. (2009) asked 40 participants to perform simulated driving tasks with and without a secondary texting task. Reaction time to brake lights, car following task performance (following distance, standard deviation of following distance, and minimal following distance) and lateral performance (lane crossings, lane reversals, lateral distance travelled) were all negatively affected. Moreover, drivers had six crashes while dual tasking, compared to one crash during baseline driving.

Cook & Jones (2011) compared the self-reported phone operating behaviour while driving of young adults responding to a questionnaire to their self-reported traffic citations and crashes. Texting was associated with increased risk of receiving traffic fines, whereas using the internet while driving increased the risk of both receiving citations and being involved in crashes. One disadvantage of this study was that the questionnaire did not ask whether the citations or crashes were due to operating the phone while driving.

A large scale naturalistic driving data analysis combined with cell phone records by Fitch et al. (2013) revealed that crash risk is mainly increased by visual-manual tasks. A naturalistic driving study by Olson et al. (2009) in the US involving 258 commercial vehicle drivers estimated an odds ratio of 23 for texting, i.e. the odds of a safety critical event occurring were highly likely when texting. This was the highest odds ratio reported in the study and compared to other odds ratios, e.g. phone dialling (6) and looking at maps (7), it is very high. The largest and most recent naturalistic driving study (Dingus et al., 2016) revealed odds ratios of 6.1 and 12.2 for texting and dialling respectively.

4.4.4. Conclusions regarding phone use while driving

The literature reveals that performing different phone-related tasks affects driving in different ways. The most important distinction is between talking on the phone and operating the phone. Phone conversations take up driver resources that are needed for driving. They certainly affect driving performance in terms of reaction time, reactions to unexpected events, speed and distance keeping. This may result in slightly more fuel-efficient driving, although it has a negative effect on traffic flow. It is not clear how these effects impact on crash risk.

Early studies showed that crash risk increases by up to four times, but recent studies favour more conservative estimates. It is not entirely clear why this is and the matter should be interpreted with care (Stelling & Hagenzieker, 2012). It is possible that awareness regarding phoning while driving raised by governments, research institutes and the media has helped drivers learn how and when it is most appropriate to start a phone conversation and they now do so in circumstances that are less detrimental to safety. Another factor is that, unlike recent studies early risk studies did not distinguish between talking on a phone and operating a phone while driving.

It is clear that texting has a significant effect on driving safety, at least compared to phoning while driving. We believe the most likely reason for this is that drivers cannot watch the road while operating a phone. For many years, voice control has been considered the solution for increasing the safety of texting while driving (i.e., Graham & Carter, 2001), but although voice control systems have improved over time and are more effective than texting by hand (e.g. Neurauter et al., 2012), they are not perfectly safe and have yet to become popular. Although voice input features have improved, the touchscreen phones that are pervasive at present have increased negative effects on driving and thus road safety.

4.5. Navigation systems: Route guidance

The year 2000 was a key point in the history of navigation systems, when the GPS signal became available for use at a sufficient level of accuracy. The market then expanded rapidly. Research had already been conducted on the less accurate navigation systems available before this time. It is difficult to compare systems over time – new systems are effectively a moving target, they evolve so quickly. However, since operating a navigation system still requires people to drive and follow instructions simultaneously, we can nonetheless learn a good deal from the less recent past.

A study by Parkes, Ashby & Fairclough (1991) asked 20 participants to drive in an unfamiliar area and compared the effects of using paper maps vs a list of written navigation instructions on an LCD display on real life driving and glancing behaviour. It was evident that drivers expend more time (driving more slowly) and effort (increased heartrate) following a route on a paper map than using written instructions. The second experiment in this study assessed two navigation systems, one of which used symbol guidance combined with a simple auditory message, and the other which depicted a map but not a route. Situation-specific route guidance advice delivered better results by reducing off-road glances and driver stress levels. One disadvantage of this study is that it did not conduct a comparison with baseline driving.

We will now turn to studies that focused on information properties, effects on driving, driver behaviour, driver attributes, and potential efficiency gains.

4.5.1. Type of information

For effective route guidance, it is crucial for drivers to receive the right information at the right time. Timing is extremely important because the visual demand of the driving environment may be too high for the driver to also look at the navigation system display. Auditory messages may help overcome this, but the timing of the last message heard is still vital. For information to be useful, it must be easily legible, easy to interpret, complete but brief. Nowakowski et al. (2003) asked experts and ordinary users to assess the usability of four relatively early navigation systems. The issues they identified are nonetheless familiar to us today. In summary, the participants were not always able to locate the start of the route; the text or the maps were too small to read; the instructions provided too little information. The voice commands were sometimes incorrect, imprecise, or mistimed. Ross & Brade (1995) argue that instructions should be given too early rather than too late and developed detailed guidelines for how far in advance instructions should be given depending on the travel speed (speed*1.973+21.307, e.g. when travelling at 100 km/h, an instruction should be given approximately 220 m before the driver needs to execute it). Wu et al. (2009) give an alternative formula for calculating distance before the decision point (speed (km/h) x 2.5 seconds). The authors note that not all navigation systems fulfil this requirement.

There are other reasons why navigation systems' timing is poor. The instructions from some systems are late because they are delayed by the preceding instruction (Brown & Laurier, 2012). In early years, system lag created uncertainty for drivers, for instance when approaching complex junctions (Burnett & Joyner, 1996, 1997).

Several studies have assessed the best way of providing route guidance instructions (Lee, Forlizzi, & Hudson, 2008). They concur that it is best to keep instructions simple, like those drivers receive in the real world. There is evidence that auditory instructions are less demanding than visual instructions, because the driving task itself is already visually demanding (Verwey, 1993). Harms & Patten (2003) found that participants performing a peripheral detection task in a driving simulator were only negatively affected they received visual and auditory instructions, whereas auditory instructions alone had no effect. Drivers are therefore generally advised to activate both the visual and auditory instructions on their navigation system (Harms & Patten, 2003; Kun, Paek, Medenica, Memarović, & Palinko, 2009). Although some auditory instructions do urge drivers to look at their navigation system to verify the instruction visually (Christoph, Van Nes, & Wesseling, 2012), visual guidance in addition to auditory guidance does decrease the number of off-road glances (Jensen, Skov, & Thiruravichandran, 2010).

According to Burnett & Joyner (1996, 1997), a moving map display creates more visual demand than symbols (arrows) alone, but symbols alone create more uncertainty which leads drivers to check the display more frequently. Auditory instructions are therefore the safest option (see also Verwey, 1993). It is also safe to include accurate distance and street name information. Burnett & Joyner (1997) recommend positioning the display near the driver's line of sight, but others add that it should not obstruct the forward road scene (Itoh, Yamashita, & Kawakami, 2005).

Dalton et al. (2013) conducted first a small-scale (N=16) user experience interview, which revealed that 75% of users use both auditory and visual guidance; 25% use only the visual guidance; and 12 users reported that they only look at the display for clarification, elaboration or reminders. The authors then performed an experiment to test whether 20 participants (aged 18-34) are better able to remember a six-step route when presented verbally or visually (paper map or written instructions). The participants had to respond to the stimuli using the four keyboard arrows. The participants made more mistakes under the map condition than under the written and verbal instructions. The authors argue that our working memory apparently functions better when instructions are presented in words than on a map. Next, 26 participants drove in a simulator and encountered conditions of differing verbal complexity (control, simple and complex). Under the most complex conditions, consisting of several simple consequential instructions simultaneously, participants missed more hazardous pedestrians, exhibited less stable steering, and drove faster. The authors argue that auditory instructions are important and valued by drivers, but should be kept as simple as possible.

Although some researchers suggest that drivers should be able to control the pace of aural route instructions by requesting them (Burnett, 1998), others believe it is better not to impose yet another decision on drivers (Zaidel & Noy, 1997).

Since visual information should be considered the most distracting, other modalities for providing route guidance in addition to auditory information have also been considered. Several studies focussed on (vibro) tactile information, for instance embedded into the steering wheel (Kern et al., 2009; Medeiros-Ward, Cooper, Doxon, Strayer, & Provancher, 2010; Ege, Cetin, & Basdogan, 2011) or into the drivers' seat (Van Erp & Van Veen, 2004; Asif & Boll, 2010). Vibro-tactile indications, always in addition to visual and/or auditory cues, may help younger drivers to maintain their focus on the road, but may lead to information overload for older drivers (Kim, Hong, Li, Forlizzi, & Dey, 2012). Some results in this area have been promising, but in the short term it is difficult to make vibro-tactile indications generally available. The navigation system would really need to be integrated into the vehicle, which is slightly more expensive. And since older drivers do not benefit from vibro-tactile information (Kim et al. 2012) and younger drivers generally have less money to spend on cars, any business model would be somewhat bleak.

Information over and above simple route guidance instructions can be useful to drivers. The majority of participants in a simulator study (Allen et al., 1991) approved when navigation systems calculated alternative routes in the event of traffic congestion. However, older drivers (>55) were less willing to take the alternative route. Furthermore, it did not make any difference whether the drivers were familiar with the area or not.

The visual guidance information itself should be clear and resemble the real world, e.g. by adding landmarks to map information. Route guidance advice that includes clear landmarks (e.g. traffic lights, petrol stations, distance, street names) works better than instructions with poor landmarks (e.g. bus stops, post boxes) or that only provide the distance before a turn. In an on-road study in the UK (May & Ross, 2006a), 48 drivers directed approximately 40% fewer glances and spent 40% less time looking at the navigation system with clear landmarks than in either of the other scenarios. Poor landmarks may in fact be worse than distance-to-turn instructions in terms of driver confidence, glancing and navigating performance. Including landmarks in route guidance advice may help reduce navigational errors, also among older drivers (Akamatsu, Yoshioka, Imacho, Daimon, & Noy, 1997). Whilst older drivers tend to glance at the navigation system for slightly longer, they do so less often when landmarks are included in the visual guidance (May, Ross, & Osman, 2005). Including landmarks may also help drivers remember the route better than only a map or cardinal heading (north/east/south/west) (Reagan & Baldwin, 2006).

Augmented reality displays the real world in combination with directions, e.g. by HUD (Head up Display on the windscreen). However, the results are not particularly promising; some components appear more difficult to understand than common navigation systems due to information overload (Akaho et al., 2012).

The route guidance provided by navigation systems also needs to be reliable. From a sample of 872 navigation system users in the UK, only 15% of respondents felt the advice was always reliable (Forbes, 2009). Approximately 82% had received incorrect instructions, and 42% reported having been led on illegal and probably dangerous routes (Forbes, 2009). Remarkably, Forbes also found that it was not only drivers who had not updated their systems' maps who received poor instructions, but also nearly half of the drivers who did so regularly.

4.5.2. What do drivers think and do?

Unreliable systems affect drivers' willingness to follow instructions. It is important for navigation system manufacturers to realise that drivers expect devices to provide absolutely reliable instructions. On the one hand, they may quickly lose their trust in navigation systems when the route advice is disappointing (Ma & Kaber, 2007b). On the other hand, drivers who feel more positively about an in-vehicle system are more inclined to follow its directions (Takayama & Nass, 2008). System proximity is also important, or at least drivers' perception of proximity. Takayama et al (2008) told one group of participants in their study that a driver assistant was in close proximity (in-vehicle), and another group that it was remote (wireless). This manipulation affected the participants' attitude to the system (increased feelings of engagement with in-vehicle systems) and actual driving performance (faster driving). More generally, some drivers may 'race the GPS' (Brown & Laurier, 2012) trying to beat the estimated time of arrival, which may lead them to exceed speed limits.

Leshed et al. (2008) observed and interviewed ten navigation system users and found that some did not feel the need to know their heading; they simply want to enter a destination and drive. Finding a destination is reduced to merely entering it into the system (see also Lo, Green, & Franzblau, 2011). The authors also found that 60% of respondents to their survey reported that they use a navigation system even when they probably are able to reach the destination without assistance. The respondents claimed that instead of learning the route, they learn to follow the instructions correctly. It is true that this entails different tasks; it has now become important to know what 300 m looks like when travelling at a given speed. However, drivers who are less adept at using a navigation system learn the route and remember how it looked (cf. Fenech, Drews, & Bakdash, 2010b). Leshed et al. (2008) also found that not all users follow instructions blindly, but also use the map display to understand and predict the road ahead. Some users said they do not mind not knowing where they are in unfamiliar surroundings, while others frequently zoom out on the map to visualise their location. In areas they know well, some people occasionally disagree with the system's instructions and take another route. Some drivers talk to the system. Others are less engaged with their environment when the system is active.

It is clear that navigation systems change people's wayfinding behaviour. Drivers also feel that using a navigation system is safer than using a map, according to a study into attitudes towards navigation system use (Axon, Speake, & Crawford, 2012). Following route guidance was rated as a low to medium level distraction (2 out of 5) by respondents in a study by Lansdown (2012). Drivers do not feel bound to use navigation systems. Indeed, some 25% of Lansdown's respondents indicated that they follow only their navigation system's advice daily or weekly. In a questionnaire study conducted by Jamson (2013), approximately 50% of respondents indicated that they had their navigation system on while driving 'occasionally', and

20% to 30% 'often'. Drivers who racked up higher mileage were also more frequent users. Most drivers indicate reduced stress and driving effort as important reasons for using a navigation system, which gives them more time to attend to traffic (Harms, Kuiken, & Fokkema, 2008).

4.5.3. How safe is navigation system use?

Navigation systems reduce workload compared to paper maps, but still require off-road glancing (Burnett & Joyner, 1993), for instance when drivers look at the system after receiving auditory instructions (Brown & Laurier, 2012).

There are some indications that driving along unfamiliar routes may be safer than familiar routes as drivers exhibit slower brake responses to unexpected events when driving on familiar routes (i.e. after following a route four times) (Yanko & Spalek, 2013). The effects are different from those of dual tasking in that drivers do not compensate for any heightened risk by increasing headway distance or reducing speed (see Chapter 2). One explanation the authors provide is that driving a familiar route may lead to low mental workload and diminished arousal, which diverts attentional resources elsewhere, which in turn leaves inadequate capacity to react to an unexpected emergency (Yanko & Spalek, 2013). Navigation systems may also help truck drivers take preferred truck routes, i.e. avoiding built-up areas (Arentze, Feng, Robroeks, van Brakel, & Huibers, 2012). Christoph (2010) acknowledged that there is a dearth of (quantitative) data available to make a valid estimate of navigation systems' (net) impact on safety, but based on the literature he favoured the view that the effect is somewhat positive.

To sum up a few best practices from the literature, it is safer for drivers to take the most appropriate roads for their needs (e.g. as many motorways as possible, no short-cuts through built-up areas – especially for trucks) and to use navigation systems with up-to-date maps capable of directing drivers to the most appropriate route (Harms et al., 2008), while it is recommendable to include lane advice as well (Forlizzi, Barley, & Seder, 2010). According to some authors, it is better to have a portable navigation system than an on-board system in terms of route finding quality and safety – they are also cheaper (Lee & Cheng, 2010). Karlsson et al. (2015) report that of 582 experienced navigation system users in Europe interviewed, approximately 30% report an increase in perceived level of safety compared to 10% who report a decrease in perceived safety. A European field operational test (Malta et al., 2012) showed that driving on urban roads may be safer when drivers use a navigation system, observing fewer incidents near intersections. However, the study was not able to estimate the impact on safety due to a lack of data regarding safety mechanisms and actual use.

Haupt, Van Nes & Risser (2015) assessed experienced navigation system users' glancing behaviour at intersections while using either a navigation system or printed instructions to follow a given route. When using the printed instructions, the participants passed the intersections more slowly than when using the navigation system. Participants using navigation systems also glanced to check for potential hazards, whereas drivers using the printed route were busy looking for orientation points. The authors suggest this may be the cause of a 'looked but failed to see' phenomenon, as street name signs are not usually in the same line of sight as potential hazards. It appears that with a navigation system, drivers had more resources available as they did not have to strategically devise a route. On the other hand, the authors reason that this may lead drivers to exhibit more risky behaviour as well (i.e. drive faster), which would negatively affect safety.

4.5.4. Older drivers

Many older drivers may not even want a navigation system, for reasons that include being unfamiliar with technology (Vrkljan & Polgar, 2007). Older drivers therefore relatively often rely on their partner to navigate using a paper map or printed route instructions. Older drivers generally report more wayfinding problems and more often avoid driving in unfamiliar areas (Bryden, Charlton, Oxley, & Lowndes, 2010). Older drivers' working memory is also more limited; according to Trick et al. (2010), recalling route instructions from memory (in the absence of any in-vehicle visual guidance) affects older drivers' reaction time and steering in a simulator. In another study, older drivers reacted slower and made fewer correct turns in a route following task in a driving simulator than younger drivers (Liu, 2001). They also reported higher workload and performed worse when under a higher driving task load. However, both younger and older drivers performed better when both auditory and visual information was supplied than when information was given by either modality alone.

Complex navigation system interfaces and over-abundant features are not appropriate for older drivers, although there are of course exceptions (Emmerson, Guo, Blythe, Namdeo, & Edwards, 2013). There are some indications that at least some areas of navigation system functionality can be improved. For instance, receiving auditory information about upcoming intersections in a driving simulator improved interactions with other traffic (e.g. decelerating less when other vehicles have right of way), and reaction times (Davidse, Hagenzieker, Van Wolffelaar, & Brouwer, 2009). However, the same study did not show improved subjective workload, which may be attributed to the fact that it was a new system. An important clue for keeping it simple comes from Merat et al. (2005), who assessed the effects of two surrogate secondary tasks – a visual information task and an auditory memory task – at several levels of difficulty. They assessed difficulty effects in a driving simulator versus an instrumented vehicle. Older participants (>60) had greater trouble with secondary task performance due to increasing secondary task load while driving than participants aged 25-50. However, no age differences were observed when performing easy secondary tasks while driving. It is important to note that no participants abandoned the secondary task when driving became unsafe.

In a paper comparing and contrasting studies on the effects of driver age, Green (2001) demonstrated that older drivers struggle more with visual driving demand than younger drivers. In a map reading task in a driving simulator, older drivers took longer to complete the task (identify current or cross street name; find a specific street on a map). This effect became even more pronounced when the font size of street names was reduced. When the study was conducted on-road, it produced similar results.

4.6. Operating navigation systems

As we saw in the texting section above, drivers who take their eyes off the road to look at a screen and operate a phone drive significantly less well than undistracted drivers. However, navigation systems generally differ to phones, therefore the effects may be similar but not equal. For instance, most navigation systems are located in a fixed location in the vehicle (may differ per trip), which may change the way they are operated. Furthermore, navigation systems usually only need to be operated once at the start of a trip, whereas phones are usually operated throughout the trip (for whatever reason). Other reasons why operating a navigation system may differ from operating a phone include:

- Drivers use phones much more often, which may imply that they have learnt to operate them more effectively.
- More phones are sold annually. We may be able to infer that more money is spent on phone R&D resulting in better interfaces/touchscreens than navigation systems, enabling drivers to operate them better.

- Having learnt to operate a navigation system, it is a predictable task and drivers are not distracted by unexpected incoming messages.

This list is not intended to be exhaustive, although it provides sufficient reason to study operating navigation systems while driving more closely.

4.6.1. Effects of operating navigation systems on driving performance

Relevant topics to consider are how often drivers enter a destination into navigation systems, how operating navigation systems affects driving performance, design recommendations, and potential improvements. Is it unsafe to operate a navigation system while driving? One way to assess this is by asking drivers. Lansdown (2012) compiled a questionnaire of such questions for a survey of 482 drivers in the UK in 2009. Interestingly, typing a text message was rated as more distracting (4 of 5) than entering a new destination in a navigation system (3 of 5), but fewer respondents (about 35%) reported that they enter destinations while driving than texting (approximately 40% for typing, and 62% for reading text messages). Around 12% of drivers reported that they enter destinations while driving daily or weekly (compared to 25% who text daily or weekly), and destination entry was relatively highly correlated to reported crashes. In a Dutch survey, most respondents did not consider it safe to operate the system while driving, yet the majority (64%) admitted to do so (Harms et al., 2008).

A number of other observable effects on driving are described in several studies. In one driving simulator study (Mora, Tontsch, & Montoro, 2012), 43 participants drove in an advanced simulator once as a baseline and a second time entering destinations into a TomTom Go 710 navigation system. In addition to the basic driving task, participants were asked to identify correct/incorrect traffic signs. The results revealed that the participants' lateral control deteriorated and that they slowed down while entering destinations compared to baseline driving. They were also less able to recognise whether traffic signs were correct or incorrect. Another study (Choi et al., 2013) recorded the effects of text messaging and destination entry on simulated driving performance as well as smoothness of body movements. On average, the 55 participants performed worse at maintaining a constant speed and a constant distance to the vehicle ahead when operating either device compared to baseline driving. Their lateral performance also deteriorated. Smoothness of movement was most reduced during destination entry, although texting also reduced smoothness compared to baseline driving. This study suggests that car handling deteriorates in line with the driver's driving control movements and the results were more pronounced for destination entry than texting. Choi et al. attributed this failure to the fact that the participants were unfamiliar with the navigation system. Ranney et al. (2011, see 4.4.1) asked 100 participants to perform several secondary text entry tasks including destination entry in a driving simulator. Although the destination entry task was less demanding than most of the other text entry tasks it took longer to complete, which exposed the drivers to more risk than the radio tuning and phone operating tasks. In a similar experiment, Ranney et al. (2012) asked 63 participants to perform secondary tasks including radio tuning, destination entry, dialling ten digits and text messaging in a simple driving simulator. This study concluded that text messaging, followed by destination entry, had the greatest impact in terms of lane exceedances and standard deviation of headway distance because of the relatively long duration of the tasks. The fact that drivers find it difficult to abandon a task (Merat et al., 2005) and the relatively long period of time it takes to enter a destination are an undesirable combination.

In view of the apparently robust results on texting, it may be surprising that not all the results regarding programming navigation systems while driving are similarly bad. Chiang, Brooks & Weir (2004) asked ten participants to drive on-road in several different types of real-life traffic conditions. While driving, the participants had to enter destinations on a built-in touchscreen. On average, the entry task took 34 seconds and a little over 17 key strokes to complete. Single keystrokes took 1.0 seconds and double keystrokes 1.5 seconds; 6% of glances took more than 2 seconds. Contrary to most other studies, the authors claim that their results show that drivers are able to enter destinations while driving in actual traffic. One potential reason for this outcome is the fact that the drivers in this study were specifically instructed to drive safely and informed that there was no need to enter the destination quickly. Ensuring that drivers are aware of this might improve driving safety.

Forbes (2009) assessed to what extent drivers are aware of how entering a destination deteriorates their driving by comparing subjective to objective ratings of driving performance, i.e. whether their perceptions are well calibrated. The results suggest that the lateral and longitudinal performance of drivers who were more positive about their driving while entering destinations was indeed better, i.e. they were not over-confident. However, overall, the subjective performance ratings only poorly correlated with the objective ratings, which suggests poor calibration. Drivers were apparently not aware that their behaviour damaged their driving performance. Providing training and informing drivers that operating a navigation system deteriorates their driving performance slightly reduced the frequency with which drivers programmed the system in the driving simulator. It also reduced the time taken to enter a destination. However, these positive effects were minimal and distracted driving performance did not improve.

4.6.2. How often do drivers operate their navigation system?

If driving performance does suffer due to entering a destination in a navigation system, it is important to know how often people perform this task. It may be argued that disabling programming navigation systems while driving does not sufficiently take account of the way drivers really interact with their system (Leshed et al., 2008).

Jamson (2013) questioned 1,500 European drivers (from Italy, Spain, the UK, Poland and Sweden) on their use of nomadic devices. 35%-55% of respondents reported owning a navigation system and 10%-30% reported that they occasionally enter or change a destination while driving. Christoph et al. (2013) studied 21 participants' naturalistic driving data and noted that the participants operated their navigation systems for 1% of the driving time, and 40% of these interactions took more than 15 seconds. Drivers did not seem to slow down while operating the navigation system.

Metz et al. (2014) reported the results of a field operational test in which 110 participants drove one of 15 specially-equipped vehicles for three months: one month with a nomadic navigation system, one month with an integrated navigation system, and one month with no system. The results indicated that drivers adapted their timing when operating the devices, especially on rural and urban roads. They reduced their speed before commencing the operation and increased headway distance during the operation. Lane keeping performance in particular deteriorated when driving with the nomadic device. No more critical driving situations were observed while the participants were operating the systems than in baseline driving.

4.6.3. Potential solutions

It appears that encouraging drivers to prioritise safe driving over completing secondary tasks (see Chiang, Brooks & Weir, 2004) may make operating navigation systems safer. Otherwise, it is better to enable drivers to complete tasks at their own pace, as this encourages longer glances at the road ahead compared to tasks that have to be carried out within a limited timeframe where drivers are able to adapt their engagement with the secondary task to the driving demands (Metz, Schomig, & Kruger, 2011).

The urge to operate a system may arise at any time while driving and drivers (and passengers) dislike not being able to operate their system while driving, which renders manufacturers unwilling to disable that functionality (Burnett, Summerskill, & Porter, 2004). Burnett et al. (2004) therefore argue in favour of finding safe ways of operating them. Although in principle speech recognition appears to have the potential to make input while driving safer, it is difficult to find an optimum setting considering the numerous variables in automated speech recognition (Burnett, 1998). Nevertheless, speech recognition has received considerable attention in the literature.

A driving simulator study by Tsimhoni, Smith & Green (2004) assessed how long it took 24 participants to enter a destination while driving across three different types of destination entry: word-based speech recognition (taking 15s), character-based speech recognition (41s), and a touchscreen keyboard (86 s). It must be noted that the speech recognition system worked particularly well because it was operated by one of the researchers. Driving performance in terms of SDLP was most affected by the manual entry, the speech recognition conditions however did also affect driving, in terms of lateral control, and driving speed. The great question is whether, even a decade later, speech recognition works as trustworthily as in this study.

Tijerina et al (2000) performed a set of studies including one to assess effects of destination entry on driving performance and glance behaviour, and one to examine the SAE recommended practice, at that time still in proposal. The effects of destination entry were assessed on a test track. 16 participants, in two age groups (<35 and >55) completed destination entry tasks on four different navigation systems, varying from manual (non-touch screen) controls to voice control, and radio tuning and dialling phone number tasks. The authors suggested voice control to be the safest task to perform, in terms of lateral control, off-road glancing time, as well as on-road glance duration, the voice controlled device rendered the best recommendable results. Barón & Green (2006) concluded, based on a short literature review that speech interfaces affect driving performance less than manual interfaces in terms of workload, looking away from the road, and lane and speed keeping. However, it is often slower, which is probably not what drivers want.

The literature regarding speech interfaces up until 2005 confirms that:

1. People using speech interfaces drive better in terms of longitudinal and lateral variation than when using manual interfaces, but still worse than baseline driving.
2. Speech interfaces receive lower workload ratings from drivers.
3. Drivers are better able to watch the road with a speed interface than with a manual interface.
4. People are able to perform tasks faster when using a manual interface (Barón & Green, 2006).

Another study showed, however, that although several speech interfaces (i.e. phone number selection and destination entry on a navigation system) had a less negative impact on simulated driving performance (measured using the Lane Change Task, gaze behaviour and subjective ratings) than operating it manually, it still did not nearly approach baseline driving (Maciej & Vollrath, 2009). Strayer et al. (2013) developed a cognitive distraction scale that they validated for several cognitive tasks based on primary and secondary task performance, as well as subjective and physiological measures. The speech recognition task rated higher on a validated cognitive distraction scale than the handheld phone conversation, suggesting that operating via speech may still be underdeveloped for use while driving.

4.6.4. System design

One important factor that affects driving performance during navigation system use is how easy the navigation system is to operate, also referred to as 'usability'. Usability is generally divided into five characteristics (Nielsen, 1993):

1. Learnability (to what extent are first-time users able to perform basic tasks in the system?)
2. Efficiency of use (how quickly can more experienced users perform tasks in the system)
3. Memorability (how well are users able to perform tasks after a period of non-usage?)
4. Few and non-catastrophic errors (how many errors do users make; how serious are those errors; and to what extent can the errors be corrected?)
5. Subjective satisfaction (how much do users enjoy using the system?)

Ideally all of these areas should be accounted for during the design process, i.e. before manufacturing commences. However, little is known about how manufacturers actually tackle usability, nor is it well covered in the literature. It has therefore become common practice to assess the usability of existing navigation systems that have been on the market for many years now (Noel, Nonnecke, & Trick, 2005). Researchers may also run trials with first-time users, experienced users and usability experts to test systems. For instance, Noel et al. (2005) evaluated a navigation system on learnability and memorability among first-time users to identify any problems.

Nowakowski et al. (2003) identified some common safety and usability problems with early devices with respect to destination input as follows:

1. Drivers do not always understand what the different controls do.
2. Drivers are confused about how to navigate via the interface.
3. Drivers are uncertain what the feedback beep does.
4. Drivers do not know how to enter an incomplete address.

When a navigation system fails it can cause driver stress, and even after the system has recovered the driver may still experience higher than pre-failure workload for some time (Morgan, 2008).

With regard to designing navigation system displays, Wickens et al. (2000) identified the following principles:

1. Perception: displays should be legible; conform to user expectations; gain from redundancy (e.g. the message on the display is reinforced by an auditory message); and ensure that different aspects can be correctly differentiated and understood.
2. Mental models: the images on the display should resemble real life, and movement should be represented in the expected direction.
3. Attention: information should be easy to access and presented via multiple resources.
4. Memory: display information so that drivers use as little memory power as possible; make things predictable (e.g. count down the distance to intersections); and ensure that the display is consistent with other displays as much as possible.

Simple human factors research shows that selecting the optimal font is a first, low-cost step towards reducing visual distraction (Reimer, Mehler, Wang, et al., 2012). Kujala & Saariluoma (2011) compared the ease with which drivers located a touchscreen button in a menu structure composed of eithers lists or grids. The results revealed that, at the first-time interaction, the list menu leads to shorter glance durations, especially when the number of items in the list increased (to nine). More traditional address entry system designs are hierarchical and menu based. Graf et al. (2008) demonstrated that search-based entry systems that provide real-time predictive entry suggestions (cf. quick search like most modern internet browsers) can shorten destination entry time. It is also important for designers to take account of users' prior experience (memory). A study by Wilfinger et al. (2012) assessed whether a new five-button entry system was more effective in terms of visual search duration, but the results did not prove better than normal ABC and QWERTY keyboards in any respect. It is clear that predictability plays an important role. Similarly, Jahn et al. (2005) found that short task duration, low visual demand and the ability to pause a task are vital for easy to operate navigation systems. Short task duration requires less memory, and pausing tasks may shift responsibility for the knowledge/memory task away from the driver to the navigation system.

Several road traffic related organisations have developed sets of rules relating to the design and use of navigation systems. Green (2008) produced an overview of a number of guidelines and standards pertaining to driver interface safety and usability. The most salient outcome was that most guidelines stem from an approximately five-year period around the year 2000. Green describes ten ISO guidelines ranging from fairly detailed (use the lane change test, use the occlusion method including performance indicators) to fairly generic ones (perform a hierarchical task analysis and conduct usability testing).

One of the guidelines that received most attention is that of the Society of Automotive Engineers (SAE), J2364, which recommended that destination entry should not take longer than 15 seconds in total (using the occlusion method). Furthermore, navigation functions that can be accessed while driving must not take a sample of ten drivers (aged 45-65 given the opportunity to practice first) longer than 15 seconds to perform while stationary. This 15-second rule has been the subject of extensive debate.

Green (2001) showed that older participants (age >65) were much slower at entering destinations in a driving simulator while stationary than middle aged (40-55) and younger participants (18-30). A more formal evaluation was performed in accordance with SAE's recommended protocol (a concept proposal at the time) (Tijerina et al., 2000). Ten participants aged 55-65 with no prior experience with any of the four navigation systems tested, performed 15 tasks, including ten destination entry tasks, while stationary and while driving. Comparing the results of each task revealed only moderate correlations between task completion time while stationary and while driving. Task completion time was not significantly predictive of lateral performance in terms of lane exceedances, nor were the results particularly consistent over the 15 tasks. However, the SAE recommended practice only related to navigation systems, which required relatively long task completion times and had a relatively high impact on lateral performance.

In a study by Nowakowski, Utsui & Green (2000), eight young (aged 20-28) and eight older (aged 55-65) participants were requested to enter destinations using a keyboard while driving. The older participants took up to twice as long to complete the entry task. Both age groups performed the destination entry task better stationary than when driving in a simulator. The task time during driving was 1.3 times that while stationary.

Jahn, Krems & Gelau (2009) found that task time when stationary corresponded well with both task time while moving and glances at the display. This study also confirmed that learnability is an important aspect, since participants operated the systems that was easiest to operate more quickly, necessitating less off-road glancing. Another study (Nowakowski & Green, 2001) assessed eight young participants (aged 20-30) entering destinations while driving on a real 70 mph two lane road and while parked. When parked, the average task time was 13.2 seconds compared to 15.85 seconds while driving. When controlled for system delay (in accordance with SAE J2364), keying time while parked was 6.13 seconds. Entry time while driving was approximately 1.2 times parked entry time. This is comparable to the results of other studies, which ranged from an increase between 1.1 and 1.7.

The Nomadic Device Forum, part of the EC AIDE project, recommended eight solutions for helping drivers safely install their nomadic device in a vehicle (Reinhardt & Jendrzok, 2009) as follows:

1. Provide mounting instructions in the navigation system's user manual.
2. Provide mounting instructions in the vehicle's user manual.
3. Create a look-up database containing specific mounting instructions for different models of vehicle.
4. Standardise vehicle manufacturers' branded in-vehicle navigation system mounting facilities.
5. Standardise the NaviFix electro-mechanical interface.

Although the NaviFix recommendation is generally considered the best long-term solution, thus far the market has made no coordinated effort to adopt it.

More recently, the US National Highway Traffic Safety Administration proposed further guidelines regarding driver distraction (NHTSA, 2013). NHTSA used manually adjusting the radio as a reference task and set certain limits for time eyes off road (TEOR), total off-road time and glance duration. It also noted several functions that should not be activated while driving in any case: functions not related to driving (e.g. setting the clock), communicating via manual text entry (e.g. texting, browsing the internet), displaying video, images or text that must be read (e.g. web page, book, etc.). Activities such as destination programming should be tested (using a driving simulator and an eye tracker) to ensure a TEOR of no longer than 12 seconds and no more than 12 seconds total shutter open time, i.e. drivers should be able to perform a task within several 1.5 s chunks totalling 12 seconds (Ranney, Baldwin, Smith, Martin, & Mazzae, 2013). Note that, since address formats differ between Germany and the US (Chang, 2010), one design may not suit all countries. Other differences may also be relevant; for instance, Germans are older on average, live in higher population density, and use vehicles differently to Americans.

To summarise, Green's (2008) regulations review concluded that there is no single cheap means of assessing driver distraction induced by a secondary task. ISO which is introducing multiple standards for researching distraction may be on the right track. From a business perspective, however, it may be more reasonable to first introduce a system and develop its usability further over time. In this regard, Ross & Burnett (2001) drew a distinction between *ex ante interface design* and *ex post evaluation methods*. They described how to evaluate navigation systems along several dimensions: context of use (real life context is better but costlier than desk-based research), technique applied (e.g. using a simple checklist or performing a task-based evaluation), subjective vs. objective measures, and experts vs. ordinary users. In all events, it is clear that simply using navigation systems is sufficient to affect drivers on many levels, let alone programming them.

4.6.5. Operating and risk

No studies were discovered that specifically examine how operating navigation systems affects crash risk.

4.6.6. Conclusions

Provided that navigation systems deliver the right information at the right time, most drivers benefit from their use, due to reduced stress and effort. Older drivers may be slightly more distracted by navigation systems and visual information in particular, although it is not clear to what extent. Nevertheless, it seems safe to assert that using a navigation system is safer, including older drivers, than using a paper map to navigate in an unfamiliar area.

Much like texting, driving performance suffers from programming navigation systems while driving, particularly lane keeping performance. Unlike when texting, drivers appear less aware of this – perhaps because people programme their navigation system less often or because navigation system use while driving has received much less attention than phone use. Better system design, including voice operation, combined with raising drivers' awareness of the implications of operating navigation systems, may be avenues for improvement.

4.7. How do impacts on safety relate to efficiency?

It is possible that people do not always consider safety when deciding whether to use a navigation system or a mobile phone while driving. They may regard it as a trade-off between safety and efficiency since most drivers are aware that distracted driving is less safe than normal driving, but still choose to distract themselves because they clearly gain by doing so. The following section explores the efficiency side of this dilemma for each of the tasks identified in Table 2.1.

4.7.1. Efficiency consequences of phone conversations

Time and money

Besides potential effects on road safety (Section 3.1), it may be argued that phone conversations while driving are more efficient. For many drivers, talking on the phone while driving saves a significant amount of valuable time. Brace et al. (2007) conducted a literature review of mobile phone use while driving, including cost-benefit analyses. They concluded that the cost saving value of crashes prevented by banning mobile phone use is in fact almost equal to the lost value of those phone calls not being made.

In general, calmer driving – including slowing down, maintaining longer headway distances, and less speed variation (see Table 4.2) – is more fuel efficient. However, Benedetto et al. (2012) observed sharper deceleration during phone conversations, potentially due to drivers' delayed reaction time. Brookhuis et al. (1991) similarly observed a delay in speed adaptation during phone conversations.

Traffic flow

We must consider not only efficiency for individual drivers, but also for traffic flows. When one driver's lateral and longitudinal performance is affected, other drivers may have to react in order to avoid a crash and cause a chain reaction.

In a four-intersection roadside study conducted at signalised intersections in the US, texting caused longer pull-up time and delaying traffic than phoning (Brumfield & Pulugurtha, 2011). In fact, drivers holding phone conversations pulled up more consistently than drivers who were not on the phone but distracted by other activities, such as grabbing things from other places in the car and watching other people (Brumfield & Pulugurtha, 2011). Knapper (2013) obtained similar results in a driving simulator study. Traffic light waiting time and speed increased whereas acceleration reduced while having a handheld phone conversation while driving compared to baseline driving.

In terms of traffic flow efficiency, Strayer et al. (2011) observed slower brake reaction times during a car-following task, longer time to recover speed, lower speeds, and longer following distances among drivers having either a handheld or a handsfree phone conversation compared to baseline driving. The authors suggest that this compensatory behaviour may increase congestion in the traffic system as a whole since reaction time, speed and following distance affect traffic flow and stability.

Cooper et al. (2009) conducted a driving simulator study to assess the effects of phone conversations in three levels of free-flowing traffic: low, medium and high flow (1,450, 1,850 and 2,250 vehicles per lane per hour respectively and mean speeds of 103, 80.5 and 69.2 km/h). Both the phone conversation and traffic conditions impacted on lane changing performance, speed, likelihood of staying behind a lead vehicle, and increased total trip time. The authors suggested that these effects could have unexpected consequences for traffic flow, especially in relatively dense traffic which easily destabilises. A similar conclusion was drawn by Stavrinos et al. (2013), who asked participants to perform normal versus distracted driving (by a phone conversation and texting) in three different traffic density conditions. During the conversation condition, fewer lane changes were observed than during baseline driving or when texting, but more lane deviations and speed fluctuations, potentially negatively impacting traffic flow.

4.7.2. Efficiency consequences of texting

Many studies show that drivers slow down when texting/operating a device while driving and that speed and distance keeping deteriorate due to drivers' poorer response to their environment (Hosking et al., 2009; Basacik et al., 2012). Texting may also lead to longer pull-up times at signalled intersections more than phoning (Brumfield & Pulugurtha, 2011), delaying traffic and affecting flow.

Stavrinos (2013) asked 75 participants to drive distracted by either texting or a phone conversation versus baseline driving in light, medium and dense traffic in a driving simulator. Several indicators suggested that distraction affects traffic flow: the number of cars the participant overtook, the number of cars that overtook the participant, fluctuations in driving speed, frequency of lane changes (the authors claimed that more lane changes indicate better traffic flow), and scenario completion time. Texting had a negative effect on traffic flow because it led to more speed fluctuations, lower lane change frequency and longer scenario completion time.

It may be possible to increase safety by making texts more efficient to read. Hoffman et al. (2005) found that participants in a simulator directed shorter glances more consistently and less often for longer than two seconds at texts that: 1. had fewer lines of text (1-2 rather than 4); 2. scrolled automatically (rather than manually); 3. scrolled page by page (rather than line by line).

4.7.3. Efficiency consequences of route guidance

Using a navigation system may reduce drivers' exposure to traffic by 5-7% by reducing route length (Oei, 2003). It has been confirmed multiple times that navigation systems lead to shorter routes and possibly also fewer driving and route choice errors, presumably due to reduced workload (TNO, 2008; Antin, Stanley, & Cicora, 2009). In one on-road study, even drivers using a phone equipped with navigation software made fewer wrong turns and spent less time on the road. And even though the routes calculated by the software were not the shortest, drivers spent less time looking at maps and saved driving time (Lee & Cheng, 2008). Early estimates suggested that 50% of drivers using a navigation system would reduce 'navigational waste' by 17% (French, 1986). What is more, route guidance advice could help drivers take more energy-efficient (green) routes by including trip length, trip duration, speed limits, and road gradients (Cerbe, Kuhnert, & Strube, 2009) and consequently lead to a 2% CO_2 reduction (Klunder et al., 2009). Efficiency gains have probably increased even more, now that some navigation systems provide live information on surrounding traffic conditions and traffic jams *en route*, but no studies were conducted in this regard yet.

For truck drivers, navigation systems can increase average travel speed, decrease average travel distance and decrease city road and motorway use in favour of secondary roads. However, truck drivers do not always comply with the suggested routes. Heavy truck drivers more often attempt to find more accessible roads, while drivers of lighter trucks tend to deviate from the advice seeking a faster route (Arentze et al., 2012).

Not only do navigation systems reduce driving exposure by guiding drivers along the most suitable route (Karlsson et al., 2015), many also create efficiency gains by providing congestion information, or by transmitting job instructions to professional drivers (ETSC, 2010). One potential disadvantage of drivers changing their route to avoid heavy traffic is that road networks may become more difficult for governments to manage and maintain (SWOV, 2010). Furthermore, the advantages of fewer kilometres per trip and reduced driving stress are sometimes cancelled out by more trips per vehicle (Karlsson et al., 2015).

Navigations systems, like smartphones, are sometimes equipped with additional software applications to provide drivers with information about the current road conditions (e.g. road works). Although these additional features may increase workload to some extent, the value of the information may compensate for this (Creaser & Manser, 2012), which may be an interesting equilibrium.

4.7.4. Efficiency consequences of operating navigation systems

People multitask to increase their efficiency. It could therefore be suggested that it is generally more energy efficient to operate a navigation system while driving than pulling over. Burnett et al. (2004) argue that since – on many trips – drivers generally drive through areas with which they are at least somewhat familiar (e.g. in their hometown), they often only wish to receive navigation advice for part of the trip, and therefore enter the destination at some point during the trip rather than from the outset. Drivers may also do this to avoid needless distraction from their navigation system while in familiar territory.

4.7.5. Conclusions

It seems safe to suggest that the predominant efficiency gain from operating a phone or a navigation system comes from not having to stop driving. The effects on longitudinal driving performance in particular may negatively impact on traffic flow, even leading to traffic jams. The evidence suggests that it is more efficient for both individual drivers and the traffic system to use navigation systems for route guidance, although road networks and traffic flows may become more difficult for local authorities to control.

4.8. Answers to the research questions and conclusions

From the discussion above, the body of research surrounding this dissertation is both broad and extensive. The research questions that were posed in Section 4.1 will now be answered as far as possible.

1. *Which impacts on safety are the result of drivers using current models of mobile phone and navigation system?*

The majority of this chapter dealt with the literature on how mobile phones and navigation systems impact on driving safety. Four phone and navigation system tasks are the focus: holding phone conversations, operating mobile phones, operating navigation systems and following route guidance advice from navigation systems.

What is striking with regard to phone conversations is that recent literature seems to be divided into two schools of thought. The first is the longer-held belief that phone use accounts for a four-fold increase in crash risk based on risk studies (Redelmeier & Tibshirani, 1997; McEvoy et al., 2005), without drawing a distinction between holding conversations and operating the phone. The more recent school of thought based on naturalistic driving studies (Olson et al., 2009; Fitch et al., 2013) is that phone conversations per se have a much smaller to almost no effect at all on (near) crash risk (Dingus et al., 2016). Researchers on this side of the fence recommend studying conversations and phone operations separately, but there are no simple answers. Every choice researchers make in relation to data collection, analysis and interpretation is significant and renders difficulties with respect to reproducibility (Silberzahn & Uhlmann, 2015). Even meta-analyses are vulnerable to these issues, as they may result in research not being published, which may lead to biased metastudies. The recent publication by Dingus et al. (2016) based solely on crashes (no near crashes) in the largest naturalistic driving study to date seems to provide good evidence that handheld phone conversations are associated with a 2.2 odds ratio of being involved in a crash.

There is almost no contention regarding the assertion that phone conversations affect reaction time, speed and headway distance control. Under specific circumstances, such as in built-up areas where children are playing, it is therefore ill-advisable to talk on the phone while driving. All the more so since, in order to initiate or answer a phone call, drivers must take their eyes off the road to reach for the phone and operate it (i.e. dial a number/select a contact, swipe or press a button) (Klauer et al., 2014).

The effects of texting on driving safety are more clear-cut. Texting on smartphones without physical keyboard feedback impedes drivers from watching the road even more than texting on older 'dumb phone' models. Texting affects lateral performance and reaction times, increasing crash risk (Victor et al., 2015).

Following route guidance advice from a navigation system is safer than using a paper map, provided that the information is presented in a digestible format in good time. This helps drivers feel less stressed, allows them more time to watch the road, and minimises their exposure to traffic and driving in general. Nevertheless, drivers should avoid operating navigation systems while driving which, like texting, negatively impacts their lateral performance. Furthermore, since drivers tend to operate navigation systems much less often, the effects may be worse than texting. Finally, people tend to be less aware of the negative effects of operating navigation systems because the issue receives less attention in both the media and the literature.

2. *How do these safety impacts relate to efficiency ?*

As discussed in Section 4.7, the relationship between the effects of using phones and navigation systems while driving on safety and efficiency is complex. In terms of efficiency, some experienced individuals can perform two tasks at the same time to an adequate degree (albeit less well than when performing them exclusively), resulting in an efficiency gain. However, this may not be sufficient to offset the increased crash risk associated with operating a device while driving in general.

Road traffic flow efficiency is negatively impacted by both operating devices and holding phone conversations due to lower speeds, longer reaction times and longer headway distances. However, route guidance advice from navigation systems optimises route choice and has a positive effect on the efficiency of individual drivers and broader traffic systems. It also reduces drivers' mental workload which produces a two-fold efficiency gain of reducing stress and freeing up resources to allocate to watching traffic and performing the driving task.

3. *How comparable are these impacts across the two types of devices, and 4. what gaps are there in the current body of research?*

When using mobile phones and navigation systems , drivers perform a range of similar tasks (operating) and dissimilar ones (conversing versus following route guidance instructions). It is therefore important to assess the effects of using both types of devices to understand how and why they affect driving performance and consequently safety and efficiency. The effects are often comparable; operating both kinds of devices affects driving performance especially glancing and lateral performance (see the HASTE findings (Carsten & Brookhuis, 2005)). But there are also notable differences due to the different types of interface, drivers' experience with these interfaces, the position of the devices within the vehicle, the goals drivers aim to achieve, and the timing of when drivers wish and decide to operate the different devices.

While researchers have now concluded that operating phones and navigation systems has similar effects on driving performance, this conclusion was reached in different ways for each type of device. Research relating to navigation systems was instigated in response to various regulations and guidelines governing their use – the first of which was the SAE J2364 (Green, 2008). It is clear that driving-related regulations were established for navigation systems but not for phones because only the former are specifically designed for use while driving. Studies also reveal that the often longer duration of navigation systems task exacerbates the negative effects of use. And yet vastly more research has been carried out in relation to the usability of mobile phones while driving, since sales figures far outstrip navigation systems by far.

This difference reveals an important gap in the literature; there is not enough know-how about drivers' use of navigation systems in real-life driving, nor how this compares to phone usage. After all, if drivers tend to interact with their navigation systems frequently but only in brief chunks and under fairly simple driving conditions, should it then still be considered a significant issue? And will improve safety by promoting best practices in this regard?

Most navigation systems work satisfactorily – with room for improvement on certain points (Nowakowski et al., 2003). For instance, navigation systems produced in Europe are adapted to the American market (and vice versa) in terms of address layout and order of entry (Chang, 2010). But it is unknown, where, when or how often real drivers use and operate their navigation systems while driving.

Another gap is that it is unknown to what extent drivers comply with route and traffic instructions provided by their navigation system. It is possible that navigation systems manufacturers have indeed examined this issue, but such studies are not acknowledged.

Finally, from the review of the literature, it seems recommendable that distraction among specific groups of drivers, such as commercial truck and bus drivers (i.e. Morgan et al., 2011), merits further research.

4.8.1. Conclusion and preview

In summary, visually distracting tasks generally affect steering and lateral control, whereas cognitive distractions affect longitudinal control, in terms of car following. While most people are aware that it is unsafe to operate devices while driving, many continue to do so. This dysfunctional use of mobile phones could warrant further investigation by psychologists as an aspect of (cyber) addiction (Billieux, 2012). It would also be valuable to focus more research on younger drivers, who are most prone to using devices and whose driving performance suffers most (Tractinsky et al., 2013). The question also remains as to how often drivers are distracted and which types of traffic participants are involved, as the different research methods used to date do not all point in the same direction (Stelling & Hagenzieker, 2012).

Since considerable time and resources have already been dedicated to investigating phone and navigation system use while driving, some may question whether yet another study (or set of studies), i.e. the present thesis would add anything to the body of knowledge. However, this thesis extends the knowledge in several respects. Firstly, multiple research methods to examine the behaviour of the same types of drivers have been applied through repeated measurements. In a driving simulator study discussed in Chapter 5, the effects of both navigation systems and mobile phones have been investigated. The route and some of the tasks used in the driving simulator study were in fact replicated from the field test, as covered in Chapter 6, establishing a validation assessment of how suited driving simulators are to testing driver distraction. The same drivers then participated in the naturalistic driving study in Chapter 7, which described how and when drivers use navigation systems while driving in naturalistic circumstances.

Drivers using these devices were examined, both when unprompted and under instruction, enabling the assessment of to what extent drivers who exhibit undesirable device usage in real driving are actually affected. Drivers were observed unobtrusively with regard to what they do while driving and how this affects their driving behaviour, describing this behaviour in more detail, hopefully gaining a still better understanding of why these behaviours occur.

5. Do in-car devices affect experienced users' driving performance?[6]

Abstract

Distracted driving is considered to be an important factor in road safety. To investigate how experienced user's driving behaviour is affected by in-vehicle technology, a fixed-base driving simulator was used. 20 participants drove twice in a rich simulated traffic environment while performing secondary, i.e. mobile phone and navigation system tasks. The results show that mean speed was lower in all experimental conditions, compared to baseline driving, while subjective effort increased. Lateral performance deteriorated only during visual-manual tasks, i.e. texting and destination entry, in which the participants glanced off the forward road for a substantial amount of time. Being experienced in manipulating in-car devices does not solve the problem of dual tasking when the primary task is a complex task like driving a moving vehicle. The results and discussion may shed some light on the current debate regarding phone use hazards.

[6] Knapper, A.S., Hagenzieker, M.P. & Brookhuis, K.A. (2015). Do in-car devices affect experienced users' driving performance? *IATSS Research, vol. 39*, p. 72-78

5.1. Introduction

The driving task is complex; next to managing the vehicle to stay on the road properly, the driver has to deal with thoughts, speed limits, flies, children, and other drivers who are doing similar things at the same time. Recent years have provided us with vast technological developments like smart phones and navigation systems, adding ease to life in general, but largely increasing the potential for the driver to engage in other, distracting, tasks while driving.

Distraction from driving has many faces, but basically consists of visual, manual, cognitive and auditory distraction (Ranney et al., 2000). Distractions may often combine these four modes (e.g., dialling the radio likely involves visual, auditory and manual resources). Definitions of distraction may be summarized as *diversion of attention away from driving, to a competing task* (see Basacik & Stevens, 2008; Lee et al., 2009).

In the 100-car naturalistic driving study, 100 instrumented cars were driven for a year or more, during which 69 crashes and 761 near-crashes occurred. Analyses showed that 80% of the drivers were inattentive to the road ahead at the moment just before a crash, while 65% of the drivers were inattentive before a near-crash (Dingus et al., 2006b). Both crashes and near crashes were highly associated with cell phone and PDA (Personal Digital Assistant) use. Since the 100-car study large numbers of (smart) phones and also navigation systems have been sold, so the problem has likely aggravated. The current study therefore specifically focuses on the effects of a (contemporary) navigation system as well as drivers using their own mobile (smart) phones on driving performance.

The tasks associated with navigation systems and smart phones are, however, substantially different; phones may be used for having conversations, which is a cognitive, auditory task, as well as for operating tasks such as texting, e-mailing or 'facebooking'/'twittering', which is visual-manual with cognitive components. Navigation systems may provide route guidance instructions (auditory and visual), but at least the destination needs to be programmed, which may be done while driving (visual-manual task). Where phone conversations while driving have been investigated in an abundance of studies, texting and, in particular navigation systems related tasks were relatively scarcely the topic of investigation.

5.1.1. Mobile (smart) phones

Phone use while driving has been present and investigated for more than two decades (see Brookhuis et al., 1991). Effects of phone conversations while driving have been assessed using driving simulators, instrumented vehicles on normal roads and on test tracks (a recent review of the literature can be found in Kircher et al., 2011). Nevertheless, effects on driving performance, or more specifically on crash risk, are still under substantial debate (Hickman et al., 2010; Young, 2012b). Many countries have only forbidden handheld phone conversations (ETSC, 2010), in spite of the fact that hands free conversations may cause equivalent effects on driving performance (McEvoy et al., 2005; Horrey & Wickens, 2006). Potential effects of phone conversations while driving include a reduction in visual scanning for other traffic (Harbluk, Noy, Trbovich, & Eizenman, 2007), which leads to a 'gaze' (Victor, Harbluk, & Engström, 2005) to the centre of the road ahead. This effect may lead to reduced detection of peripheral events, for instance, traffic signs (Strayer & Drews, 2007), whereas lane keeping performance seems to be hardly influenced (Törnros & Bolling, 2005). Handheld conversations while driving lead to lower speed (Patten, Kircher, Östlund, & Nilsson, 2004; Törnros & Bolling, 2005), whereas hands free driving may even increase speed compared to baseline driving (Patten et al., 2004). Furthermore, having a phone conversation has been shown to increase workload anyway (Rakauskas, Gugerty, & Ward, 2004).

Operating a phone while driving has only become increasingly popular in the last decade, but few studies have assessed operating a phone compared to conversations per se. Still, it has been recognized as a hazard; While being involved in a phone conversation predominantly leads to cognitive distraction, reading and operating will additionally lead not only to visual distraction (Brookhuis & Dicke, 2009; Owens et al., 2011), but may also have a physical effect. This may lead to a substantial increase in reaction time (Cooper et al., 2011), as well as deteriorated lateral control (Drews et al., 2009; Owens et al., 2011; Alosco et al., 2012) and reduced speed (Törnros & Bolling, 2005; Cooper et al., 2011). Furthermore, drivers report higher mental workload while texting (Owens et al., 2011).

5.1.2. Navigation systems

Navigation systems have been available for drivers in private cars for about 15 years, and in recent years have become increasingly affordable for the mass market. Portable specific navigation devices are the topic in this study, specifically nomadic devices that are brought into the car by the driver, although navigation software has become available on smartphones as well (Ghosh & Cowan, 2011). Effects on driving performance have not received much attention in the literature.

The main function of a navigation system is to provide route guidance to a driver, turn by turn, visually and/or auditory. The driver does not need any paper map, notes with instructions, or pre-trip search and learning by heart. Compared to driving with a paper map, route guidance has been found to decrease mental workload, increase speed and improve drivers' lateral performance (Srinivasan, 1997). Though leading to a somewhat increased speed, route guidance decreases drivers' exposure to traffic due to the shortened routes, which might be safer (Feenstra, Hogema, & Vonk, 2008; Lee & Cheng, 2008).

At the start of the ride, the navigation system must be programmed in order to provide the proper route guidance. Besides destination entry, drivers may operate the device for several other reasons such as adjusting the volume or the screen or check for current traffic jams on the route. Most often, this is done using a touch screen, although other options such as voice control and remote controls are available as well.

Compared to voice control, destination entry through a touch screen keyboard requires much more time to complete, and renders a higher standard deviation of lateral position (SDLP) (Tsimhoni et al., 2004). It has also been reported that drivers tend to drive with reduced speed while operating a navigation system (Chiang et al., 2004; Tsimhoni et al., 2004) and that they look less towards the road ahead (Tijerina, Parmer, & Goodman, 1998; Chiang et al., 2004).

5.1.3. Approach

The current study investigates several types of distraction to the same experienced users in the same environment. The distractions come from two types of modern, extended devices that have improved considerably over the years, as may have drivers' strategies of using them. Experienced users have learned to some extent to use the devices which could lead both to lower task demands (as the secondary task may be easier) and a higher capability of dual tasking (Task Capability Interface model, Fuller, 2005). Thus, they may be expected to show fewer negative (learning) effects while participating in the study (cf Shinar, Tractinsky, & Compton, 2005).

The main research question is: to what extent is driving, in a driving simulator, affected by two current sources of distraction, i.e. navigation system and mobile phone use. Specifically, driving performance is investigated while following route guidance and performing destination entry, while having mobile phone conversations and texting, as compared to driving without secondary task.

5.2. Method

5.2.1. Participants

In total 21 paid volunteers participated, one suffered from simulator sickness and was removed from the study, i.e. 20 persons remained. They were recruited via posters and newsletters at Delft University of Technology (DUT). All participants reported to be frequent users (at least once a week) of both navigation systems and mobile phones, and indicated to drive at least 10,000 kilometres per year (M=23,638, SD=6,893). The research sample consisted of 6 females and 14 males aged 27 – 59 (M=37.65; SD=9.75) and had their drivers' license for 2 to 39 years (M=15.55, SD=9.32). By definition of Rothengatter et al. (1993), the sample does not include any novice drivers, and most (13 of 20) participants should be classified as very experienced drivers.

5.2.2. Apparatus & driving environment

The fixed base driving simulator (see Figure 1) consisted of a mock up car with real car seat and controls, and three screens. Its software was developed by StSoftware © (Van Wolffelaar & Van Winsum, 1992). The system allowed for recording several variables, derived from lateral and longitudinal position in the virtual world such as speed and position on the road, at 10 Hz. Two webcams were used to record drivers' face and the central screen. The simulator was set up in an air conditioned room that allowed for a constant 20 degrees Celsius, in order to minimize simulator sickness (Stoner et al., 2011).

Figure 5.1: The driving simulator, with the touch screen navigation system attached to the right-hand screen.

Two simulated tracks were implemented that resembled different parts of a 'real' route that was driven in the framework of the EU INTERACTION project in the Delft-Leidschendam area. The first track consisted of about 10 km urban area (50 km/h speed limit) and 9 km of motorway (100 km/h limit), while the second track resembled a 10 km interurban road consisting of several speed zones (50, 70, 80, 100 km/h). Road signs, layout and size were simulated as accurately as possible, whereas other surroundings (buildings, trees, etc.) were mimicked more loosely. Other traffic was programmed to drive interactively, resembling off-peak real life traffic density. The first two kilometres of both tracks were used for familiarising participants with driving in the simulator.

5.2.3. Experimental design

The repeated measures research design consisted of four experimental conditions: phone conversation, texting, driving with route guidance and entering a destination, each with a baseline condition. The comparative condition for driving with route guidance consisted of way finding using a paper map, while the baseline for all experimental conditions involved driving the same route without a device.

Each participant participated in all (eight) conditions. Carryover and learning effects were controlled for by partial and reverse counterbalancing.

The partial counterbalancing was performed for track 1 (see Table 5.1), on which the driving with route guidance, texting and destination entering were performed. The destination entry section was followed by the texting section, and difficult to perform. Therefore it was decided never to combine them in one drive. Furthermore, for convenience reasons it was decided that phoning and texting could always take place in a single session, so participants only needed to bring their personal (smart) phone to one session (see Section 5.2.5.1).

Next, the two tracks (see Table 5.1) were reverse counterbalanced over the two meetings, so drivers could meet four distinct track orders (i.e., first drive track order 1 → 2, second drive 2 →1, or vice versa). In total, this led to eight distinct potential orders, and participants were assigned such that at least two met each of the eight orders.

Table 5.1: Four tasks, each with baseline condition, and assignment to tracks.

	Track 1			Track 2
Layout Speed limits (km/h)	Urban 50	Urban 50	Motorway 100	Interurban 50,70,80,100
Phone tasks			Texting	Handheld conversation
Phone baseline			Normal driving	Normal driving
Navigation system task	Follow route guidance	Destination entry		
Navigation system baseline	Paper map way finding	Normal driving		

5.2.4. Procedure & materials

Participants were asked to drive in the simulator twice, with at least seven days between appointments. Five participants were driving the simulator prior to participating in other parts of the INTERACTION project on a comparable route. They provided their informed consent during the first visit, while the others had already consented to participate in the full study. Each visit to the simulator, the participants were told they would have two drives, with a short break in between during which a few questionnaires would have to be completed.

The questionnaires contained the Rating Scale Mental Effort, RSME (Zijlstra & Van Doorn, 1985; Zijlstra, 1993) in order to get an indication of how much effort drivers reported to put into each task. Next, during the first drive, another questionnaire, developed in the INTERACTION project, was filled in, and in the second meeting break the Driver Behaviour Questionnaire, DBQ (as used in Reason et al., 1990; Lajunen, Parker, & Summala, 2004) was completed.

Before the start, the participants were provided with information about the test drive, dependent on the specific experimental condition they were in. They were always instructed to drive as they normally would. Bugs in the software could occasionally cause objects to behave unnaturally (i.e., indicating the wrong way, not giving priority), due to the complex environment, thus instructed, this was ignored by the participants. Participants were informed that cameras would be recording them. After they had adjusted their seat and felt comfortable, the test drive was started. The fact that each drive included over two kilometres of getting used to driving the simulator was not told to the participants in order to avoid any intentional changes in behaviour.

After finishing the two drives, the participant filled in RSME's for the remaining conditions, and signed a receipt for receiving a gift voucher.

5.2.5. In-vehicle tasks

Phone conversations

Participants were requested to use their own (smart) phone for texting and having a conversation.

For the handheld phone conversation, the participant was called by an experimenter, from a remote location. The experimenter held a conversation based on a questionnaire that was devised for the INTERACTION project, which consisted of (translated) questions from the Rosenbaum Verbal Cognitive Test Battery (as used in Waugh et al., 2000; see Rakauskas, Ward, Bernat, Cadwallade, & De Waard, 2005), and of questions used by (2008). It consisted of four blocks with five types of questions: True or false questions (e.g., France is a bigger country than Luxembourg), listing questions (i.e. towns beginning with an A), describing questions (i.e., describe a relative), repeating a sentence and answering a question (e.g., which girl is taller if Jane is shorter than Kim?). Each conversation took about seven minutes.

Texting
Texting was performed on a nine kilometre motorway track (speed limit 100 km/h). When the participant reached a certain point, the experimenter asked whether he or she was ready to send a few text messages, allowing the participant to reach for the phone. Then the experimenter asked the participant to text the first sentence from Dutch children's songs (four different texts of 50-63 characters). As soon as the participant had finished texting, the experimenter asked to type in the next text, going on to a maximum of four texts, depending on the participant's texting speed.

Route guidance versus paper map
Driving with route guidance was implemented using the driving simulator's built-in device resembling a simple navigation device mounted on the dashboard providing auditory and visual (arrows) cues 200 and 50 meters before the turn. In the 'no guidance' condition, participants received a paper map of the driving environment (see Figure 5.2). Participants were informed that all intersecting streets and side-streets present were also drawn, the tunnels/overpasses (grey) and roundabouts were shown on the map, and the first two were shown in the simulator to give the participant a feeling of the map's scale. In case the participant was about to take a wrong turn, the experimenter interfered, redirected and registered the error.

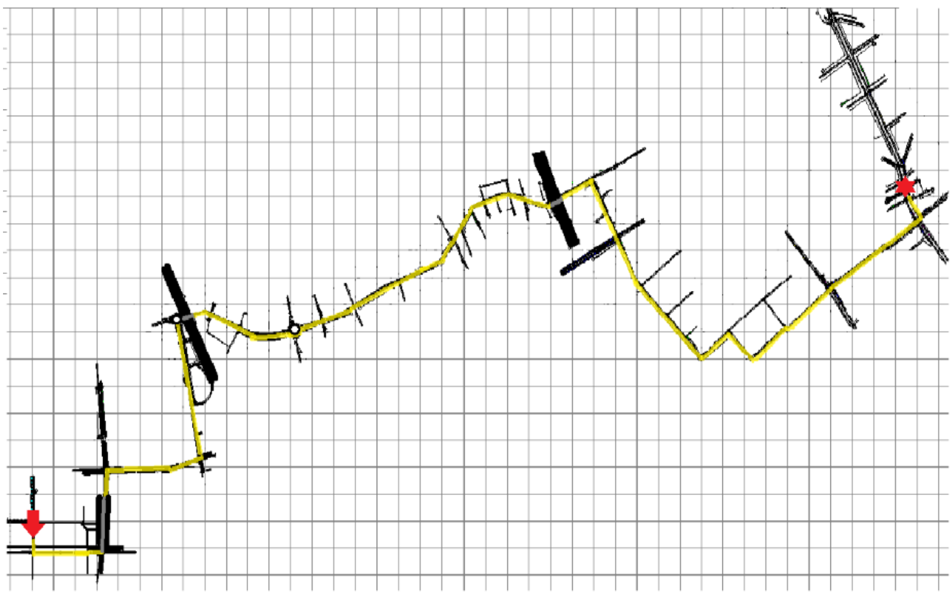

Figure 5.2: The paper map. Participants were requested to use this map to drive from the starting point (red arrow) to the red asterisk.

Destination entry
A retail TomTom XL Live navigation system was used for destination entry. Before the drive, participants were asked to demonstrate how they would enter a destination, to check whether they understood the device menu. When an example destination was entered successfully, the drive started. During the drive, the experimenter read six destinations that would take 14 to 17 button operations each. As soon as a destination entry was finished and the route had been selected, the experimenter would read the next, to keep the participant constantly busy entering destinations until reaching the end of the selected part of the route.

5.2.6. Dependent variables

On the one hand, a driver may compensate for a secondary task, increasing demand, by decreasing speed. On the other hand speed and trajectory may not be compensated for due to too high task demands, leading to loss of control (cf., Fuller, 2005). The measures of driving performance thus included speed, standard deviation of speed and standard deviation of lateral position (SDLP). In order to calculate the SDLP, lane changes were removed from the data, and SDLP was calculated for each driving lane. Furthermore, RSME scores were obtained, following Fuller's reasoning (Fuller, 2005) that through 'stepping on the accelerator of mental (…) effort' (p. 464), the capability component of the TCI model may increase. Looking ahead is regarded a high priority task by (Fuller, 2005), that may suffer from increasing task demands. Therefore glancing behaviour in terms of percentage of time eyes off the road (%TEOR) and number of glances off the road (#GEOR) were assessed. Glancing behaviour was scored manually, based on the webcam recordings, using six-second movies (14 frames per second) starting on fixed locations, and should therefore be considered a coarse measure. Concerning secondary task performance, the number of texts sent, destinations programmed, the number of questions answered during the phone conversations and the number of route errors were recorded. Only straight sections where drivers could select their driving speed freely were included in the analyses.

Pairs of variables with non-normally distributed difference scores (Kolmogorov-Smirnov test with Lillifors correction, $p<.05$) were analysed using the Wilcoxon signed-rank test, other variables that did meet the assumption of normally distributed data were analysed using the paired samples t-test.

The experimental conditions differed in, for instance, the specific speed limits present on the route, due to the fact that a real world route was replicated. For that reason analysing statistical differences between conditions was not regarded useful. Therefore, only baselines and experimental conditions for each variable on each task are compared.

5.3. Results

5.3.1. Phone conversation

Table 5.2 (page 108) shows the results for the phoning task versus baseline driving. As this task was performed on a ring road with several different speed limits, results are presented for all four different speed limits separately. We found no significant effects on SDLP, but drivers did slow down significantly during the phone conversation compared to baseline. This was, however, not the case for the 50 km/h speed limit section (see Figure 5.3). The phone conversation rendered higher scores for RSME, and participants glanced off the forward road less often, and for a shorter period of time.

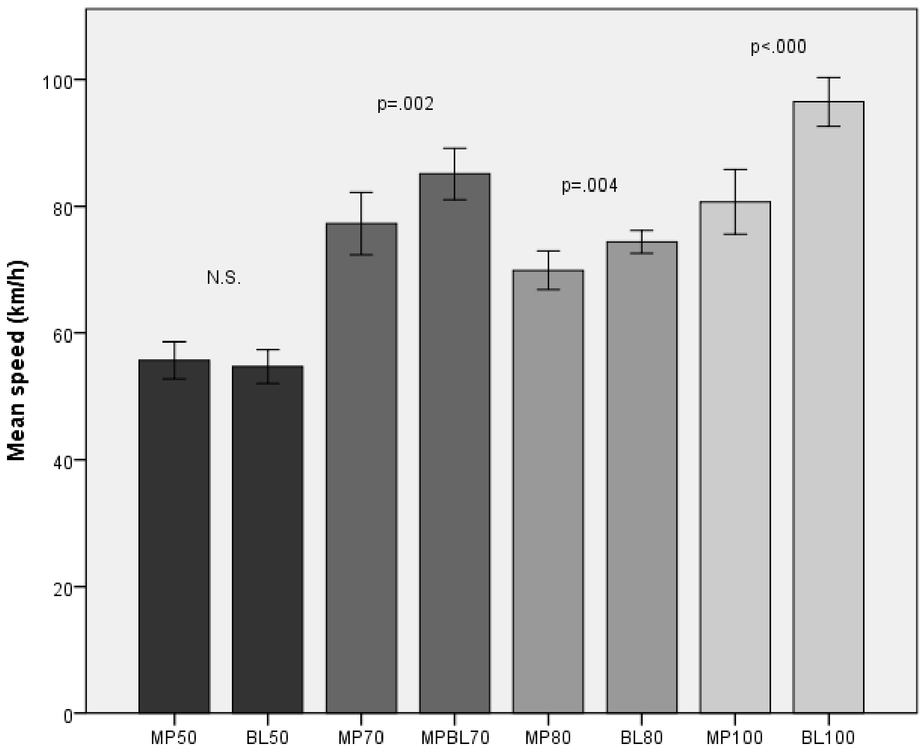

Figure 5.3: Mean speed including 95% confidence intervals and p-values during a phone conversation (MP) and baseline (BL) driving for the four speed limits (i.e., 50, 70, 80, 100 km/h).

Table 5.2: Means and standard deviations (in parentheses) for (handheld) phone conversations and their respective baseline (N=20), and effect sizes for significant pairs.

Speed limit (km/h)	**50**		**70**		**80**		**100**	
Length analysed (m)	**150**		**200**		**1,600**		**1,200**	
Condition	**Phone**	**Baseline**	**Phone**	**Baseline**	**Phone**	**Baseline**	**Phone**	**Baseline**
Mean speed (km/h)	55.70 (6.27)	54.72 (5.72)	77.27 (10.59)	85.11 (8.62)	69.89 (6.47)	74.37 (3.87)	80.69 (10.91)	96.47 (8.22)
Test statistic, p-value	*t*=.54, *p*=.60		z=-3.50, *p*=.002*		*t*=-3.26, *p*=.004*		*t*=-5.44, *p*=.000*	
Effect size (r)	N.S.		r=-.63		r=.60		r=.78	
SD of speed (km/h)	3.14 (1.32)	2.29 (1.05)	6.50 (3.32)	10.10 (3.93)	3.72 (.94)	3.34 (.81)	2.59 (.82)	1.80 (0.57)
Test statistic, p-value	*t*=2.66, *p*=.016		*t*=-2.77, *p*=.012		*z*=-1.33, *p*=.200		*t*=3.603, *p*=.002*	
Effect size (r)	r=.52		r=.54		N.S.		r=.64	
SD of lateral position (m)	.128 (.062)	.096 (.055)	.177 (.090)	.144 (.087)	.224 (.048)	.198 (.046)	.207 (.063)	.222 (.066)
Test statistic, p-value	*t*=1.91, *p*=.071		*t*=1.08, *p*=.296		*t*=1.78, *p*=.091		*t*=-.83, *p*=.416	
Effect size (r)	N.S.		N.S.		N.S.		N.S.	
Percentage time eyes off forward road (%)							6.32 (8.11)	15.00 (10.77)
Test statistic, p-value							*t*=-3.28 *p*=.004*	
Effect size (r)							r=-.60	
Number of times eyes off forward road (#)							.55 (.61)	1.50 (1.10)
Test statistic, p-value							*z*=-3.08, *p*=.002*	
Effect size (r)							r=-.69	
Average duration of glance off road (s)							.298 (.370)	.503 (.344)
Test statistic, p-value							*t*=-1.91, *p*=.071	
Effect size (r)							N.S.	
Max glance duration off road (s)							.635 (.371)	.614 (.329)
Test statistic, p-value							*t*=.19, *p*=.901	
Effect size (r)							N.S.	
Rating scale mental effort (mm)							73.00 (19.67)	37.55 (24.69)
Test statistic, p-value							*t*=5.26, *p*=.000*	
Effect size (r)							r=.77	

* Significant at α=.05 (2-tailed), t refers to t-test, *z* refers to Wilcoxon Signed-rank test for non-normal data.

Note: r is calculated using $r = \sqrt{\frac{t^2}{t^2+df}}$ for paired samples t-tests, and $r = \frac{Z}{\sqrt{N}}$ for Wilcoxons Signed-Rank tests. Results for eyes glancing were obtained only at a 100 km/h section, RSME scores regard the entire condition.

5.3.2. Texting

The results for texting are shown in Table 5.3. Texting was performed on a 100 km/h motorway. Results show a substantial reduction in speed during texting, as well as a higher standard deviation of speed and a considerably increased SDLP. Participants glanced off the road ahead for a longer period of time, and also more often. Furthermore, the average and maximum glance duration was longer. Effort ratings were substantially higher for the texting condition than in the baseline condition. During texting, four crashes occurred that were most probably due to having the eyes off the road and swerving (the crashes were removed from the data).

Table 5.3: Means and standard deviations (in parentheses) for texting and their respective baseline (N=20).

Speed limit (km/h)	**100**	
Approx. length analysed (m)	**5,100**	
Condition	**Texting**	**Baseline**
Mean speed (km/h)	93.39 (11.70)	107.04 (12.05)
Test statistic, p-value, effect size (r)	*t*=-5.66, *p*=.000*, r=.79	
Standard deviation of speed (km/h)	1.60 (.60)	1.15 (.55)
Test statistic, p-value, effect size (r)	*t*=2.67, *p*=.015*, r=.52	
Standard deviation of lateral position (m)	.318 (.084)	.185 (.044)
Test statistic, p-value, effect size (r)	*t*=6.60, *p*=.000*, r=.83	
Percentage time eyes off forward road (%)	49.76 (17.12)	19.71 (15.31)
Test statistic, p-value, effect size (r)	*t=8.03*, *p*=.000*, r=-.88	
Number of times eyes off forward road	3.25 (1.12)	2.05 (1.61)
Test statistic, p-value, effect size (r)	t=2.70, *p*=.014*, r=-.53	
Average duration of glance off road (s)	.962 (.335)	.576 (.360)
Test statistic, p-value, effect size (r)	*t*=3.98, *p*=.001*, r=.67	
Max glance duration off road (s)	1.500 (.591)	.664 (.389)
Test statistic, p-value, effect size (r)	*z=-3.81*, *p*=.000*, r=.85	
Rating scale mental effort (mm)	86.00 (28.29)	31.85 (22.34)
Test statistic, p-value, effect size (r)	*t=6.86*, *p*=.000*, r=-.84	

* Significant at α=.05 (2-tailed), t refers to t-test, *z* refers to Wilcoxon Signed-rank test for non-normal data.

5.3.3. Destination entry

The results for entering destinations versus baseline driving are shown in Table 5.4. Average speed was substantially lower while entering destinations, as compared to the baseline condition, and participants had their eyes off the forward road scene for a considerably longer period of time, but the number of glances off the road ahead was not substantially different from baseline driving. However, the glances were significantly longer during entering destinations. SDLP was higher, indicating more swerving during operating the navigation system. Ratings for mental effort were substantially higher in the experimental condition.

Table 5.4: Means and standard deviations (in parentheses) for entering destinations during driving and respective baseline (N=20).

Speed limit (km/h)	**50**	
Approx. length analysed (m)	**450**	
Condition	**Destination entry**	**Baseline**
Mean speed (km/h)	41.86 (6.071)	51.85 (6.722)
Test statistic, p-value, effect size (r)	*t*=-5.46 , p=.000*, r=.80	
Standard deviation of speed (km/h)	2.721 (.842)	2.781 (.805)
Test statistic, p-value, effect size (r)	*z*=-.236 , p=0816, N.S.	
Standard deviation of lateral position (m)	.259 (.089)	.144 (.048)
Test statistic, p-value, effect size (r)	*t*=5.607 , p=.000*, r=.79	
Percentage time eyes off forward road (%)	60.91 (20.01)	22.41 (17.61)
Test statistic, p-value, effect size (r)	*t*=8.46 , p=.000*, r=.89	
Number of times eyes off forward road (#)	2.85 (1.089)	2.35 (1.663)
Test statistic, p-value, effect size (r)	*z*=-1.54 , p=.124, N.S.	
Average duration of glance off road (s)	1.337 (.598)	.470 (.306)
Test statistic, p-value, effect size (r)	*t*=5.39 , p=.000*, r=.78	
Max glance duration off road (s)	1.86 (.676)	.621 (.407)
Test statistic, p-value, effect size (r)	*t*=6.48 , p=.000*, r=.83	
Rating scale mental effort (mm)	78.30 (27.51)	41.30 (26.87)
Test statistic, p-value, effect size (r)	*t*=5.51 , p=000*, r=.78	

* Significant at α=.05 (2-tailed), t refers to t-test, *z* refers to Wilcoxon Signed-rank test for non-normal data.

5.3.4. Route guidance versus paper map

Results for both way finding conditions are presented in Table 5.5. Participants did not drive significantly faster during route guidance, while subjective efforts, indicated by the RSME scores, during driving with a map were substantially higher. Other differences between driving with route guidance and using a paper map were not significant.

Table 5.5: Means and standard deviations (in parentheses) for following route guidance and respective driving with a paper map (N=20).

Speed limit (km/h)	**50**	
Approx. length analysed (m)	**680**	
Way finding condition	**Route guidance**	**Paper map**
Mean speed (km/h)	48.71 (3.74)	47.71 (4.15)
Test statistic, p-value, effect size (r)	*t*=1.207, *p*=.242, N.S.	
Standard deviation of speed (km/h)	3.048 (.937)	3.165 (0.816)
Effect size (r)	*t*=-.65, *p*=.522, N.S.	
Standard deviation of lateral position (m)	.176 (.027)	.181 (.035)
Test statistic, p-value, effect size (r)	*t*=-.684, *p*=.502, N.S.	
Percentage time eyes off forward road (%)	14.00 (12.20)	19.41 (15.21)
Test statistic, p-value, effect size (r)	*t*=1.88, *p*=.075, N.S.	
Number of times eyes off forward road (#)	1.45 (1.191)	1.75 (1.164)
Test statistic, p-value, effect size (r)	*z*=-1.11, *p*=.268, N.S.	
Average duration of glance off road (s)	.468 (.422)	.594 (.440)
Test statistic, p-value, effect size (r)	*t*=1.34, *p*=.196, N.S.	
Max glance duration off road (s)	.720 (.500)	.526 (.433)
Test statistic, p-value, effect size (r)	*t*=1.78, *p*=.091, N.S.	
Rating scale mental effort (mm)	48.75 (31.33)	68.05 (21.97)
Test statistic, p-value, effect size (r)	*t*=-2.17, *p*=.043*, r=.45	

* Significant at α=.05 (2-tailed), t refers to t-test, *z* refers to Wilcoxon Signed-rank test for non-normal data.

5.4. Discussion

The main objective of this study was to investigate how experienced users of in-car devices performed the driving task in a simulator under various distracted and baseline conditions.

5.4.1. Limitations

Although a driving simulator provides excellent opportunities for investigating distractions that one would not dare to require from a driver in real traffic, the results should be approached with care. Firstly, the car does not move like a real car does, in braking, steering, accelerating. Even though the drivers had sufficient experience not to let the driving task as such be interfered by inexperience, the simulated driving task inarguably is somewhat different. Secondly, some participants reported some dizziness, or light nausea afterwards and other forms of light discomfort due to simulator driving, which may have had its influence on driving performance.

The route as simulated in this study was quite complex, which adds perhaps to realism, but makes it more difficult to program and perhaps to drive, as reflected in relatively high baseline mental effort scores of 32-50 (compared with for instance De Waard (1996), who found real road effort scores of 15-30). Moreover, most participants had no experience with driving in a simulator, whereas people do learn to drive better through practicing (Shinar et al., 2005). Finally, in real life, drivers may be quite aware of the dangers of distracted driving and only seldom engage in doing so by carefully planning for less complex situations (Kircher et al., 2011).

5.4.2. Handheld phone conversation

Participants rated the handheld conversation while driving to be demanding. They lowered their speed during the conversation, except for the 50 km/h speed limit sections. A closer look at these data revealed that the vast majority of participants slowed down in the 70, 80 and 100 km/h sections, i.e., 18, 15 and 17 participants respectively (out of 20). For the 50 km/h section only seven participants slowed down. The two sections with a 50 km/h speed limit both followed immediately after an 80 km/h limit section, so supposedly during phoning participants did not slow down (sufficiently) because they missed the 50 km/h sign. Alternatively, participants experienced this as an unexpected disruption of the required speed and kept on driving at the same speed as they did on the previous section (cf. OECD, 1990; Saad et al., 2004).

Consistently, the fact that on the 70 km/h limit sections participants drove faster than on 80 km/h sections is most probably due to the 70 km/h sections following a 100 km/h limit section, whereas the 80 km/h sections were surrounded by two 50 km/h sections. Lane keeping did not seem to change over the two conditions, which may logically be connected to the fact that participants less often and shorter glanced away from the forward road scene during phoning (cf. Victor et al., 2005).

These results contribute to the current debate on whether phone conversations really affect risk (cf. Kidd & McCartt, 2012; Young, 2012b). On the one hand, it could be argued that since neither lateral performance nor glance behaviour is affected (much), added to a (safe) slower driving, phoning while driving may not be that much more hazardous than normal driving. In addition, if drivers are aware of the risks, and self-regulate the timing of conversations to sensible moments, it seems reasonable to suggest that phone conversations may not be as risky as previously thought. On the other hand, however, some participants missed an important, i.e. speed sign, so it is important that drivers should be aware of the distracting nature of phone conversations, which seems more demanding than passenger conversations (Drews, Pasupathi, & Strayer, 2008). Moreover, emotional conversations may be less harmless than mundane talks (Dula et al., 2011; cf. Strayer, Cooper, Turril, et al., 2013). Furthermore, answering and dialling still require a visual-manual act, hence increasing risk, even in case of hands free installation (Fitch et al., 2013).

5.4.3. Texting

Participants reported texting during driving to demand most effort on average. One of the causes may be the fact that most participants had a touch screen smart phone, which is difficult to operate compared to button phones, due to limited feedback on finger position. Moreover, four participants indicated never to text while driving in normal conditions. It seems that especially SDLP suffered from distraction by texting, followed by mean speed. Furthermore, participants had their eyes off the road for about 50% of the time, which is comparable to earlier research findings (Owens et al., 2011). Four drivers had a “crash” while texting instead of watching the road. Manually operating the phone, be it for a short time, apparently adds to the statement in the previous section about the risks of distraction (see also Brookhuis et al., 1991).

5.4.4. Destination entry

Destination entry results showed the same trend as texting, though the tasks may not be fully comparable here due to different speed limits and road design. This was expected due to the visual-manual nature of both tasks. The longer glances and the higher percentage eyes off road time as compared to texting may be the result of the fact that the navigation system was placed on the right hand screen (see Figure 5.1), which implied that participants needed to turn their head slightly away from the forward road. In addition, the urban area may have been more interesting than the more tranquil motorway environment. Both lower speed and degraded lane keeping follow the lines of earlier work (Tsimhoni et al., 2004).

5.4.5. Following route guidance

The route guidance versus paper map results revealed few significant differences. Participants did report higher mental effort scores for driving with the paper map; so following the route using the map apparently was not too easy, which confirms earlier findings (Feenstra et al., 2008). Two participants recognized the route from driving it before (both lived in the area near the route) although it was not a habitual route, i.e. they would normally not drive this specific sequence of roads.

5.4.6. Synthesis

In summary, participants, all experienced users of both mobile phone and navigation systems, generally drove significantly slower in all distracting conditions, and found that the secondary tasks required more effort, compared to baseline driving. Visual-manual tasks appeared to cause loss of control including deteriorated lane keeping performance, in line with Fullers TCI model (Fuller, 2005). Texting on a motorway in this study led to a 72% increase in SDLP, while destination entries on an urban road led to an 80% increase. Furthermore, participants significantly reduced glancing to the forward road, both by number and duration of glances. Thus, through the comparison with texting, prohibiting destination entries while driving seems to make sense, in spite of arguments against this (e.g., Burnett et al., 2004). Keeping an eye on the road seems helpful in keeping in control of the vehicle. In conclusion, being experienced in manipulating in-car devices does not solve the problematic effects of dual tasking when the primary task is a complex demanding task like driving a moving vehicle.

This finding may be due to two lines of reasoning. First, one might argue that drivers become habituated to the risks involved in potentially dangerous behaviour, so that they are no longer capable of assessing the real risks involved in their behaviour (cf Summala, 1988). This would lead to lower efforts compensating for increased risk, which in turn affects driving performance, according to the TCI model (Fuller, 2005). This would imply that education on risk and awareness of risk might help diminish the detrimental effect. On the other hand, it might be that drivers, even though they may be experienced in each of the two tasks, they just may not be able to perform the two tasks concurrently. In that case, only a few supertaskers (Watson & Strayer, 2010) would be capable by talent. Either way, most should be advised to just refrain from demanding secondary tasks while driving.

5.4.7. Conclusion

The results indicate that most secondary tasks lead to a decrease in driving speed, while visual-manual tasks additionally takes drivers' eyes of the road, deteriorating lateral performance. Regarding the results of the mobile phone conversations per se, it seems reasonable to suggest that drivers, through careful planning, may well be able to compensate for the distracting effects of the conversation by slowing down. The fact that they are able to keep their eyes on the road may be indicative of this, though distraction from relevant signs is looming continually.

Additional research data are needed to identify to what extent the impacts hold for these tasks in real life driving.

6. Comparing a driving simulator to the real road regarding distracted driving speed[7]

Abstract

Relative and absolute validity of a driving simulator were assessed regarding effects on mean speed and speed variation during distracting secondary tasks, and normal driving. 16 participants drove the same route four times, twice in a simulator and twice in the real world. They performed way finding tasks, using either a paper map or a route guidance system, and mobile phone conversation tasks. Furthermore, driving without secondary tasks on other road segments in the two methods was compared. As both mean speed and standard deviations of speed were not equivalent, absolute validity could not be established. However, as effects found in the experimental conditions varied in the same directions, evidence for relative validity was provided. It is concluded that driving performance regarding speed under distracting conditions may validly be researched in the driving simulator employed here.

---

[7] Knapper, A. S. Christoph, M., Hagenzieker, M. P., Brookhuis, K. A. (2015) Comparing a driving simulator to the real road regarding distracted driving speed. *European Journal of Transport and Infrastructure Research, 2; 15*, p. 205-225.

6.1. Introduction

6.1.1. Driving simulators and their validity

Driving simulators provide an attractive option for studying driving behaviour. Reasons for this appeal include the fact that driving in a simulator is safe both for the driver and the experimenter (Lee, Cameron, & Lee, 2003; Lee et al., 2007), and for other traffic. Furthermore, the experimental control (Kaptein, Theeuwes, & Van der Horst, 1996; Carsten & Jamson, 2011) in terms of traffic, weather and locations, provides a scientifically sound method for studying effects on driving performance, for instance, by in-vehicle technology or roadway design changes. However, despite endeavours to develop simulators that realistically simulate driving, the road, and the surrounding environment (Törnros, 1998; De Waard, Van der Hulst, Hoedemaeker, & Brookhuis, 1999a), their validity is often criticised (e.g., Farber, 1999, but see also De Waard, Van der Hulst, Hoedemaeker & Brookhuis' response, 1999b), for instance due to the lack of danger (Evans, 1991). Such critical stances should not be easily discarded, as it is important to verify that what is studied and found in a simulator is also applicable on the road (Shechtman, 2010; Mullen, Charlton, Devlin, & Bédard, 2011), all the more because of the large number of studies applying simulators.

Various factors can potentially affect validity of data collected in a driving simulator. One effect may stem from learning, as many drivers are not used to a driving simulator (Blana, 1997). Second, being observed may involve effects, as few drivers are used to driving while knowing to be monitored and recorded, and they may adapt their driving style to what they think the observer finds desirable (see also the Hawthorne effect, cf Jones, 1992). Third, drivers who are affected by feelings of discomfort due to simulator sickness, may cause selective drop-out (Davidse et al., 2009). This is relevant when investigating, for instance, the effect on drivers' performance when using their mobile phone or the effects of taking medication or drugs on driving performance (Young et al., 2009b).

We therefore need to know how performance in a simulator relates to on road performance. Hence, driving simulator validation studies are needed. In fact, they have been performed all along the development of driving simulators (McRuer & Klein, 1976; Blaauw, 1980) and a number of literature reviews exist (cf Kaptein et al., 1996; Blana, 1997; Hoskins & El-Gindy, 2006; Shechtman, 2010; Mullen et al., 2011). However, no generic method is available to test whether a simulator delivers valid results. This may be due to the circumstance that validity comprises many aspects; the specific driving simulator itself, the tasks studied, the subject populations (sample similarity), research design, and even terminology (Mullen et al., 2011). Strictly speaking, this means that for each simulator, each task investigated should be validated separately (Kaptein et al., 1996; Hoskins & El-Gindy, 2006). However, that would in turn invalidate most reasons for using simulators (i.e., cost and safety).

Then how should a driving simulator be validated? Blaauw (1980, 1982) distinguished between physical and behavioural validity. Physical validity comprises the extent to which a simulator itself resembles an on-road moving car in terms of similarity of controls, layout of the vehicle, and dynamics. Behavioural validity refers to how well changes in drivers' behaviour due to experimental conditions in a simulator resemble changes in real life driving, and is also referred to as predictive validity (Törnros, 1998). For the latter type of validity two directions are often distinguished, namely absolute and relative validity (Blaauw, 1982; Kaptein et al., 1996). Absolute validity is obtained in case the numerical values measured in the simulator and the comparing method are equivalent. Relative validity refers to values changing in the same direction and with comparable amplitude across methods. A hypothetical example may be that blindfolding drivers suddenly while driving may lead to braking in both simulated and real world driving (relative validity), but not with the same braking force (hence no absolute validity). Concerning the usefulness of applying a driving simulator as a method for investigating driving, Törnros (1998) indicates that relative validity may, with care, suffice for generalising to real world driving.

Driving simulator validity can be investigated by comparing driving performance during similar tasks (Blaauw, 1982). The standard for investigating validity is therefore obviously comparing it to on-road driving (Reimer, D'Ambrosio, Coughlin, Kafrissen, & Biederman, 2006; Shechtman, 2010), although some have achieved valuable results comparing simulated driving to self-report tests (Lee & Lee, 2005; Reimer et al., 2006; Bédard, Parkkari, Weaver, Riendeau, & Dahlquist, 2010), to road crash databases (Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008) and to other simulators (Groeger, Carsten, Blana, & Jamson, 1999; Jamson & Jamson, 2010). Other validation studies compared their high-end simulator to both on-road driving and a lower end simulator (Reed & Green, 1999; Santos, Merat, Mouta, Brookhuis, & De Waard, 2005).

6.1.2. Speed

The current study compares data from a driving simulator study and data from an on-road driving study regarding driving speed during way finding, cognitive distraction due to phone conversations, and baseline driving, in an attempt to determine relative as well as absolute validity. The on-road study was part of a European project (INTERACTION). Specifically for validation purposes, the simulated route was designed to closely match the on-road study track, but the validation study was not an aim of the INTERACTION project. We first discuss results of other studies that aimed at validating speed data. Elaborate reviews including other driving task components such as lateral performance are widely available elsewhere (i.e., Hoskins & El-Gindy, 2006; Shechtman, 2010; Mullen et al., 2011).

Driving speed is an important component of the driving task for several reasons. Firstly, it influences crash severity outcomes; higher speed of impact leads to more severe injuries (Joksch, 1993; Elvik, Christensen, & Amundsen, 2004). Secondly, driving speed is associated with crash risk (Aarts & Van Schagen, 2006). Thirdly, drivers may use speed to keep in control of the driving task demands as described in the Task-Capability Interface model (Fuller, 2005), by slowing down, for instance in adverse weather (Hoogendoorn, Van Arem, Hoogendoorn, Brookhuis, & Happee, 2012). Likewise, drivers being distracted by for example interacting with in-vehicle devices often apply compensatory strategies including reducing speed (Young & Regan, 2007; Stelling & Hagenzieker, 2012).

Table 6.1 considers a number of studies on the topic of driving simulator validity, specifically focusing on speed related measures reported in those studies. The studies were obtained by an extensive literature search, using internet search engines (Scopus, Web of Science, Google Scholar) and other studies' reference lists. Although it is by no means exhaustive, it does provide a broad view on earlier findings.

Table 6.1: Speed relevant measures found in several studies investigating driving simulator validity. Note that the validity scores (yes, no, or absent) in many studies were not explicitly stated in the original publications, and therefore needed to be inferred from the data reported.

Study	Dependent variable	Abs val	Rel val	Speed relation	Simulator type	Note
Harms (1996)	Mean speed driven	Yes	Yes	Insignificantly higher in the simulator	Moving base	
Törnros (1998)	Mean speed driven	No	Yes	Higher in simulator	Fixed base	Tunnel driving
Groeger, Carsten, Blana, & Jamson (1999)	Speed estimates	No	Yes	Mixed	Fixed base	
Klee, Bauer, Radwan, & Al-Deek (1999)	Mean speed driven	No	Yes	Lower in simulator	Fixed base	Relative validity not in the paper, but as reasoned by Mullen et al. (2011)
Reed & Green (1999)	SD of speed driven	No	Yes	SD of speed was higher in real driving, but larger effect for age (old subjects had higher SD speed)	Fixed base	
Bittner, Simsek, Levison, & Campbell (2002)	Speed on curve entry	No	No	Simulated speed higher in easy curves, lower in difficult curves	Moving base	
Godley, Triggs, & Fildes (2002)	Mean speed driven	No	Yes	Mixed	Moving base	
Santos, Merat, Mouta, Brookhuis, & De Waard (2005)	Mean and SD of speed driven	No	No	Speed lower in advanced simulator, similar to real driving in simple simulator. SD of speed highest in simple simulator.	Simple and advanced, both fixed base	
Brown, Dow, Marshall & Allen (2007)		No	-	Speed somewhat higher in the simulator, on average	Advanced moving base	Relative validity not specifically in the paper.
McAvoy, Schattler, & Datta (2007)	Mean speed driven	No	No	Mixed	Fixed base	Night, at work zone
Shinar & Ronen (2007)	Speed estimates and reproductions	No	Yes	Higher speed reproductions in simulator	Fixed base single screen	
Bella (2008)	Driving speed	Yes/ No	Yes	Higher where road had weakest curve	Fixed base	Real driving speed from speed gun data. Yes: 9 demanding road sections. No: 2 low demand sections
Jamson & Jamson (2010)	Mean speed driven	(Yes)	Yes	Similar	Low-cost and mid-level (fixed base)	Compared 2 types of simulators
Wang al.(2010)	Mean speed driven	No	Yes	Lower in simulator	Fixed base, car replicated	
Mayhew et al. (2011)	Subjective speeding errors	No	Yes	Similar number of speed related errors	Fixed base (both 1 and 3 screens)	Errors, speed was a subset, somewhat subjective.
Hallvig et al. (2013)	Mean speed driven	No	No	Higher speed in simulator, stable over night/day driving	Moving base	Effects of sleepiness, night driving

Inspection of the table indicates that

- Night time driving may not be simulated very well in terms of mean speed (McAvoy et al., 2007).
- Moving base simulators may provide a slight advantage over fixed base simulators in terms of various speed measures. However, for some research questions a moving base will not be cost efficient (De Winter et al., 2009; Lee et al., 2011).
- Driving speed in a simulator as compared to real driving may be influenced by types of curves. In easy, high radius curves, simulator drivers may adopt a higher speed (Bella, 2008) or entry speed (Bittner et al., 2002), whereas in more difficult curves, driving speed may not differ (Bella, 2008), and entry speed may be lower (Bittner et al., 2002)
- Drivers may not be able to estimate and reproduce absolute driving speed correctly, but they are well able to distinguish between faster and slower driving (Groeger et al., 1999; Shinar & Ronen, 2007)
- Few studies report absolute validity, whereas the majority report indications for relative validity regarding speed related measures.

The picture painted in Table 6.1 may serve to position the current study, as the employed simulator has not been subject to a formal validation study before. Moreover, it adds to the literature through comparing the effects on speed measures of performing different distracting secondary tasks while driving on the real road to while driving in the simulator.

6.1.3. Overview of the experiment

In this paper we compare driving speed data obtained in a driving simulator study to speed driven in a real road study. The participants drove a route four times in total; twice on the real road and twice in a driving simulator. They drove while performing tasks of way finding, with a paper map (as opposed to driving with a route guidance system), and while having a phone conversation. We report the results of the comparison of speed parameters in terms of absolute and relative validity of driving simulators as research tools.

We address the following research questions regarding driving speed data from the field test and the driving simulator experiment.

- To what extent are results on speed from both studies comparable with regard to the way finding conditions (using either a paper map or instructions by a navigation system) and the phone conversation conditions?

- To what extent are the driving speed results obtained from simulated baseline driving valid in the absolute sense, when compared to driving in the real world?

The first question addresses both the issues of absolute and relative validity. Absolute validity is studied in terms of equivalence of driving speed during the specific conditions, relative validity may be extracted from the direction and amplitude of the effect. The second research question relates to absolute validity regarding driving speed.

6.2. Method

6.2.1. Participants

In total 21 persons initially participated in the project. However, one participant was excluded because of simulator sickness, and four were not included because the instrumented vehicles' data acquisition system had not recorded both field test drives. The final sample for analysis therefore consisted of 16 paid volunteers, six females and ten males, aged 27-59 (m=37.8, SD=10). They had their drivers' licence for 3-39 years (M=15.8, SD=9.5). All participants indicated to use a navigation system and mobile phone at least once a week while driving, and to drive at least 12,000 kilometres per year. Participants signed an informed consent and before each drive they were explicitly instructed to feel free to stop participating at any time, for any reason.

6.2.2. Apparatus

The instrumented vehicles were either one of four Lancia Ypsilons or a Peugeot 207. The instrumentation consisted of four cameras and several sensors that recorded driver behaviour on each trip. The data were recorded by a computer located in the trunk. The instrumentation included a GPS device that recorded at 1Hz the GPS position, at about five meters precision. GPS data were matched to map data, and included information on speed, direction, and time. GPS speed measures have been reported to be more reliable than a car odometer driving on straight lines at a constant speed, and are therefore regarded an accurate measure for speed (Witte & Wilson, 2004). The computer started automatically when the driver side door was opened, and it would shut down automatically after about 10 minutes of inactivity. Some of the trips were not recorded due to the fact they started while the computer was still shutting down (these were excluded, see 2.1). All vehicles were equipped with a TomTom Go Live 1005 navigation system and Parrot Minikit Slim Bluetooth hands free phoning device.

According to several classifications (i.e., Kaptein et al., 1996; Young et al., 2009b), the driving simulator used here may be described as mid-level; it has no moving base (which would make it high-level), nor is it only a desktop computer with a steering wheel. It does consist of a mock-up cabin including real steering wheel, car seat and controls, surrounded by three LCD screens allowing for a 180-degree view of the driving environment. The centre screen resolution is 1920x1080 (HDTV), both side screen are 1360x768 pixels. Refresh rate is 60 fps. The simulator software was developed by STSoftware © and runs on two connected personal computers. The computational vehicle model has three degrees of freedom: X, Y and vertical axis rotation. The model includes a simple combustion engine simulation, simulating a 90 hp car engine. The road contact model is based on the Pacejka 'magic formulae' (Pacejka & Bakker, 1992). The model simulates steering as a result of lateral front tire force, and allows for quite realistic steering. Friction and wind force are also included in the model. Furthermore, brake force is included as a counterforce, and depends on pedal pressure. The user controls did not provide active physical feedback. The simulator manual gearbox was used, the real vehicles were also manual. This is representative for most Dutch cars, and the participants were used to manual driving. The simulator was situated in a 20 degree Celsius air conditioned room in order to minimize potential simulator sickness (Stoner et al., 2011). The simulator is visualised in Figure 6.1.

Figure 6.1: The driving simulator.

6.2.3. Driving environment

For the field test a route was selected in the The Hague area, depicted in Figure 6.2. It started in Leidschendam (X in Figure 6.2), and the first two kilometres were discarded from the data. These were meant for familiarising the participant with being observed (although the participants were not informed about this). The route in fact started at A in Figure 6.2, via B to the A4 motorway (C to D), then to E and back to Leidschendam. A to B and B to C are both 50 km/h speed limit urban areas, with B-C being the most busy one, because it consists of a heavy used exit road out of The Hague. C to D is the 100 km/h A4 motorway, D to E contains several different speed limits (50, 70, 80, 100 km/h), and may be best described as an arterial road or a ring road, as it leads from Delft to several motorways such as the A4 and the A13.

Figure 6.2: Route (© Google Maps), normally starting in X, in the The Hague area.

For the simulator study, the environment was replicated from the field route as accurately as possible in terms of road structure, road signs and layout. However, as the simulator was not designed to replicate reality on a micro level, components like bus lanes were omitted, traffic lights had to be moved and lowered for visibility reasons, and some intersections had a slightly different lay out. Furthermore, no street name signs or signage was included. Buildings, trees and bushes were simulated as available from the standard software database. Figure 6.3 includes four scenes comparing the simulator to the real world.

Other traffic was programmed to resemble typical 10:00 to 16:00 (light) traffic, which resembled field test traffic (field test drives all started between 9:30 and 15:00). In order to minimize simulator sickness, the route was cut in two parts (X-D and D-E in Figure 6.2), so participants could rest in between the two routes. Each of the parts started with about two kilometres of roads that allowed for the participants to practice driving in the simulator. These parts were not analysed and differed from the real road to avoid recognising the route from one method to the other.

Figure 6.3: Several simulated environments alongside their approximate real-world counterparts (© Google Maps; Simulator pictures and real life screenshots have different viewing angles).

6.2.4. Experimental design and analyses

All 16 participants included in this study drove both in the simulator and in the field test. Some differences between both studies pertain to the order of conditions. The field test order normally was the same, whereas the simulated conditions were counterbalanced. In order to control for potential order effects between the two methods, four participants first drove the two simulator drives, the others first completed the field test. Full counterbalancing was not possible due to the practical constraints of the INTERACTION project. There were two exceptions to the normal field test order of conditions: Two of the drives, on the participant's request, started at Delft University (between D and E), but the route then still consisted of the same roads and tasks were carried out at the same sections.

6.2.5. Procedure and materials

Participants drove an instrumented vehicle instead of their own vehicle for five to six weeks, as part of the INTERACTION project. Regarding the field test, participants performed the first drive after having used the instrumented vehicle for at least one week, so that they were used to driving it. They were invited to come to the SWOV (Institute for Road Safety Research), in Leidschendam, where they were briefed. In the briefing, they were informed that they would have a 42 kilometre drive, with two observers in the vehicle, one in the front seat, and one in the rear seat, and that they would be asked to perform certain secondary tasks while driving (see 6.2.6). It was emphasised that if for whatever reason the participant felt uncomfortable to perform a certain task while driving, he or she would not have to perform it. The participants were not informed that the front seat observer recorded interactions with other road users and special events, whereas the rear seat observer performed standardised observations such as correctness of speed, lateral performance, distance to other road users, according to the Wiener Fahrprobe methodology (Chaloupka & Risser, 1995). Participants were requested to drive as they normally would do through the entire drive. Also, they were allowed to talk during driving, which would be a sign that they felt at ease, but the observers did try to limit conversation. After returning, the observers interviewed the driver, to discuss specific traffic events that sometimes had occurred during the drive.

The second field test drive was normally planned together with the participant handing in the vehicle, which was about four weeks after the first drive. As in the first drive, participants were briefed first, then drove the route together with two observers while performing some in-vehicle tasks, and had an interview afterwards. Two second drives were postponed due to adverse weather conditions and/or illness.

The two simulator drives were separated by at least seven days. During each visit, participants had to drive two routes (in Figure 6.2: A to C and D to E), in different orders. During the break between the two routes, participants were requested to complete some questionnaires (results not reported here), and after finishing the second route, participants signed a receipt for a €30 gift voucher.

In-vehicle tasks

During both the field study and the driving simulator study, participants performed several secondary tasks. Way finding was performed on the A to B sections in both studies, the phone conversations on the D to E segments. B to D in the field test contained no specific tasks, whereas in the simulator, participants programmed a navigation system (B to C) and texted on a mobile (C to D) on this stretch. The trips in which no task was performed (baseline driving) on B to D served as comparison to field test driving. Table 6.2 provides an overview of the tasks.

Table 6.2: Overview of the road sections (see Figure 6.2) and their respective in-vehicle tasks. Each line represents one comparison of driving speed between field test and simulated driving. Parts of the road where no specific task was performed are referred to as baselines.

Section	**Description**	**Road type (speed limit)**	**Field test**		**Driving Simulator**		**Results in section**
			Drive 1	Drive 2	Drive 1	Drive 2	
A-B	Way finding	Urban (50)	Route guidance	Map	Route guidance	Map	3.1
B-C	Baselines	Urban (50)	Baseline 1	Baseline 2	Baseline	Destination entry	3.3
C-D	Baselines	Motorway (100)	Baseline 1	Baseline 2	Baseline	Texting	3.3
D-E	Phone conversation	Ring road (50, 70, 80, 100)	Baseline	Phone conversation	Baseline	Phone conversation	3.2

Way finding

In the first field test drive, on the A to B section (see Figure 6.4), participants were told to follow the navigation system's route guidance, and, when arriving at B (Figure 6.4), to follow instructions by the observers for the remainder of the route. On the second drive, A to B consisted of following a paper map route. The paper map was printed from Google Maps, and consisted of both the map and the written instructions. Participants were given a few minutes to study the map before the drive. In both drives, in case participants (almost) took a wrong turn, the observers redirected them and marked one way finding error.

In the simulator, both conditions were counterbalanced across the two drives. Participants were requested to either follow the simulator's simple navigation system's instructions (arrows and spoken instructions) or use the paper map. In the simulator, the paper map consisted of a top view of the environment as it was built in the driving simulator (see Figure 6.4), containing all intersecting streets, roundabouts and tunnels. Participants were requested to drive from the red arrow to the red star. Similar to the field test, (potential) way finding errors led the experimenter to redirect the participant and register the error. Both maps included landmarks such as intersections, tunnels, and bends, that could aid the driver in finding the way (cf. May & Ross, 2006b), and the routes were not particularly difficult.

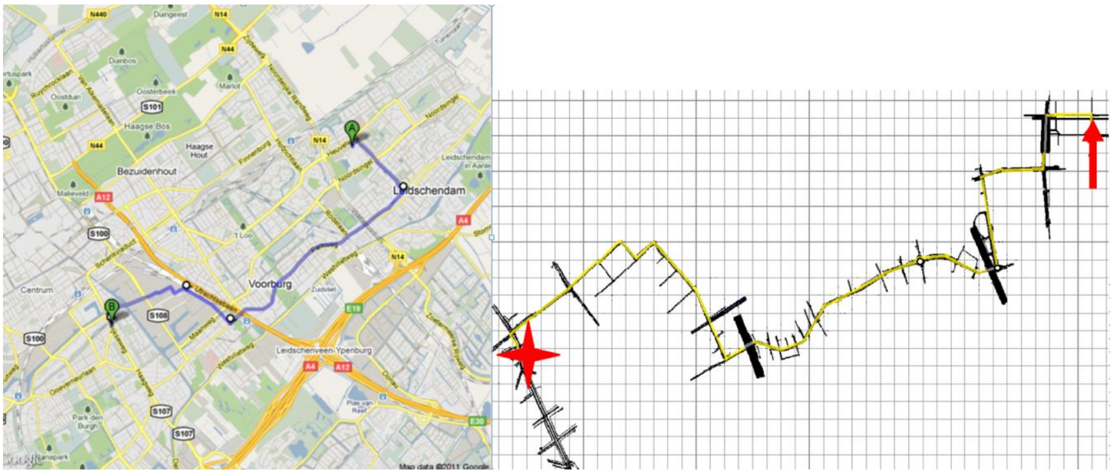

Figure 6.4: Two paper maps used in this study. The left map (© Google Maps) was used in the field test, and participants were instructed to drive from A to B, whereas the right map was used in the driving simulator, and participants drove from the red arrow (top right) to the red asterisk (left; both signs are enlarged for printing clarity). Note that the first two kilometre differ, which was meant for avoiding participants recognising the route immediately so they would not be engaged in way finding but in remembering the route by heart.

Phone conversation

The phone 'conversation' consisted of a questionnaire containing a total of eight blocks of five questions (four blocks were used in the field test and four in the simulator). Each block included five questions of different categories: list as many (e.g., rivers) as possible, true or not: (i.e., 100 grams of caviar is more expensive than 100 grams of tuna), repeat a sentence (i.e., the home team was playing well until the third quarter of the match), answer the following question ("If I say Jack stole Ann's ball who is the thief?"), and describe (i.e., a friend). The questions were translated to Dutch, and had been based on the Rosenbaum Verbal Cognitive Test Battery, as used by Waugh et al. (2000, see also Rakauskas, Ward, Bernat, Chadwallade, & De Waard, 2005), and on questions used by Perreira et al. (2008). Answers were rated by the remote experimenter.

The hands free phone conversation in the field test was always part of the first of the two drives. During the briefing session, a set of example questions had been read to the participant. During the drive, after having reached the end of the A4 motorway (C-D), the participant was asked whether he or she was ready to have a phone conversation with another experimenter. If so, the rear seat experimenter would instruct a remote colleague by phone to start making the phone call. The phone conversation consisted of a short introduction, including an instruction to watch the road and traffic during answering the questions. The four blocks were administered in two sets. After the first set of two blocks of questions, a second phone call followed about one minute later. Then, approximately one minute later, the next two blocks were administered. During the second drive, no instructions were provided, other than to drive normally.

In the driving simulator, the remaining four blocks of questions were all administered to the participant in a single hand held phone call. Again, the experimenter phoned a colleague on a remote location, who immediately started the phone call. The procedure was similar to the field test, except for the one minute pause in between the two sets of two blocks.

Baseline driving

The B-C and C-D sections in the field test were driven twice without any instruction (except for the necessary route instructions). In the simulator study (see Table 6.2), on these sections baseline driving was compared to driving while texting and programming a navigation system. As these tasks were not performed in the field test, only the baselines served to be compared to the same sections in the field test here.

Dependent variables

In both the driving simulator (at 10 Hz) and the field test (at 1 Hz), speed was recorded. For the analyses, we chose to focus on straight road stretches where speed could be selected freely. In order to compare the standard deviation of speed as accurately as possible, the first of every ten simulator data points were included in the analyses.

Next to that, as a coarse measure of secondary task performance for the way finding condition, each (potential) clearly wrong turn (as judged by indicator use) was tallied. This was done both in the field test and in the driving simulator. Furthermore, in both studies response quality of the participant to the mobile phone conversation questionnaire was recorded. If an answer was not rated good or sufficient by the telephonist, it was marked, which resulted in a score for bad answers for each participant, with a maximum of 20 per method.

Matching data

Based on notes and video recordings, irregularities were removed from the field data, including eventualities such as open bridges, refuelling stops, road works, and traffic jams, in order to ensure comparing driving speed that was as unconstrained as possible. As a result, about 23% of GPS data rows were removed, which together account for about 7% of the total distance covered. Similarly, some "crashes" and road stretches where the phone conversation had started late in the driving simulator data were removed (approximately 9% of data rows). At first sight, the removal percentages seem high, but do include a considerable amount of stopping time. For example, one six-minute refuelling stop may already account for 2 of the 23% removal.

Statistical analyses

To analyse the differences in the two way finding conditions in both methods, and for the phone conversation induced distraction, we used a 2x2 factorial design (GLM repeated measures), examining mean speed and standard deviation of speed (SD speed). In cases where the residuals were not normally distributed or the data were ordinal (way finding errors) we applied an aligned rank transformation (ART, see Wobbrock, Findlater, Gergle, & Higgins, 2011).

If the main effect for experimental method is reported to be significant, this means that the mean scores on both conditions for each method are different, i.e., absolute validity is untenable. A significant main effect for condition implies that scores on both conditions, averaged across methods for similar conditions, are different. These scores do not reveal much information about validity, but do show whether an experimental effect was present. A non-significant interaction would indicate relative validity, as no differences would have been observed between effects in the simulator and in the field test, in other words, the same trend is found in both methods (Shechtman, Classen, Awadzi, & Mann, 2009).

As two baseline conditions were obtained in the field test, to be compared with the simulated baselines, we applied a repeated measures ANOVA, if necessary corrected for sphericity violations (based on Mauchly's test being <.05) using the Greenhouse-Geisser adjustment, both for urban driving (50 km/h speed limit) and for motorway driving (100 km/h). The results for the mobile phone questionnaire were assessed using a Wilcoxon Signed-Rank test.

6.3. Results

6.3.1. Way finding

The results concerning the way finding data are summarised in Table 6.3. A substantial main effect for mean speed was found for both the method, indicating higher speed in the simulator, $F_{ART}(1,15)=4.70$, r=.49 and the conditions, $F_{ART}(1.15)=14.69$, r = .70, indicating higher mean speed using the paper map. The interaction effect was non-significant, $F_{ART}(1,15)=.74$, r=.22, indicating that the methods had no different effect on participants' driving speed in the paper map or route guidance conditions.

SD speed revealed a main effect for method, $F_{ART}1,15)=12.1$, p<.05, r=.67, with more speed variation in the driving simulator, whereas neither the condition (navigation system versus paper map) main effect ($F_{ART}(1,15)=1.52$, r=.30) nor the interaction effect ($F_{ART}(1,15)=.11$, r=.09) showed significance.

The results did show that participants made more route errors while driving with the paper map, as compared to driving with a route guidance device, $F_{ART}(1,15)=26.21$, p<.05, r =.80 , but the average number of errors for the methods did not differ ($F_{ART}(1,15)=.28$, r=.13). Neither an interaction effect ($F_{ART}(1,15)=.024$, r=.04) was found, indicating that the effects were similar in both methods.

Table 6.3: Descriptive statistics of the several measures in the different conditions and methods. Displayed are means and standard deviations (in brackets).

	Field test		Simulator		Effects		
	Navigation system	Paper map	Built in route guidance system	Paper map	Method	Condition	Interaction
Mean speed	44.98 (4.26)	47.47 (3.02)	48.32 (5.29)	49.04 (3.63)	*	**	NS
SD speed	5.02 (1.88)	4.47 (1.97)	7.24 (3.61)	6.43 (2.17)	**	NS	NS
Route errors	.13 (.34)	1.5 (1.41)	0 (0)	1.44 (1.36)	NS	***	NS

NS = not significant at α =.05, * p<.05, **p<.01, ***p<.001.

6.3.2. Cognitive distraction

Figures 6.5a and 6.5b show the results that were obtained in both studies related to cognitive distraction induced by a phone conversation. The drives were performed on a ring road equipped with several speed limits. Regarding mean speed (Figure 5a), on all speed limit regimes a substantial main effect on method was revealed (50: F(1,13)=21.38, r=.79, p<.001; 70: F(1,13)=44.15, r=.89, p<.001; 80: F(1,15)=10.55, r=.64, p=.005; 100: F(1,14)=27.49, r=.81, p<.001), with simulated mean speed being higher on all speed limit zones. The main effect of condition showed significance for the 80 (F(1,15)=20.41, r=.76, p<.001), and the 100 km/h (F(1,14)=29.59, r=.82, p<.001) speed limit, but not for the 50 (F(1.13)=1.192, r=.29, p=.295) and the 70 km/h (F(1,12)=3.099, r=.45, p=.104) speed limit. None of the interaction effects reached significance (50: F(1,13)=4.589, r=.51, p=.052; 70: F(1,13)=.064, r=.45, p=.805; 80: F(1,15)=1.74, r=.32, p=.207; 100: F(1,14)=3.70, r=.46, p=.075).

SD speed (Figure 5b) showed no main effect for method on the 50 km/h zones (F_{ART}(1,13)=.66, r=.22, p=.432), but the effect was considerable in the 70 (F_{ART}(1,12)=16.59, r=.76, p=.002), 80 (F_{ART}(1,15)=10.48, r=.64, p=.006) and the 100 km/h (F_{ART}(1,14)=14.49, r=.71, p=.002) speed limits, with higher SD speeds in the simulator than in the field test. A main effect on condition was absent in the 50 (F_{ART}(1,13)=.25, r=.14, p=.626), 70 (F_{ART}(1,12)=3.45, r=.49, p=.088) and the 80 km/h (F_{ART}(1,15)=3.34, r=.43, p=.088) speed limits, but did show significance in the 100 km/h zones (F_{ART}(1,14)=9.43, r=.63, p=.008), with higher SD speeds for phoning as compared to baseline. We also found a significant interaction effect on the 100 km/h speed limit (F_{ART}(1,14)=4.6, r=.50, p=.049), indicating absence of relative validity here, as in the simulator a baseline driving showed less speed variation, whereas in field test hardly a difference between conditions surfaced. Interaction effects were non-significant on the 50 (F_{ART}(1,13)=1.98, r=.36, p=.183), 70 (F_{ART}(1,12)=1.47, r=.33, p=.248) and the 80 km/h (F_{ART}(1,15)=.08, r=.07, p=.788) speed limits.

Comparing the numbers of questions in the phone conversation questionnaire that were not answered sufficiently, in the simulator (Mdn=1) and in the field test (Mdn=1), the scores were not substantially different (Z=-.577, p>.05, r=-.14).

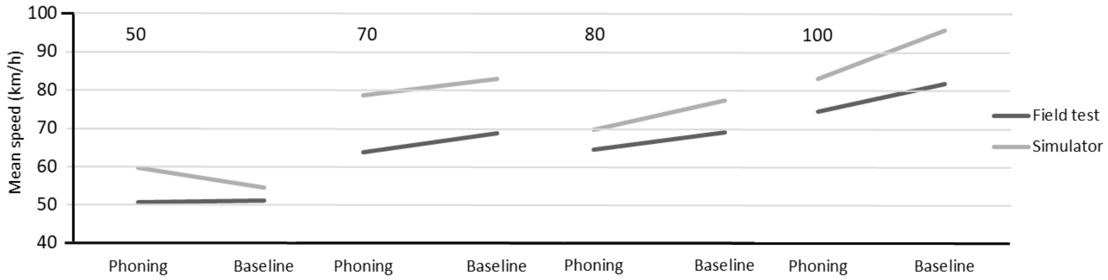

Figure 6.5a: Mean speed results from the cognitive distraction data, per speed limit. None of the interactions was significant at α=.05.

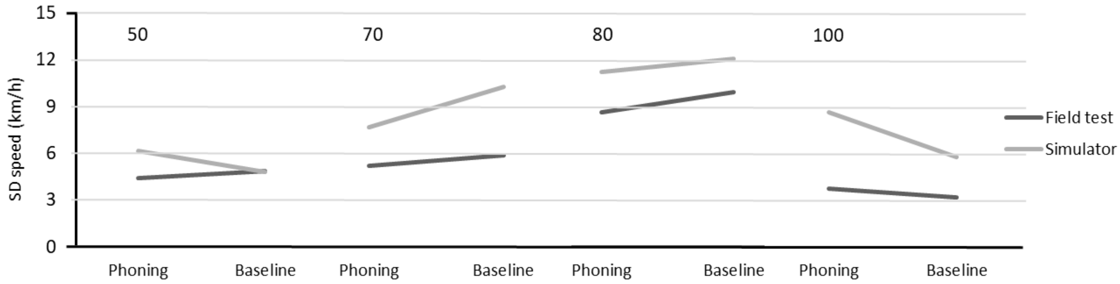

Figure 6.5b: Speed variation results from the cognitive distraction data, per speed limit. Only the interaction for 100 km/h speed limit was significant at α=.05.

6.3.3. Baseline driving

Mean and SD speed results were also obtained for driving on an urban 50 km/h speed limit road (B-C, see Table 6.2), and on a 100 km/h speed limit motorway (C-D in Table 6.2). The two field test drive results were compared to the simulated baseline drive, as shown in Table 6.4.

Urban mean driving speed showed a substantial main effect (F(2,30)=4.16), post hoc pairwise comparisons revealed that mean speed in the driving simulator was substantially faster than both field test drives (F(1,15)=16.86, r=.73, and F(1,15)=19.44, r=.75). Average SD of speed did not differ significantly (F(2,30)=.252, post hoc pairwise comparisons: F(1,15)=.528, r=.18, F(1,15)=.28, r=.14).

Motorway mean speed was also substantially higher in the driving simulator (F(2,30)=8.80, post hoc comparisons: F(1,15)=5.41, r=.51 and F(1,15)=4.97, r=.50). SD speed measures indicate a higher speed variation in the simulator (F(2,30)=8.80, post hoc comparisons: F(1,15)=14.23, r=.70 and F(1,15)=8.53, r=.60).

Table 6.4: Descriptive statistics of the measures regarding driving without specific secondary tasks. Displayed are mean scores and standard deviations (in brackets). Note that simulated experimental conditions are not taken into comparison as participants performed destination entries (urban) and texting (motorway) tasks, which are not of interest here.

Speed limit	Variable	Field test		Simulator	F-Test
		Drive 1	Drive 2	Baseline	
50 (urban)	Mean speed	44.32 (4.11)	45.17 (6.20)	51.62 (5.03)	*
	SD Speed	5.59 (2.23)	5.29 (1.34)	4.96 (2.38)	NS
100 (motorway)	Mean speed	101.12 (4.87)	100.85 (4.97)	104.25 (7.15)	***
	SD Speed	3.15 (1.00)	3.18 (1.37)	5.13 (2.47)	***

NS = not significant at α =.05, * p<.05, **p<.01, ***p<.001.

6.4. Discussion

We compared field test driving to simulated driving at several levels. Generally, mean speed and variation of speed were higher in the driving simulator than on the real road. Therefore, we found no evidence for absolute validity. However, as results of both studies regarding driver distraction did reveal similar results in the same direction, we found support for relative validity. A detailed discussion of each of the components follows.

6.4.1. Way finding

Regarding validity of results when investigating way finding using either a paper map or route guidance instructions, results indicate that mean driving speed in the simulator was higher, therefore denying absolute validity. However, the results did vary in the same direction, indicating relative validity. A similar conclusion holds for speed variation. Although the results between methods differed, they did not differ within either method between both conditions, again indicating relative validity. The recorded route errors showed a similar picture, with a main effect for condition, but not for method, and no interaction effect found.

Actually, two methods differed in a number of ways, and care must be taken when drawing conclusions like these. Firstly, while the simulated conditions were counterbalanced across participants, in the field test, the navigation system was always used in the first drive, whereas the paper map was always used in the second drive. This was decided based on evidence that the development of a cognitive map of the driving environment is negatively affected by the turn-by-turn route guidance (Burnett & Lee, 2005; Willis, Hölscher, Wilbertz, & Li, 2009; Fenech, Drews, & Bakdash, 2010a). This assertion was not confirmed by the results of our simulator study. Comparing mean speed driven in the map condition in the driving simulator between the two groups (i.e., first drive map, second drive navigation system vs. first navigation system, second map) revealed no significant differences; however, we realise this does not rule out any order effects in the field test.

There were also a number of differences between both maps, for instance regarding street names, scale and familiarity. However, given their relatively simple nature and the presence of useful landmarks on both maps, we do not expect this to have affected our findings regarding relative validity, which is supported by the similar number of errors found. Furthermore, the route guidance function in the simulator, providing two instructions for each turn, was different from a traditional navigation system, because it lacked a moving map and the use of distance to the next turn as a component of the instruction. This may have caused a slight speed increase in the field test, taking into account that simple auditory instructions interfere less with driving performance than more complex instructions, which even led to a speed increase in a study by Dalton, Agarwal, Fraenkel, Baichoo, & Masry (2013).

6.4.2. Cognitive distraction

During the phone conversation, mean speed in the field test differed substantially from simulated speed for all speed limits, while all interaction effects showed that there was no difference in effect caused by method, again revealing relative, but not absolute validity. With regard to the variability of speed, results were somewhat mixed; within most speed limit zones, a main effect of method occurred, but not on the 50 km/h speed limit stretch. This might be related to these stretches being close to traffic lights, which may have induced somewhat more stop-and-go related variation, specifically in the field test. Moreover, most stretches did not show an interaction effect, except for the 100 km/h speed limit stretch. It is unclear why this occurred, but it might be due to subtle differences in traffic or more difficulties to keep a constant speed in the simulator.

Some cautiousness is warranted here, as cognitive distraction was implemented slightly differently in both methods, through having hands free conversations with a short pause in the field test, but hand held without a pause in the driving simulator. Regarding differences between hand held and hands free driving, a meta-analysis by Caird et al. (2008) suggests there may be a slightly larger speed reduction effect in hand held conversations compared to hands free conversations, which may be reflected in the somewhat lower effects for the field test data (Figure 5a). However, according to Caird et al., the small number of studies that could be incorporated in that meta-analysis, and the fact that one study contributed two effect sizes might have favoured this larger effect for hand held phone conversations while driving.

Furthermore, a different way of counterbalancing was applied in both methods, which also may have had an effect. However, counterbalancing would have probably led to an even stronger effect, in that the field test mean speed results regarding the phone conversation condition would have been rather lower than higher – participants in the phoning condition do not all recognise the route from the first drive, so they compensate more to this lack of familiarity by driving slower. As those effects would be small, they are not likely to induce interaction effects, at least for the 80 and 100 km/h sections. Therefore, despite these counterbalancing issues, we think relative validity is established.

6.4.3. Baseline driving

When baseline driving was compared between both methods, mixed results for SD speed were obtained. They were similar for both methods in urban driving, but substantially different on the motorway. Furthermore, the results showed differences between mean driving speed, i.e. in the simulator participants drove slightly faster, at both speed limits.

One reason for the absence of absolute validity regarding speed, apart from the 'genuine' differences in driving behaviour and performance itself, may be the fact that measuring speed using GPS is less than perfect, especially when compared to speed recordings very accurately derived from a simulator (cf

Godley et al., 2002). Moreover, the differences between mean speed in both methods may disappear if we take into account the fact that the speedometers in the real cars always show a slightly lower speed than the recorded GPS speed, whereas current speed in the simulator was recorded exactly as shown on the simulator speedometer. This may lead to lower recorded field test speed (see the hypothetical example in Table 6.5), whereas participants in fact kept the same speed. However, this does not clarify the differences in SD speed on the motorway. which suggest we did not fully succeed in mimicking real traffic, that was rather light during most test drives.

Table 6.5: Example of potential differences between speedometer and reported speed.

	Field test	**Driving simulator**
Speedometer (hypothetically)	100 km/h	100 km/h
Reported here	95 km/h	100 km/h

6.4.4. Limitations

Validation of the driving simulator was a secondary objective of both studies, therefore some differences between the two studies could not be avoided. Most are discussed above, and concern differences in experimental setup, tasks, and equipment, and were due to practical constraints. Another source of error may be that in the simulator, some participants reported light simulator sickness, feelings of dizziness or nausea, which may have had an influence on behaviour and performance. However, for older adults, Domeyer, Cassavaugh, & Backs (2013) found that having a (two day) delay between an initial familiarisation drive and a second drive may significantly decrease reported simulator sickness. Given the counterbalanced design, those effects may be ruled out for the simulated effects, but in comparison to field data be the cause of some of the differences.

Likewise, several disturbances such as road works and random error caused by other road users may have had an influence on field test driving, although the direction of these effects can only be guessed and effects are unlikely to be substantial. In addition, the research sample studied may bear some resemblance to the overall population in terms of gender distribution, but their experience in using mobile phones and navigation systems while driving most probably disqualifies them from being representative for all other drivers, although this does not necessarily affect the relationship between effects of distraction in both methods.

6.4.5. Conclusion

The main significance of the current study is that results concerning driving speed during distracting tasks, as obtained in the current driving simulator, render conclusions in a very similar way and direction as compared to real road (observed) driving, i.e. we found evidence for relative validity with regards to studying effects on speed for distracted driving in this particular simulator. However, in terms of absolute speed, conclusions seem to be much less stable and results should be interpreted cautiously. Still, driver behaviour and performance in traffic psychology research may be validly conducted in at least the simulator applied here.

6.5. Acknowledgements

Thanks to dr. Casper Albers for invaluable help regarding the statistical analyses performed here, in particular with the application of the Aligned Rank Transformation (ART), as described in 2.9. This transformation enables researchers to apply nonparametric factorial analyses without the need to abandon familiar ANOVA procedures (Wobbrock et al., 2011). Some of the research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under the project INTERACTION (grant agreement no218560).

7. The use of navigation systems in naturalistic driving[8]

Abstract

Objective: In this study we assessed the use of portable navigation systems in everyday driving by applying in-vehicle naturalistic driving.

Method: Experienced users of navigation systems, seven female and fourteen male, were provided with a specially equipped vehicle for approximately one month. Their trips were recorded using four cameras, GPS data and other sensor data. The drivers' navigation-system use data were coded from the video recordings, which showed how often and for how long the system was activated and how often and for how long a driver operated the system.

Results: The system was activated for 23% of trips, predominantly on longer and unique trips. Analyses of the percentage of time for which the speed limit was exceeded showed no evidence of differences between trips for which the navigation system was used or not used. On trips for which the navigation system was activated, participants spent about 5% of trip time interacting with the device. About 40% of interacting behaviour took place in the first 10% of the trip time, and about 35% took place while the car was standing still or moving at a very low speed, i.e. 0-10 km/h.

Conclusion: These results shed light on how and when drivers use navigation systems. They suggest that although drivers regulate their use of such systems to some extent, they often perform risky tasks while driving.

[8] Knapper, A. S., Van Nes, N., Christoph, M., Hagenzieker, M. P., Brookhuis, K. A. (2016). The use of navigation systems in naturalistic driving. *Traffic Injury Prevention 17 (3)*, p. 264-270

7.1. Introduction

Navigation systems have become common in the last decade. They are mainly classified as driver comfort systems (Brookhuis et al., 2001), but their economic and ecological benefits (due to shorter routes) are unequivocal. Although we know a lot about how navigation systems affect driving, their effects on driver and road safety are largely unknown, as experimental studies do not tell us how drivers use navigation systems. Operating a navigation system, for example, might cause a driver to become distracted, which in turn could lead to unsafe behaviour in traffic. It is reported that visual-manual distraction in particular is typically associated with 5-25% (Hurts, Angell, & Perez, 2011), and some believe even up to 80%, of all crashes (Dingus et al., 2006b), as well as significant increases in risk (Klauer, Guo, Sudweeks, & Dingus, 2010).

The current study focuses on the use of nomadic navigation systems: how and when they are used in naturalistic driving, and whether this can affect driving speed. First, we address the literature regarding two distinct tasks involved with navigation systems; namely, following route guidance instructions and operating the system.

7.1.1. Following Route Guidance Instructions

The primary task of a navigation system is to provide the driver with route instructions. Compared to traditional navigation methods, this is especially helpful when the driver is in unfamiliar surroundings, in terms of workload and driving errors, for instance (Antin et al., 2009). One clear benefit of using a navigation system is that it can allow for decreased exposure to traffic by providing a shorter/faster route (Feenstra et al., 2008; Antin et al., 2009). On the other hand, the fact that navigating has become so easy may also encourage some drivers to go to places that they would not otherwise have visited, thus increasing exposure (Emmerson et al., 2013). Furthermore, having alternative routes may lead drivers off motorways onto access roads, which reduces safety (SWOV, 2010).

Between 35% and 55% of European drivers own a navigation system (Jamson, 2013) and roughly 25% of drivers, mostly high mileage drivers (Jamson, 2013), use such systems on a regular basis (Lansdown, 2012; Jamson, 2013).

Compared to driving with a paper map, driving with a navigation system reduces the driver's mental workload (Feenstra et al., 2008). Other differences appear to be small (for example, a slightly higher mean speed) to non-existent (Feenstra et al., 2008). Olson et al. (2009) report that for commercial vehicle drivers, looking at paper maps is associated with a substantially increased likelihood of having a crash or near crash (odds ratio 7.02). In short, the literature seems to suggest that as long as route guidance instructions are kept simple (Dalton et al., 2013) and instructions are reliable (Ma & Kaber, 2007a), drivers have sufficient support when using a navigation system for route guidance.

7.1.2. Operating the Navigation System

Several studies have investigated destination entry by the driver (e.g., Burnett et al., 2004; Chiang et al., 2004). The respondents in a study by Lansdown (2012) rated the level of distraction caused by destination entry as 'medium' (3 on a 5-point scale). About 35% of respondents reported that they entered data while driving, while 12% did so on a daily or weekly basis. Jamson (2013) found that 10-30% of drivers say that they sometimes enter or change a destination while driving. In a field study by Metz et al. (2014), the drivers reduced their speed just before operating the navigation system and they maintained a longer headway distance. Furthermore, the nomadic device used in that study led to deterioration in lateral performance, whereas a built-in navigation system did not.

Operating a navigation system is a visual-manual task. Another visual-manual task, texting, increases the risk of being involved in a crash in naturalistic commercial vehicle driving (Olson et al., 2009) and normal car driving (Fitch et al., 2013). It could be argued that practising visual-manual tasks could help drivers to avoid some of the consequences. Indeed, in a study by Nowakowski, Utsui, & Green (2000), practice shortened destination entry duration; however, lateral driving performance in particular still deteriorated.

Whereas voice-controlled destination entry may seem less distracting than manual programming, drivers still take their eyes off the road, because they seek confirmation that the input is correct. However, these glances are generally more rapid and the overall eyes-off-road time is shorter (Tijerina et al., 1998).

In short, although following route guidance instructions may hardly affect driving, it is likely that operating a navigation system does. The net effect on safety is unclear, however, as we lack information about how drivers use their systems in practice and how this can affect their driving. Moreover, as navigation systems are changing rapidly and their use is increasing, past studies may not accurately represent current experiences.

7.1.3. Study Objectives

The present study assesses how experienced users of recent navigation systems are actually using such systems in everyday driving. The general research question addressed is: *How do drivers use their navigation systems in real driving?* More specifically, we investigated:

- On what kinds of trips, how often, when and for how long do drivers use navigation systems?
- What are the effects on speed behaviour of driving with a navigation system?

We analysed patterns of drivers' use of navigation systems in order to identify behaviour that could potentially affect safety. Furthermore, as navigation systems often display information regarding speed (i.e., the current speed, the current speed limit and speed-check information), and speed is an important driving safety-related measure (Aarts & Van Schagen, 2006), we assessed whether we could infer the effects of using a system supplying such information on speed behaviour. For instance, as GPS speed shows a realistic speed (and the speedometer in many motor vehicles, including the ones used in our project, shows an optimistic speed), it could be the case that drivers drive slightly faster than they otherwise would when using a navigation system.

7.2. Method

7.2.1. Participants

Drivers were invited to participate by means of posters and digital newsletters distributed at the Delft University of Technology. Those who expressed an interest were sent a short questionnaire. Drivers who indicated that they use (1) a mobile phone and (2) a navigation system at least once a week, and (3) drove at least 200 km per week were selected. The eventual sample consisted of 21 drivers (fourteen male and seven female) with an average age of 37 (SD=9.7). They had had their driver's licences for fifteen years on average (SD=9.4) and reported that they drove an average of 23,226 km per year (SD = 6,974).

7.2.2. Procedure

Participants were briefed about the project, but not about the research goals. The project included driving in a vehicle for five to six weeks that had been equipped with a camera and other recording devices. The participants gave their consent and were asked to use the car as if it were their own. All participants received financial compensation after completing the study.

7.2.3. Vehicle

Participants were given either one of four Lancia Ypsilons or a Peugeot 207. All five cars were equipped with a data acquisition system containing several components, including a PC, four cameras (directed at the driver, the driver's face, the forward view and the navigation system, all recording at 12.5 Hz) and a 1 Hz GPS/GSM device. The system did not require participants to perform any tasks extraneous to their normal driving behaviour. Booting took about two minutes and the GPS device took another four minutes to receive a proper signal (depending on conditions), meaning that speed-related data were incomplete for some trips. This applied in particular to the beginning of trips, although GPS reception could sometimes also be distorted during trips.

Participants were provided with a Bluetooth hands-free device and a five-inch touch-screen TomTom Go Live 1005 navigation system that could be mounted in the car (see Figure 7.A1[9]). In the Lancia Ypsilons, the navigation system windscreen mount was installed to the left of the steering wheel, with a camera facing it. In the Peugeot 207, the system was mounted to the right of the steering wheel. The different vehicle dashboards layouts did not allow for an identical installation set-up. The navigation system was equipped with modern functions, including real-time traffic information, voice control, current speed and (mobile) speed camera information, and was fully operable during driving. One participant used his own navigation system (a different brand).

[9] Figures in this Chapter that include an A in the title were provided in the appendix in the original article.

Figure 7.A1: Vehicle cabin layout (Lancia Ypsilon), including a navigation system photo. The navigation system mount is installed to the left of the steering wheel, with a camera facing it. In the Peugeot 207 the system was mounted to the right of the steering wheel.

7.2.4. Data Analyses

Trips in the test vehicles made by drivers other than the registered participants were omitted from the analyses. Furthermore, each participant's first week of driving was excluded to ensure that they had become familiar with the vehicle. This was not communicated to the participants beforehand.

The video data were manually coded by four data reductionists using in-house designed software that allowed for connecting the numeric data (such as GPS speed) to the video data, and for enriching the data with observations inferred from the video recordings. For each task, the start time and end time were coded. The navigation system visual-manual tasks were defined as follows:

1. *Reaching, grabbing or mounting* (all interactions that were needed to make the navigation system ready for operation). This event would start as soon as the driver started looking for the device, and ended when the driver was either back in his normal driving position or started operating the device.
2. *Programming a destination*, including voice control. Operation would start with the driver's first glance at the device (before touching), or the first time the driver's hand started moving from its resting position

(often the steering wheel). An event ended when the driver's hand was back to a normal position, or, when insecure, when the driver looked at the road again.

3. *Other operating* was coded when the driver was holding the device in his hands while operating it, as it was not possible to verify whether the operation concerned destination entry. This code also applied to other functions (volume, map zooming), so the coders were instructed to watch the navigation screen if available.

Coding always began at the start of a trip in order to record the mounting and destination-entering that was done before driving. Coding was paused when the car was parked during a trip (e.g., when waiting for passengers, not participating in traffic). Coding ended at the end of the trip, when the driver had parked. Hence, coding did not take place when drivers demounted the system at the very end of the trip, while parked. This avoided the data being contaminated with actions that did not involve any kind of actual driving.

Trips were randomly assigned to the coders, who watched each trip at a high video speed and slowed down or paused the video when an event (i.e. a task) occurred. They coded the start and the end of each event. In order to ensure high-quality data, the coders discussed potentially ambiguous behaviour on a weekly basis. Inter-coder reliability was assessed by having a total of 50 randomly-selected trips coded a second time, in addition to normal coding. The duration and presence of all events coded in those trips were compared and tested statistically using Krippendorff's α (Hayes & Krippendorff, 2007). The agreement level for code presence (nominal measurement level) was α = .89, and for duration (ratio) α = .83, which are both above the recommended level of agreement of α = .80.

7.3. Results

Regarding the route guidance function, we included all trips during which the navigation system was activated, regardless of whether the destination was set or not. On a general note, the data did not reveal any crashes or major incidents.

7.3.1. Following Route Guidance Instructions

What kinds of trips?

The navigation system was activated for about 23% of trips (300 of a total of 1306 trips). The 21 participants' general driving behaviour is summarised in Table 7.A1.

Table 7.A1: General figures relating to participants' trips, including navigation system use.

	Total number of trips	Number of trips with Navigation System activated	Total duration (h)	Total duration of trips with Navigation System (h)	Total distance driven (km)	Total distance driven with Navigation System (km)
Total	1306	300	572.3	229.6	26,327.6	12,895.9
Mean per participant (M)	62.2	14.3	27.2	10.9	1253.7	614.1
Standard Deviation (SD)	21.0	9.5	10.9	8.3	635.6	520.3
Min.	28	3	13.1	1.3	506.2	39.6
Max.	109	35	51.1	31.2	2450.1	2043.7

It was determined whether trips were driven only once or repetitively over the observation period. Trips were considered repetitive if the start was within 1,000 m, the finish was within 500 m, and the difference in trip length was shorter than 3 km. A total of 740 (M 35.2, SD = 19.1) trips were recorded that matched other trips (that is, that were repetitive), and 566 that were unique (M = 27.0, SD 10.6), including a distinction between long (longer than 5 km) and short trips (shorter than 5 km). Not surprisingly, navigation systems were used the least for short, repetitive trips, while the average percentage of trips in which a navigation system was used was highest for unique long trips, which constituted almost half of the trips (see Table 7.A2). A three-way loglinear analysis (navigation system use x repetitiveness x trip length) revealed a model that retained the three two-way interactions. The model's Likelihood Ratio was $\chi^2(1)= .019$, $p=.89$. The interaction navigation system use x repetitiveness interaction was significant, $\chi^2(1)= 75.2$, $p<.001$, indicating that participants used the navigation system less often on repetitive trips (odds = .13) than on unique trips (odds = .60), odds ratio = 4.53. The navigation system use x trip length interaction was significant, ($\chi^2(1)= 112.3$, $p<.001$. The odds ratio revealed that the odds of using the system were ten times more likely on long trips (.49) than on short trips (.049). Finally, the repetitiveness x trip length interaction was significant,

($\chi^2(1)$= 38.0, p<.001). This means that short trips had a higher likelihood of being repetitive (2.81) than long trips (.91), ratio 3.09.

Table 7.A2: Percentage of trips for which the navigation system was used, distinguishing between 'repetitive' and 'unique and long' (<5 km) and 'longer trips' (>=5 km).

	Trip repetitiveness	
Trip length:	**Repetitive**	**Unique**
<5 km	3.0%	9.2%
>= 5km	19.0%	45.2%

Table 7.1: Characteristics of trips for which participants did or did not use the navigation system.

	Without navigation system		With navigation system		T-test (df=20)	
Trip characteristic:	**Mean**	**SD**	**Mean**	**SD**	**t**	**P**
Number per participant	47.9	20.3	14.3	9.5	-6.32	.00
Distance driven (km)	13.8	8.8	40.7	21.3	-5.79	.00
Duration (s)	1249.0	487.8	2661.4	938.2	-6.48	.00
Mean speed (km/h)	31.7	7.8	52.4	11.2	-7.00	.00
% of time on urban road	64.7	12.8	48.2	15.5	3.93	.00
% of time on rural road	13.0	10.8	16.7	7.6	2.16	.04
% of time on motorway	12.6	9.6	34.4	15.6	-6.34	.00
% of time road type unknown due to incomplete map	9.7	7.3	0.7	1.8	5.46	.00

Next, trips for which the navigation system was used were compared to trips with no use, as depicted in Table 7.1. Trips for which the navigation system was used were on average longer. Furthermore, the average speed was considerably higher, which is probably due to the higher percentage of motorway driving on longer trips. Table 7.2 shows the mean speed in several speed limit zones. In order to assess whether the participants on average drove faster with a navigation system than without, for different speed limits, a 2 (with or without navigation systems) * 5 (50, 70, 80, 100, 120 km/h speed limit sections) factorial repeated measures ANOVA was carried out. Mauchly's test indicated that sphericity could be assumed for the navigation system-use main effect. The navigation system-use main effect was not significant (p=.097, r=.13), meaning that the participants drove slightly but insignificantly faster during trips for which they were using the navigation system.

Table 7.2: Mean speed for several speed limits, with and without use of navigation system.

	Trips with navigation system		Trips without navigation system	
Speed limit	Mean speed	SD	Mean speed	SD
50	23.4	4.9	20.1	4.3
70	59.3	13.2	62.6	16.4
80	61.9	10.4	58.3	13.1
100	87.3	11.6	85.7	9.6
120	86.3	17.3	78.2	18.8

Table 7.3 shows the mean percentage of trips for which participants used a navigation system, across different temporal units. During the morning peak (excluding weekends), a relatively high percentage of use was observed compared to during the afternoon peak. Related to this observation, in the mornings and afternoons (including weekends) the percentage of trips for which the navigation system was used was relatively high compared to the evenings. Distinguishing between the first trip of the day, the last trip of the day and other trips (including trips on days when only one trip was made), it appears that participants used the navigation systems less often for the last trip of the day.

Table 7.3: Mean percentage of trips for which the navigation system was used in several time-related units.

Temporal unit	Proportion of trips for which navigation system was used	
	Mean (%)	**SD (%)**
Week (Mo-Fr)	24.0	17.2
Weekend (Sa, Su)	25.6	19.3
Mondays	23.0	22.7
Tuesdays	25.0	19.7
Wednesdays	28.9	23.9
Thursdays	21.4	25.9
Fridays	19.3	22.2
Saturdays	24.6	25.4
Sundays	34.6	33.7
First trip of the day	26.9	17.6
Last trip of the day	19.0	18.1
Other trips	27.0	20.8
Morning peak (7.00-10.00)[a]	34.1	29.4
Afternoon peak (16.00-19.00)[a]	21.2	20.4
Off-peak/other hours[a]	25.4	19.6
Night (0.00-6.00)	n/a[b]	
Morning (6.00-12.00)	29.3	20.9
Afternoon (12.00-18.00)	25.3	18.9
Evening (18.00-24.00)	17.3	17.4

[a] Excludes weekends
[b] Only 9 trips fit this criterion

Navigation system use and speeding

We investigated whether navigation system use affects drivers' speed, as navigation systems provide information about current speed (based on GPS data), the current speed limit and speed cameras. Furthermore, drivers who know that GPS provides a realistic speed measure may drive closer to the limit or exceed the speed limit somewhat more often when using a navigation system. We compared the percentage of time the speed limit was exceeded for trips in which a navigation system was used and other trips. Table 7.4 shows the results for different speed limits and the extent of speeding. When we compared driving with or without a navigation system, no significant difference was found for exceeding the speed limit for either 50% or 20% of the time. The only substantial difference was found when the total percentage of time driving above the current speed limit (i.e. 50.1 km/h) was compared for trips with and without the navigation system.

Table 7.4: Percentage of time that drivers exceeded the speed limit, driving with or without a navigation system.

		Trips with navigation system		**Trips without navigation system**			
		Mean percentage	SD	Mean percentage	SD	T-test (df=20)	Effect size (r)
>50% over speed limit	Overall	.6	.5	.5	.4	NS	.13
>20% over speed limit	50	4.6	2.7	3.2	2.4	NS	.41
	70	10.9	11.9	14.7	20.3	NS	.17
	80	3.9	4.1	3.3	4.9	NS	.22
	100	5.9	8.0	5.0	7.2	NS	.17
	120	.2	.4	.1	.2	NS	.28
	Overall	4.1	2.8	3.2	2.6	NS	.40
All speeding (any speed above the speed limit)	50	12.2	5.4	9.7	4.1	NS	.40
	70	29.2	17.9	31.6	21.0	NS	.10
	80	22.2	13.4	19.2	14.0	NS	.21
	100	34.6	20.3	37.0	22.9	NS	.14
	120	15.2	18.4	15.5	19.7	NS	.03
	Overall	20.4	11.7	14.8	7.8	2.61, p=.017	.50

Note: Effect size r is calculated using $r = \sqrt{\frac{t^2}{t^2+df}}$

7.3.2. Visual-Manual Tasks

When performed?

The study distinguished between three visual-manual tasks (see data analyses section). The results regarding these coded events are presented in Table 7.5. The table shows that participants on average operated the device approximately 50 times in total, and that destination entry required the most time. For about 5% of the driving time, participants were engaged in operating/installing the device during trips that involved navigation system use, which adds up to about 1% of total driving time. Furthermore, participants showed more navigation system interactions during unique trips.

Table 7.5: Visual-manual task characteristics, as coded from the video data (see methods/data analysis section for definitions).

	Reach, grab, mount		Destination entry		Other operating	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Total number of times the task was performed	11.5	10.3	18.1	14.3	31.9	28.0
- In repetitive trips	2.6	3.6	5.9	8.0	7.1	10.7
- In unique trips	8.9	8.2	12.2	9.2	24.8	22,8
Task completion time (s)	12.0	4.7	26.6	12.9	15.3	9.7
Number of actions performed in trips for which system was used	.7	.4	1.3	.4	2.2	1.2
% of driving time engaged in task (in trips for which system used)	.8	0.4	2.4	1.1	2.0	1.2
% of driving time engaged in task (for all trips)	.1	.1	.5	.5	.5	.5

For each operating event, we determined for which part of the trip (as a percentage of trip time) the event started. Figure 7.1 shows that almost half of all the operating events occurred in the first 10% of the trip durations. The small increase in reaching/grabbing/mounting at the end of the trip (see the right side of Figure 7.1) reflects the fact that some drivers removed the navigation system from its mount near the end of the trip, while they were still driving. Likewise, about 40% of all interactions were performed at very low speed (up to 10 km/h; see Figure 7.A2).

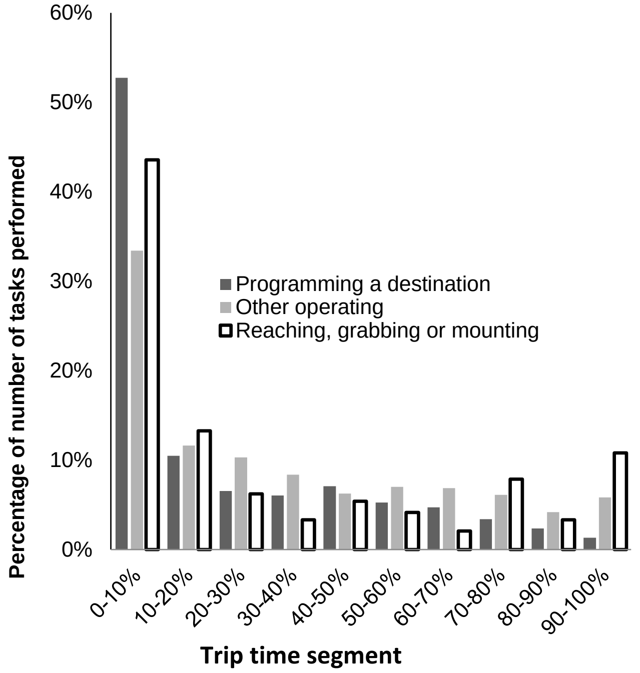

Figure 7.1: On which part of the trip did visual-manual tasks start? (See the data analyses section for a detailed description of these tasks.) To determine the trip time segment to which each operating event belonged, the following formula was used: $\frac{\textbf{event start time in s}}{\textbf{total trip time in s}} * \mathbf{100}\%$.

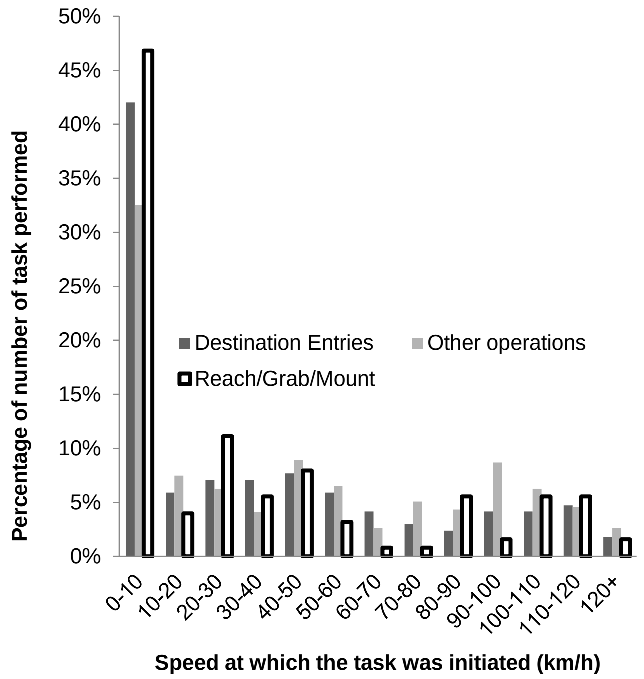

Figure 7.A2: Percentage of visual-manual tasks that were performed at 10 km/h speed intervals.

Effects of visual-manual tasks on speeding

The percentage of time (in seconds) that drivers drove at a speed above the speed limit was calculated for three timeframes: six seconds before operating the system, during the operation and for six seconds after the operation. Before operating, drivers drove above the speed limit for 10.3% of the timeframe; during operating, they were above the speed limit for 9.2% of the timeframe; and after, 13.8%. These differences are statistically significant ($F(2)=3.666$, $p<.05$, no sphericity violations). Comparison revealed no difference between the 'before' and 'during' conditions ($F(1)=.76$, $p>.05$), but in the six seconds after the operation, substantially more speeding was observed ($F(1)=5.51$, $p<.05$) than during the operation. Figure 7.A3 presents these results as a boxplot.

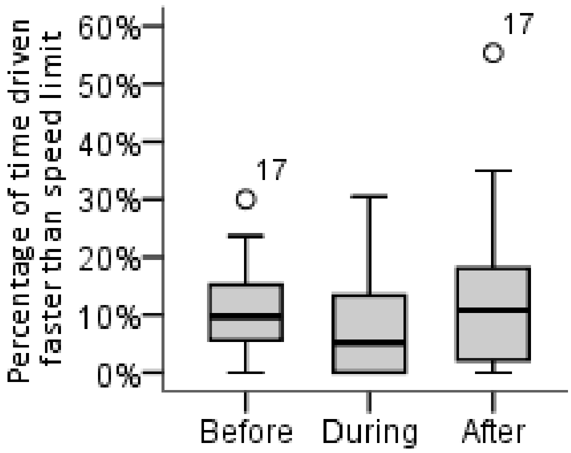

Figure 7.A3: Percentage of time participants drove above the speed limit, 6 seconds before, during, and 6 seconds after they visually-manually operated the navigation system. The dots marked '17' represent outliers (by one participant); the boxplots show minimum, first quartile, median, third quartile and maximum.

7.4. Discussion

The data reveal that the participants used the navigation system for about a quarter of all trips. Relatively frequent use was observed for trips that participants made only once during the observation period and for longer trips, both in terms of distance (over 5 km) and time (more than 40 minutes). Furthermore, morning peak hours showed higher use than afternoon peak hours, which may be attributed to the fact that trips home (in the evening, after work) tend to be to familiar destinations. The trips for which the navigation system was used showed higher percentages of time driving on motorways. This is probably related to the fact that these trips were longer and motorways are the fastest way to reach a destination. When controlling for speed limit, we found that drivers did not drive substantially faster with a navigation system than without.

Next, we compared GPS speed recordings to the posted speed limits, as we suspected that the drivers might know that the GPS speed shows a more realistic speed than many car speedometers (that are optimistic about speed, Wikipedia, 2015). During trips in which participants used a navigation system, we observed a slightly higher percentage of speeding, but only when including all speeding, including driving slightly above the speed limit (0.1 km/h or more). Several participants indicated that they knew that GPS data typically provide a lower speed than the car speedometer. Thus, drivers may drive slightly faster when using the speed information from the navigation system, which is reflected in the higher percentage of speeding. This effect might be tempered by the fact that drivers quickly learn how optimistic their vehicle speedometer is and adjust for it. A study by Feenstra, Hogema & Vonk (2008), also an on-road driving study, likewise found that somewhat higher speeds were driven while using a navigation system compared to driving with a conventional map. Note that this might be for another reason: as reading a map is so demanding, drivers may choose to drive more slowly.

During trips for which they used their navigation system, the participants operated their system mostly (about 50%) in the first 10% of the trip time. They spent about 5% of trip time mounting or operating the system, while practically standing still for about 40% of that time. This 5% is probably an underestimation, since the GPS often took a while to start up. Nevertheless, the results confirm Funkhouser & Sayer's (2012) finding that drivers regulate their behaviour to some extent by operating the system while (practically) standing still or driving at low speed, probably recognising the fact that this is the safest moment to do so. However, drivers still do a relatively large amount of operating during normal driving. Given the significant impact of operating navigation systems on driving performance, this may have a considerable effect on safety, certainly when we take into account the finding by Merat et al. (2005) that drivers have difficulties abandoning a secondary task, including when circumstances become more demanding. When they operated the navigation system the drivers slowed down somewhat, as compared to right before and right after operating. It is not uncommon for drivers to slow down when demands are high, for instance during texting (for an overview, see Caird et al., 2014; also see Metz et al., 2014). Although not entirely surprising, these are the first figures that accurately describe how and when drivers use navigation systems.

7.4.1. Limitations

Several limitations should be noted. Our sample was relatively small and consisted of voluntary participants, which could have caused self-selection bias. Furthermore, the fact that recruitment took place at Delft University could mean that the sample is somewhat biased. Our participants were both frequent drivers and experienced users of navigation systems, however, which may make them relatively safe users (Dingus, Hulse, & Mollenhauer, 1997). Furthermore, actual use for five weeks is a relatively long observation period, and this is the first study to report on real-life use in such detail.

Participants were not informed beforehand about the purpose of the study, but they may have suspected that the navigation system was the target of the investigation when they noticed the camera pointed at it. In addition, the fact that we provided a windscreen-mounted navigation system may have added to the ease of using the system, potentially increasing the use.

Another limitation is that the GPS system became active only after several minutes. This meant that a relatively small amount of valuable information was lost, because the speed, speed limit and environment could not be determined during the whole period. One important issue affecting the specific navigation system used in this study was the fact that the power button did not always function as expected: when pressed for too long, the system would shut down again. Participants were informed about this issue during the briefing. This did occasionally cause participants to perform actions that were related only to the specific device, however minor. Furthermore, although participants reported that they soon forgot that they were being observed, we received some signals that this may have occasionally influenced participants' behaviour.

7.4.2. Conclusion

In real-life driving, the participants used their navigation systems predominantly on relatively long, infrequent trips. During the trips for which they used their navigation systems, there was a mild increase (approximate 5%) in instances of speeding and they drove at slightly (but insignificantly) higher speeds. Our general conclusion is that while these effects are small, they have a negative impact on road safety, as driving at higher speeds increases the risk and severity of crashes (Aarts & Van Schagen, 2006).

In addition, of the time that participants spent operating the navigation system, about half of this time was spent at the beginning of the trip. During this time, the car was not moving for about 40% of the time, meaning that the major part of operation was performed while driving. Operating a navigation system is a visual-manual task. Conducting visual-manual tasks such as texting means taking one's eyes off the road, and thus increases the risk of crashing (Klauer et al., 2014).

7.5. Acknowledgements

The research leading to these results received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under the project INTERACTION (grant agreement no. 218560). We would like to thank to three anonymous referees for their helpful comments.

8. Answers to research questions, discussion and conclusion

This dissertation provides insight in how mobile phones and navigation systems affect driving behaviour and performance. Chapter 8 first formulates answers to the research questions that were posed in Chapter 1, by returning to Chapters 2-7 (8.1). Next, a number of limitations to the studies are described (8.2), followed by a discussion on the implications for several stakeholders and potential follow up research topics (8.3). The chapter ends with a lookout into the future, of the interaction of phones, navigation systems and driving (8.4) and a concluding section (8.5).

8.1. Answers to the research questions

The main question overarching this thesis, as formulated in Chapter 1, is *what are the road safety and efficiency effects of using a mobile phone or a navigation system while driving?* The next paragraphs will provide arguments and findings by discussing the underlying research questions that were formulated in Section 1.3, by looking at Chapters 2-7.

8.1.1. How should we understand the effects of using mobile phones and navigation systems on the driving task and on driver behaviour? (Chapter 2)

Chapter 2 provided the current state of affairs regarding both theoretical and empirical knowledge about driving, in order to find indications for a model that may describe effects of mobile phones and navigation systems on driving behaviour and performance. The theory so far indicates that driving a car is a complex task, that requires a lot of effort but becomes easier, more automated and less error prone with experience. Operationally, driving may be described as keeping a vehicle in a lane, at a safe distance from objects while making both longitudinal and lateral movements. The driver needs to be aware of the situation, should process all relevant incoming information and react accordingly. Clearly, visual information is of major importance here. How (well) the driver performs the driving task depends on both the task difficulty and the driver's general competences and capabilities (Fuller, 2005). That is, most drivers can only process a limited amount of information within a certain time frame, but some perform better than others, for instance because of experience or exerted effort. Within drivers differences in performance occur, due to the state the driver is in at particular moments, for example when they are tired, under the influence of alcohol or distracted. One paradigm (e.g. Summala, 1988; Wilde, 1982) suggests that drivers may by and large be motivated by feelings of fear for inadvertent events. They may try to maintain their feelings of risk within certain limits, which makes some drivers perform certain distracting activities such as texting while driving, while others refrain from doing so.

The theoretical model that appeared most useful for the general topic of this thesis was Fullers Task-Capability Interface (TCI) model (2005). This model describes the interaction between drivers' capabilities and motivations as well as the complexity of the driving task and the environment. Furthermore, the model incorporates different levels (i.e., the strategic, tactical and operational, cf. Michon, 1985) and is able to involve distractions from tasks which are secondary (or tertiary) to the driving task, thereby increasing the difficulty.

Although this thesis does not have the intention to test models, the TCI model seems suitable to understand results regarding distracted driving. Moreover, it provides suggestions how to reduce some of the detrimental effects of distraction. Chapter 5, for instance, demonstrated that visual-manual tasks resulted in loss of control, in terms of speed keeping and lateral performance. The TCI model suggests that education, for instance through advertising campaigns, about the risks of distracted driving can help drivers to refrain from distracting activities during driving, in order to avoid loss of control. The results as reported in Chapter 6 could also be understood in terms of the TCI model. Drivers can adjust the task demands from a distracting secondary task by reducing their driving speed. Chapter 7 showed the reverse, namely that a mild increase in speed was found after drivers had completed the operation of their navigation system, which is also in line with the model.

Nevertheless, the TCI model has certain limits. Not only does it hardly account for a driver's errors, the model also largely ignores the influence of other actors in the road traffic system (e.g. road designers, or the role of police enforcement). It could well be that if the systemic driver task demand model by Lansdown et al. (2015) and the PARCC model (Parnell et al., 2016) would be taken into account as well, these models together would provide some next steps in the direction of a more encompassing theory of driver behaviour, including distraction.

8.1.2. How can we investigate the effects of phones and navigation systems use on driving? (Chapter 3)

Before answering and discussing this question, in Chapter 3 first a distinction was made between several (sub) tasks related to mobile phones and navigation system use while driving, and how they affect the driver. Table 8.1 shows these distinct tasks, including several examples, and in which distraction categories these examples may affect the driver. This distinction was important throughout this dissertation.

Table 8.1 (similar to Table 2.1): The different (sub) tasks distinguished in this dissertation, and how they may distract the driver.

Device	Tasks distinguished in Chapter 3	Examples	Distraction category (x when present, (x) when not necessarily present)			
			Visual	Cognitive	Manual	Auditory
Mobile phone	*Operation*	Texting, e-mail, games	x	x	x	
		Answering a call	(x)		x	x
	Conversation	Handheld		x	x	x
		Handsfree		x		x
Navigation system	*Operation*	Alternative route selection, destination entry	x	x	x	
		Volume change	x		x	x
	Use	Following route guidance	(x)	x		(x)
		Speed warnings, speed camera warnings	(x)	x		(x)

Researchers have used a range of different methods to study the effects of the use of mobile phones and navigation systems on driving. Firstly, lab tests and driving simulator experiments have been used. These allow a great deal of experimental control and detail, enabling to study (causal) effects of various manipulations. However, often the question remains whether the results hold in the real world. While field experiments introduce real traffic, the possibilities for experimental control and ditto effects are less clear, as any measured effect might well have been caused by the changing environment or the unpredictable traffic itself. Finally, naturalistic driving studies and accident studies offer a great deal of realism, but it appears difficult to determine cause and effect. Crashes may be caused by driver behaviour and performance, however there is no telling to what extent the weather, other drivers, or road conditions are contributing factors. Figure 8.1 shows how the different methods can be positioned relative to each other with regard to both realism or face validity, and experimental control.

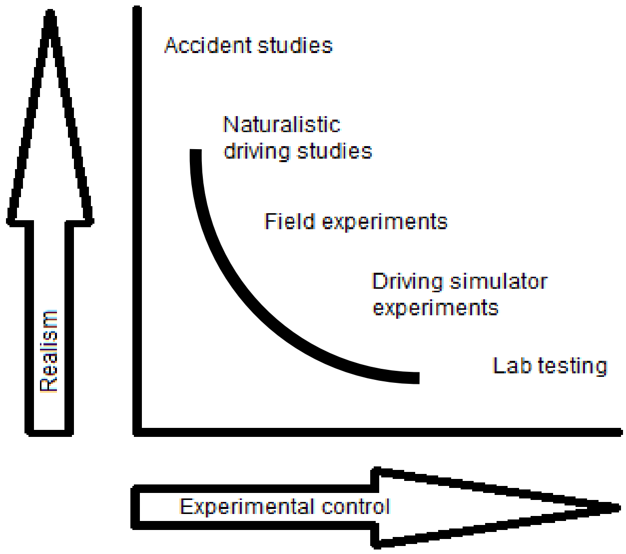

Figure 8.1 (similar to Figure 3.1): Graphical summary of how methods score on experimental control and realism.

Depending on the aforementioned methods and accompanying equipment, several variables can be measured and compared in a study. Dependent variables that have been shown relevant for studying effects of using phones and navigation systems on driver performance are for instance both lateral and longitudinal control. The latter is often measured in terms of the standard deviation of lateral position (SDLP) and speed choice. Also relevant is where the driver is looking (i.e., on the road or not), which may for instance be measured in time eyes off road (TEOR).

Overall Chapter 3 illustrates that not one perfect method exists to assess how mobile phones and navigation systems affect driving, as all methods and measures have their pros and cons (cf. Young et al., 2009b; Carsten et al., 2013). This is a sound reason to apply a mix of measures and methods.

8.1.3. What results have been reported in the research literature so far?

Since mobile phones as well as navigation systems have been around in cars for about two to three decades, in Chapter 4 the available literature was analysed, in order to answer the following research questions:

- Which impacts on safety are the result of drivers using mobile phones and navigation systems?
- How do these safety impacts relate to efficiency?
- How comparable are these impacts across the two types of device?
- What knowledge gaps are there in the current body of research?

Which impacts on safety are the result of drivers using mobile phones and navigation systems?
The main effects found in the literature are discussed, by the four main tasks underlined below, all associated with using mobile phones and navigation systems while driving.

The effect on accident risk of having a phone conversation has been the topic of widespread discussion during the past decades. The most recent findings indicate an odds ratio[10] of 2.2 of being involved in a crash while having a handheld mobile phone conversation (Dingus et al., 2016). Other recent findings indicated that using a phone while driving may sometimes be even safer than normal driving, with odds ratios below 1, (Olson et al., 2009; Klauer et al., 2014), which (re)fuelled the debate that earlier seemingly had been settled at an earlier estimated four-time risk increase (NSC, 2010). The future will show whether this debate is over now. The results of Dingus et al. (2016) appear solid, although still a lot of questions remain. It could even be that all findings were true, and the risk just developed over time, through a learning effect (adaptation, cf. OECD, 1990; Saad et al., 2004). What is more, we still hardly know how these results translate exactly to for example the Dutch, let alone the European situation. The effects of mobile phone conversations on driving performance, which probably intermediate increased accident risk, have not led to so much debate. Solid effects have been reported that drivers for instance react slower while having a phone conversation, and since almost every conversation needs to be either answered or initiated, a driver's eyes drift off the road.

[10] A 2.2. odds ratio may be interpreted as: the odds of being involved in a crash when using a mobile phone are 220% higher than during normal driving. Note that this is not fully similar to the chance of being involved in a crash (cf. Osborne, 2008).

Operating a mobile phone manually while driving affects how well the driver is able to watch the road. Especially operating a touchscreen smartphone requires the driver to frequently watch the screen for feedback on what buttons he presses. Older ‘dumbphones’ and Blackberries at least gave some physical feedback (one finger is on that button), so some drivers were even able to operate those (almost) blindly. Not watching the road leads to swerving and increased reaction times, hence increasing the risk of having an accident. Drivers are aware of this to some extent. A recent large-scale European questionnaire study, called ESRA (Trigoso, Areal, & Pires, 2016), showed that only 7.4% of the respondents think that phoning while driving is acceptable, while 4% think that even texting is acceptable. Still, at least a quarter of the respondents indicated to have texted / e-mailed at least once during the past 12 months. This compares to findings in a Dutch questionnaire study performed by Christoph, Van der Kint & Wesseling (2017), that found that about 87% of the Dutch think it is dangerous if they use their phone while moving in traffic, while about a third of car drivers use their phone at least sometimes during a trip. Apparently, many people engage in behaviour they themselves do not think is acceptable. Probably the well-known cognitive bias of illusory superiority is in place here, that makes up to 80 percent of drivers think they drive better than the average driver (Svenson, 1981; McCormick, Walkey, & Green, 1986).

Programming a navigation system while driving equals texting to some extent. Both tasks require the driver to look at the screen, and thus off the road. Furthermore, workload increases and both lateral and longitudinal driving performance decrease, largely depending on the navigation system’s interface usability. A recent study by Strayer et al. (2017) assessed 30 2017 model-year vehicles that represented 30% of sales in the US, regarding how impairing tasks would be that were specifically related to the infotainment systems. One of the tasks assessed was starting and cancelling a route using the infotainment systems’ navigation feature. The navigation tasks took significantly more interaction time than any of the other tasks assessed (e.g. calling/dialling, text messaging, audio entertainment) and was most demanding, in terms of visual and cognitive demand. Vehicles also differed considerably in how demanding interacting was. This demand differences stem from the interaction mode (i.e. position of the system, voice control) but also from ‘awkward and confusing machine interfaces’.

Although it would seem that voice control could solve problems regarding programming navigation systems, the literature does not wholeheartedly support that, as apparently voice control systems still have not evolved into viable alternatives to touch screen controls (Strayer et al., 2015). Furthermore, the reader may recognise the urge to still check the screen in order to see whether the voice input was successful. What is more, the study by Strayer et al. (2017) revealed that the voice-based interaction provided in new vehicles required significantly longer interaction times than other (e.g., visual-manual) interaction types, which reduces the benefits of lower visual demands.

Following a navigation system's route guidance advice reduces driver stress, provided that the right information is presented in a timely fashion. Depending on the system's settings, older drivers may profit less as their information processing and reaction time capacities are on average reduced compared to younger drivers. Still, in general it is safe to conclude from the literature review that, also for older drivers, it is safer to navigate using a navigation system than a paper map. Navigation systems may also lead older drivers to drive more often (Emmerson et al., 2013) because navigation systems may help them overcome some of the problems that used to make them avoid driving (Ball et al., 1998). This however does increase exposure, which probably increases crashes.

How do these safety impacts relate to efficiency?
Road safety is not the only factor that drivers take into account when deciding to use a phone or a navigation system while driving, they may also think it is more efficient because they can avoid traffic jams or discuss work while driving. Moreover, efficiency may be important from a road traffic control or policymaker perspective. For instance, speeding may be less safe but more efficient to an individual driver, whereas a shorter route may be safer (less exposure to traffic) as well as more time efficient (for both the driver and traffic). However, speeding and speed variability may also lead to more traffic jams. Therefore, this thesis also addressed the question how the effects on safety relate to efficiency, on the personal and the aggregate level. The literature found on this topic was scarce. The primary gain identified for operating a navigation system or a phone while driving seems the fact that one does not need to stop to perform the task. However, the predominant effects of these activities that have been found on longitudinal driving performance, namely speed decrease and increase in speed variability, may also negatively affect traffic flow. The same holds for efficiency effects of phone conversations, as they may lead to fiercer braking, although to a lesser extent. Apart from the aspect of operating the device during driving, the use of route guidance by a navigation system leads to more efficient driving and

traffic in general, and drivers 'save' resources because of a lower mental workload, which may then become available to allocate to driving-related tasks.

How comparable are these impacts across the two types of devices? What knowledge gaps are there in the current body of research?
The effects on driving performance of operating a phone and operating a navigation system during driving appeared comparable. Both tasks influence the way drivers watch the road and their performance in terms of lateral control deteriorates. The longer it takes to perform such a task, the worse the effects become (cf. Green, 2008; Strayer et al., 2017). It is not clear from the literature how often drivers engage in such very long tasks while driving, as research regarding this is scarce.

Knowledge gaps that were identified in Chapter 3 include how differences between various countries affect the effects of navigation systems, and how many drivers comply with the route guidance advice provided. Furthermore, many effects may be different for commercial and bus drivers as compared to private vehicle drivers, but no literature regarding differential use of navigation systems by user group was found; it would be interesting to learn how and why usage and effects on performance differ. The knowledge gaps identified apparently relate mostly to navigation systems, much less to mobile phones.

This dissertation set out to investigate whether the effects reported in the literature could be replicated in a driving simulator, using a sample of 21 regular drivers (Chapter 5), whether these findings resemble real road driving (Chapter 6), and how and when the drivers in this same sample would use their navigation system in a naturalistic driving study (Chapter 7).

8.1.4. To what extent is driving in a driving simulator affected by navigation system and mobile phone use? (Chapter 5)

In Chapter 5, the driving simulator study showed that lateral control deteriorated as a result of visual-manual tasks that required drivers to glance off the road, which is in line with earlier findings (Owens et al., 2011). Furthermore, Chapter 5 showed that drivers reduced speed when distracted, as compared to normal driving. This is in line with Fuller's (2005) TCI model, that states that when the driving task is more difficult (because of the secondary task), loss of control may occur, but also a driver may reduce task demands by reducing speed (see Figure 2.5). The Chapter 5 study showed hardly any differences regarding driving with a paper map in comparison with a navigation system, except for a lower rating in effort for driving with the navigation system. The latter is in line with an earlier study (Feenstra et al., 2008). However, that study did find that drivers drove somewhat faster with a navigation system. The results of Chapter 5 are further summarised in Table 8.2.

Table 8.2: Summary of results presented in Chapter 5.

	Phone conversation vs baseline	Texting vs baseline	Operating the navigation system vs baseline	Following route guidance advice vs driving with paper map
Mean speed	Lower	Lower	Lower	Ns[1]
Speed variance	Varied	Higher	Ns	Ns
SDLP	Ns	Higher	Higher	Ns
Teor%	Lower	Higher	Higher	Ns
RSME	Higher	Higher	Higher	Lower

[1] Ns means that the results are not statistically significant at α = .05. SDLP = Standard Deviation of Lateral Position; Teor% = percentage of time eyes off road, RSME = Rating Scale Mental Effort.

Methodologically important was the notion that in this study, the baseline RSME scores for mental effort were relatively high (32-50) as compared to for instance De Waard (1996), who found on road RSME scores of 15-30. This was probably due to the fact that the participants were not experienced in driving in a simulator (Shinar et al., 2005) in combination with the realistic but therefore complex route used in the experiment.

8.1.5. To what extent are results from a driving simulator study comparable to results from the real road? (Chapter 6)

As the route driven in the driving simulator study was a simulated replica of a real route driven in the Interaction project, the results regarding speed choice and speed variation from both studies allowed comparison. The average speeds driven turned out not to be equal across both studies, so no absolute validity with regards to the simulated speed was established. This may partly be due to the differences in measurements of the two ‘vehicles’: The driving simulator registers speed accurately and displays it on the speedometer accordingly (Godley et al., 2002). The real vehicle’s speed was measured using GPS, but the speedometer displayed a higher “measured” speed. It could be that some of the differences originate from the differences between GPS and projected speed. However, relative validity was established, i.e. the results from both studies regarding speed rendered similar conclusions.

Recently, Branzi, Domenichini and La Torre (2017) reported they did find relative as well as absolute validity. However, in less demanding circumstances drivers drove faster in the driving simulator. Methodologically, their study was rather different from Chapter 6, as in their field measures they recorded the overall traffic speeds and compared those to simulated driving. The Chapter 6 study had a within-subject setup, i.e. compared results of the same drivers driving in both the real and the simulated environments (but not in their own vehicles). These methodological differences may be part of the cause of the different outcomes.

Still, most studies show that the data and the effects found in both simulated and real driving are comparable, which is evidence for relative validity of driving simulator research. This means that the effects found in driving simulators, in this thesis related to how speed is affected by distracting tasks, are not falsified yet. This does of course not imply that other variables and measures are similarly comparable too. Veldstra et al. (2015), for instance, show that although the driving simulator (that resembles the one used in this thesis) was useful for assessing effects of drug use on weaving, car following behaviour in the simulator was not comparable to car following behaviour on the road.

8.1.6. How do drivers use their navigation systems in real driving? (Chapter 7)

Having seen from Chapter 5 that operating a navigation system during driving deteriorates lateral driving performance as well as looking behaviour (glances off road), Chapter 7 assessed how and how often drivers use their navigation system in real life driving. The 21 participants, who were regular users of navigation systems by self-report, used the system in 23% of the trips. These trips were typically longer than non-use trips, and the participants did not repeat these trips during the period they took part in the study (i.e., likely the trips were unique). In about 1% of total trip time (5% of trip time when the navigation system was activated) participants interacted with their device, of which about two third while driving faster than 10 km/h (i.e., not in standstill). This is evidence that drivers to some extent regulate their behaviour (e.g., Funkhouser & Sayer, 2012; Metz et al., 2014), but still their performance is deteriorated during a certain part of their driving time.

A slight but insignificant effect of using a navigation system on instances of speeding was found in the present data. Both preceding studies (Chapters 5 and 6) did not find convincing differences in speed when comparing driving while navigating with a navigation system to driving while navigating with a paper map. Apparently, the way in which drivers navigate hardly changes their speed choice. From the literature, there is also reason to draw such a conclusion. In for instance Dalton et al. (2013), the speed effect found is probably due to an order effect. In a study regarding truck drivers using navigation systems (Arentze et al., 2012) it is argued that speed differences from using a navigation system are by and large due to driving on larger roads, and to some extent to the fact that drivers did not need to slow down to be able to watch for road signs.

8.1.7. In conclusion: What are the road safety and efficiency effects of using a mobile phone or a navigation system while driving?

The main question overarching this thesis was posed in Chapter 1. Chapters 2-7 provided theoretical as well as empirical evidence for the sub questions as formulated and discussed above. The results showed that drivers are clearly affected by performing secondary tasks related to mobile phones and navigation systems. By distinguishing between several subtasks, that is, operating phones and navigation systems, having phone conversations, and following route guidance information provided by a navigation system, we were able to study in depth how driving is affected.

The tasks that affect driving performance most, are those that involve visual distraction, specifically when combined with the need to manually operate phones and navigation systems. Circa 1% of the driving time participants performed visual-manual tasks pertaining to the navigation system. During these visual-manual tasks the drivers' behaviour was clearly negatively affected, which would consequently also lead to a negative impact on driving safety. Moreover, in about 4% of the driving time these drivers were interacting with their phone (Christoph, Van Nes, Knapper, & Wesseling, 2013). This leads to a considerable amount of hazardous driving, even when during a third of that time drivers were driving slower than 10 km/h. A more recent naturalistic driving study (Dingus et al., 2016) used a much larger sample (3,542 participants). This study found a combined prevalence of 3.61% for drivers operating devices (i.e., texting, browsing, dialling and other touchscreen menus). Moreover, it showed that of the 905 observed crashes (injury or property damage), 68.3% involved an observable distraction. Distracted drivers (overall) had a 2.0 times higher risk to be involved in a crash than 'model drivers' (attentive, sober and alert). For the distraction related to the navigation system, this was 4.6 times higher, for phone dialling 12.2, and for texting 6.1 times. An important question is whether these American findings compare to the Dutch and/or the European situation. For instance, Metz et al. (2014), in the EU project euroFOT, found that the 99 participating drivers interacted with their navigation systems very cautiously, by slowing down or even stopping. Compared to baseline driving, no increase in safety-critical events were observed. Apparently, operating a device while driving is not hazardous per se, but the risk depends on the circumstances.

The findings in this thesis provided no reason to claim substantial effects on driving performance (regarding glance direction, longitudinal and lateral performance) from driving while following route instructions from a navigation system as compared to driving with a paper map. However, compared to driving with a paper map, drivers did report that they needed less effort with navigation using a navigation system, which leaves more resources to be allocated to driving, at least potentially. So overall, the net effects are probably rather positive than negative, which concurs with other current studies (e.g., Metz et al., 2014). The participating drivers used the navigation system mostly on trips that they did not drive often (in five weeks of participating in the study, they drove most of these routes only once). Although they also used the navigation system on relatively long trips, this of course does not imply that using navigation systems leads to longer trips. From the data recorded for these studies, we cannot provide definitive answers to the efficiency effects of navigation systems, but the literature (e.g., Oei, 2003; Antin et al., 2009) suggests positive effects in the sense that generally shorter routes are driven and fewer route choice errors are made.

Phone conversations did not lead to large effects on most of the variables recorded, but drivers did reduce their speed somewhat and reported exerting more effort into simultaneously performing the driving and conversation task. Furthermore, drivers looked ahead for a large proportion of the time during the conversation, which may be considered a beneficial effect (e.g., Victor, 2005). The comprehensive naturalistic driving study by Dingus et al. (2016) recently provided evidence of a relatively limited negative safety effect (odds ratio 2.2) of having a phone conversation, in comparison to particularly dialling (odds ratio 12.2), reaching for the phone (odds ratio 4.8) and texting (odds ratio 6.1) which affect safety much more. The relatively small effect found by Dingus et al. (2016) probably means that phone conversations are not unsafe at all times, anywhere, anyhow. Further assessment of the Chapter 4 driving simulator data (Knapper, 2013), that zoomed in on all the data recorded by the driving simulator, revealed some interesting additional insights with regard to efficiency. The results of that analysis showed that a phone conversation led to more conservative driving (less speeding, longer waiting time at traffic lights, and overall more time needed to get from a to b), which in terms of time makes the trip less efficient.

It is difficult to provide a complete answer to the overarching thesis question, as *the* effects are presumably more than the ones this thesis addressed. For instance, we hardly used subjective driver data, we barely saw how the driver is affected physically, and we do not know how a vehicle's cabin layout affects the use of devices such as phones and navigation systems. The next section further reflects on the research presented in this thesis and discusses its limitations.

8.2. Reflections and limitations

This thesis describes a set of studies that were the result of a collaboration between SWOV and Delft University of Technology. It was therefore possible to apply a combination of methods (naturalistic driving observations, driving a motor vehicle and a simulator) in one project. The result is a validation study to assess a valid set of variables that are specifically related to distracted driving. Importantly, the participants in all the studies within the project were the same, which enhances the reliability of the results (Cohen, Manion, & Morrison, 2013). We assessed how driving performance is affected by using phones (texting and conversations) and navigation systems (programming and route guidance) and how well this may be assessed in a driving simulator, while additionally registering how the same drivers used these devices in real driving. As every method has its flaws, as demonstrated in Chapter 3 (cf. Carsten et al., 2013), even this thorough approach has limitations, some of which were already mentioned in Chapters 5, 6, and 7.

First, the research sample of at best 21 drivers (data loss and simulator sickness in the simulator validation study reduced the number of fully comparable participants in that study to 16), is relatively small, and not representative for the Dutch driver population. The drivers were recruited via Delft University of Technology (some were employees but not all), they predominantly drove in the Randstad (busy western part of the country), they reported to drive at least 10,000 km per year, and they were selected because they had indicated to use their phone and navigation system at least once a week. However, the latter precondition ensured some experience, which also prevented the occurrence of learning and novelty effects regarding the use of phones and navigation systems while driving, which was important for the driving simulator validation study. Validation studies are rare, in spite of the undisputable importance of knowing whether an instrument measures what it intends to measure.

Next, the extent to which the participants exhibited their normal, real driving behaviour (as they were instructed) in the studies is unknown. This question may be most urgent when it comes to the driving simulator and its validity study, as those circumstances do not evoke the same responses regarding emotions such as feelings of fear (feeling risk) and pleasure (driving is fun, cf. Rothengatter, 1988). This is due to, for instance, researcher presence (Jones, 1992) and the absence of real risk (Evans, 1991), as opposed to the unusual presence of real risk (in the field test). Furthermore, although it is assumed that in the naturalistic driving study after a week the driver shows his/her normal behaviour, there is no guarantee that the driver continuously does so.

Another relevant matter is whether the methods applied in this thesis were the best to answer the main research question. There exists no easy answer, as argued in Chapter 3. Real, valid safety effects are difficult to obtain, it depends on the methods used. Did the naturalistic driving study really capture all the incidents? Were those incidents caused by distraction, or are other causes viable as well, did the driver correct or compensate? If we would have only interrogated the driver, would his/her self-assessment live up to an observable truth? All in all, this thesis applied several methods that delivered empirical data, while using the same participants in all trials, rendering a comprehensive, but indeed still incomplete picture. Likewise, this thesis hardly covers the topic of legislation, whereas for governments this is, combined with enforcement and campaigning, the main instrument that may be applied to reduce driver distraction.

The outcome of the driving simulator study and its related validation study delivered some new and novel data and insights, but produced a lot of replication data as well. It is easy to understand that novelty ‘sells’ better, even though the scientific community in general advocates replication studies. In practice, the importance of replication was not always reflected in journals' article submission processes. Considering that in the past some studies proved too novel to be true (cf. Stapel, 2012), it may not be far-fetched to claim that the scientific world needs to rebalance this somewhat perverse incentive, as both novel ánd replicating research is needed for further extending our knowledge.

Distractions do not come isolated. Rather, the driver is part of a continually changing system of factors, including the driver's own state and traits, the primary driving task itself, the environment, and the distracting task (Lansdown et al., 2015). This thesis added to this systemic way of thinking, be it modestly.

8.3. Policy and research implications

In short, this thesis implies that

- Operating any device during driving deteriorates driving performance considerably in terms of vehicle control, thus increasing the risk of getting involved in a crash.
- The main cause for this deterioration is the fact that the driver is physically unable to watch a device and the road simultaneously.
- It is not uncommon, henceforth increasingly common that drivers operate devices during driving.
- Following route guidance advice by a navigation system is generally safe and efficient. However, the route should not be programmed or altered while driving.
- Having a phone conversation during driving negatively affects driving performance (higher task demand, less stable speed keeping, reduced reaction time). However, drivers may also adapt their behaviour positively (lowering speed, more on-road glancing), which to some extent may compensate the negative effects.
- Recently obtained odds ratios for talking on the phone while driving indicate that it is about 200% more likely to get involved in a crash as compared to driving without talking on the phone. This was comparable to effects of operating the in-vehicle climate control (Dingus et al., 2016), which is scientifically important to know, but for policy and practice probably less relevant.

From a road safety perspective it would be best to try to diminish distracted driving that involves glancing off road in the first place. Considering the fact that phone conversations often require some manual operation, particularly in case of outgoing calls, and voice control does not (yet) overcome all troubles, it seems recommendable to include phone conversations in the attempt to avoid distraction. Driver behaviour may be changed using several instruments, ranging from technology to communication, legislation, and enforcement.

Communication can for example involve advertising campaigns aimed at educating drivers about the negative effects of distracted driving. On the one hand campaigning is an appealing instrument, stimulating drivers to feel responsible for their own actions, potentially reducing accidents by 6-12% (Phillips, Ulleberg, & Vaa, 2011). Conveying the message near the situation in which the targeted behaviour may occur is most effective (Phillips et al., 2011). On the other hand, campaigns often use so-called threat appeals that stress the dangers by focusing on the negative outcomes, which may not reliably affect behaviour (Carey, McDermott, & Sarma, 2013). Educational campaigns are expensive and should not be employed without careful preparation, and evaluation.

The results of the naturalistic driving studies regarding navigation system use seem to indicate that drivers to some extent strategically plan when to operate their navigation system. It may be recommendable to further strengthen this behaviour by pointing out to drivers that they could probably wait for the traffic situation to allow it. Timing, speed and other traffic may occasionally allow drivers to use devices in a less risky way. Perhaps further research should investigate how best to convey such a message, and what in fact are safe moments during driving. Rewarding drivers with lower (or no) fines for well-timed risky behaviour and with higher fines in unsound situations, taking into account that drivers operate their devices anyway, may be an interesting direction, as this would make drivers aware of good and bad timing. Still, before conveying such a message and implementing such policy, it should be assessed whether it would improve overall safety. Furthermore, this requires clear definitions of which situations are suited and which are not Currently there is far from sufficient knowledge about the conditions in which these activities are particularly unsafe or relatively less unsafe, with regard to e.g. road types, specific manoeuvres, presence of other road users.

In the Netherlands, since 2010, driving exams may include programming a navigation system and following its route guidance advice (CBR, 2010). This means that new drivers have at least learnt when and how to use a navigation system. To date, it is not (yet) clear whether this training results in better use (programming is done while standing still), but already teaching novice drivers to sensibly place and use their system could be a good start.

Legislation determines the boundaries of what is allowed and what is not, and the penalty for noncompliance. One solution often coined is to forbid operating and using any device. Arguing from only a safety perspective this may make sense, but drivers will have their own reasons, such as efficiency, to continue using their devices. One EU study showed that stringency of legislation may not affect texting behaviour (Jamson, 2013). Another option may be to (gradually) increase the penalty in case of recidivism, but the effects of such a measure are not clear yet (SWOV, 2017). Perhaps governments should consider obligatory software that signals and logs when drivers' phones or navigations systems are operated while not in standstill. This type of law enables drivers to be tested, similar to alcohol testing, for having operated devices during driving. The measure would be rather invasive, and therefore its feasibility depends on the societal and political acceptance and support, which probably depends on the public aversion to distracted driving. From this thesis' results, it makes sense to not only include manual phone operating, but any device operating in the legislation (cf. Parnell, Stanton, & Plant, 2017).

The Dutch law (Wegenverkeerswet par 1. art. 6, 1994) currently includes a generic article that aims to prohibit any dangerous behaviour in traffic, which should be followed by specific clauses clarifying hazardous behaviour. The Dutch public prosecution office penalty database to date only specifies handheld phoning, including holding the phone (Openbaar Ministerie, 2017), based on art. 61b in the regulations regarding traffic rules and traffic signs (1990). Recently, the Dutch Court has judged touching one's phone that is fixed in a holder (i.e. not in one's hand) is allowed (Raad voor de Rechtspraak, 2018). The Court argued that even though having a phone conversation or operating a phone may be dangerous, the lawmaker does not prohibit this, as long as the driver is not holding it.

This thesis argues that operating a (fixed) navigation system is about as unsafe as texting, and it seems not far-fetched that this would mean that operating a phone that is fixed in a holder is not safer by any means. Although according to the generic law mentioned above, drivers may still be fined if their driving appears dangerous, this issue has been unclear for decades now, which arguably has not encouraged police to fine phone operating drivers. Moreover, Dutch road safety has stopped improving in recent years, and smartphone use while driving might be a significant reason for this. If road safety is a major goal, forbidding operating any device seems low hanging fruit that has not been harvested until now.

Enforcement relates to both the perceived and the actual probability of detection when committing an offence. Enhancing the actual probability of detection is easy but costly, i.e. by increasing the number of enforcement activities, or alternatively by automation. In recent years, the level of enforcement regarding road safety in the Netherlands has been limited, due to a lack of priority at the national level (Rijksoverheid, 2016). Currently, drivers engaging in illegal distracting activities can only be fined when caught in the act by police officers. It may be technically feasible to recognise such behaviour with for instance traffic cameras. Future research, taking into account also legal and ethical questions, for instance regarding privacy, may shed light on the real potential of such measures, including how to deal with all forms of holding a phone, for instance having it on one's lap.

The perceived probability of detection is more difficult to affect, while it may be important being proximate to the actual behaviour of drivers. How drivers perceive the probability of detection depends on personal and peer experiences and the consequent risk appreciation. This may be affected by all aforementioned instruments, and therefore a balanced mix of the instruments is needed, as no single instrument will provide a panacea. Moreover, systematic and regular evaluation may be required. By anecdote, one participant in the driving simulator during the texting task held his phone rather high up, such that it would visible for a viewer outside the 'car'. He reported that normally he would keep his phone in a much lower position, so he would not be caught by the police. But since that risk was not present in the driving simulator, he held it high to combine texting and driving better, not needing as much time to shift his eyes between both tasks, and even being able to watch the other, non-focal task from the corner of his eyes. Hence, (even) enforcement might also lead to undesirable, crash risk-increasing behaviour.

From a driver's perspective, efficiency may remain an issue. This could imply that drivers value efficiency more than safety considerations and rules regarding distracted driving, in spite of authorities' attempts to change drivers' behaviour. After all, from a behavioural point of view, the to a certain extent comparable act of drunk driving may have diminished in the past 30 years, but certainly not to zero. Therefore, next to the general advice not to engage in distractions while driving, drivers who choose to operate phones or navigation systems or have phone conversations would be better off if they

- Try and keep their eyes on the road as much as possible
- Try and refrain from distracting activities in busy and unpredictable traffic
- Try and keep phone conversations limited to incoming calls only
- Try and keep phone conversations simple and short

Another way of minimising risk due to operating phones or navigation systems during driving relates to their manufacturers. In order to minimise prevalence (and risk), the tasks that drivers perform other than driving should be as few and as short as possible. With regard to phones, this may be somewhat awkward to carry out from a road safety perspective alone, as phones were never primarily designed to be used while driving. However, manufacturers could focus their software still more on efficient use. Furthermore, some applications may aid the driver by disabling certain functionalities during driving. These apps could be made broader available.

Regarding navigation systems, one obvious default would be disabling programming while driving, with the option to enable this (aimed at the passenger). Furthermore, part of the problem may be solved with faster hardware and software that shorten programming, usable and intuitive interfaces, and removing all options that do not relate to programming the route (the navigation systems in the naturalistic driving study for instance could show the weather at the destination).

8.4. Future

It is interesting to consider how navigation systems and mobile phones have developed differently in the past. Navigation support made a slow start, and only began to develop faster when the accurate GPS signals became publicly available in 2000. Research on the effects on driving behaviour is rather scarce and has focused on the following of route guidance as well as on effects of programming the system. On the other hand, phones have been available in cars for a few decades, and they have received scientific attention already since the early nineties. As a result, both types of devices have also developed differently through the years. While early on, phones were only used for conversations, later on texting, and thereafter, in particular since the introduction of the iPhone in 2007, e-mail, apps, and touch screens were introduced. But where are we heading now?

Navigation systems are nowadays often built in the vehicle, and there is no reason to believe that this development will not continue. Hopefully, interfaces will improve, with better usable programming options.

Mobile phones may integrate into car design / dashboards much more in the coming years. With large tech companies that are involved in both the development and/or manufacturing of phones and (self-driving) vehicles (Google/Waymo, Apple), this integration might suddenly go very fast in the near future, but forecasting how long this could take is difficult. Furthermore, mobile phones may become much more tailored to their owners in the future, facilitating or possibly even replacing visual-manual tasks. It would be good if manufacturers and developers would only make all those integrated devices technically available, provided the use is safe. This includes for instance taking into account whether, when and where and in what traffic circumstances the user is driving and having the system prioritise safety related information and warnings accordingly, in order not to distract the driver in demanding circumstances.

Advanced driver assistance systems, such as advanced cruise control or lane departure warning systems, have promising safety potential too and can make the driving task much easier. However, it has also been shown that drivers often do not know which features their cars actually have or how they should use them - and then decide to switch them off (Harms & Dekker, 2017). Furthermore, devices are being developed that assess the driver state, and provide warnings when drivers for instance do not sufficiently watch the road ahead.

In future automated driving the problem of distraction might not even be relevant anymore. However, although all sorts of ‘auto auto’ (Hagenzieker, 2015) are under development, current “self-driving” vehicles still require that the driver needs to remain vigilant, and keep monitoring, in order to be able to take over vehicle control when necessary. When automation takes over (large) parts of the driving task, it is tempting for driver to dedicate his attention to other activities than driving, which probably leaves the topic of distraction and associated risks a relevant issue for many years to come.

8.5. Conclusion

To conclude, driving is a rather complex task in itself, which makes it difficult if not hazardous to perform secondary tasks alongside. Visual-manual tasks such as operating devices deteriorate lateral and longitudinal control, increasing the risk of crashing. Cognitive tasks affect speed and reaction time. Billions of people drive regularly, and many are regularly distracted while driving, be it from something like swatting a fly or a beautiful sundown, or by the technology we carry along. Even relatively safe drivers (which most drivers think they are), might be distracted by a ringing or bleeping phone or an unexpected message on the navigation system. Some even check Twitter or Facebook and send a message using Whatsapp. As long as drivers see no imminent danger, being distracted for a short while is not more than a nuisance or a choice to them, but sometimes it is the last straw that breaks the camel's back. A video issued mid-2017 by a Dutch insurance company (Interpolis, 2017) shows both the impact of distractions on driving performance and a moving story told by a distracted driver who had crashed into another car, killing a child. The video went viral in the Netherlands, gaining that many were aware of the dangers of distracted driving. However, the past taught us that such awareness quickly wears off. Hopefully, this thesis will indirectly help drivers realise how driving performance suffers from those unimportant activities, so we may all have safe trips.

References

Aarts, L., & Van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis and Prevention, 38*(2), 215-224.

Akaho, K., Nakagawa, T., Yamaguchi, Y., Kawai, K., Kato, H., & Nishida, S. (2012). Route guidance by a car navigation system based on augmented reality. *Electrical Engineering in Japan (English translation of Denki Gakkai Ronbunshi), 180*(2), 43-54.

Akamatsu, M., Yoshioka, M., Imacho, N., Daimon, T., & Noy, Y. I. (1997). Analysis of driving a car with a navigation system in an urban area *Ergonomics and safety of intelligent driver interfaces.* (pp. 85-95). Hillsdale, NJ England: Lawrence Erlbaum Associates, Inc.

Allen, R. W., Stein, A. C., Rosenthal, T. J., Ziedman, D., Torres, J. F., & Halati, A. (1991). *Human factors simulation investigation of driver route diversion and alternate route selection using in-vehicle navigation systems.* Paper presented at the Proceedings - Society of Automotive Engineers, Dearborn, MI, USA.

Alm, H. (1995). Driving simulators as research tools - a validation study based on the VTI driving simulator. *VTI report*.

Alosco, M. L., Spitznagel, M. B., Fischer, K. H., Miller, L. A., Pillai, V., Hughes, J., & Gunstad, J. (2012). Both texting and eating are associated with impaired simulated driving performance. *Traffic Injury Prevention, 13*(5), 468-475. doi:http://dx.doi.org/10.1080/15389588.2012.676697

Andersen, G. (2011). Sensory and perceptual factors in the design of driving simulation displays. In D. L. Fisher, M. Rizzo, J. K. Caird, & J. D. Lee (Eds.), *Handbook of driving simulation for engineering, medicine, and psychology*: CRC Press.

Antin, J. F., Stanley, L. M., & Cicora, K. F. (2009). Conventional versus moving-map navigation methods. *Transportation Research Record, 2138*, 34-41.

Arentze, T., Feng, T., Robroeks, J., van Brakel, M., & Huibers, R. (2012). Compliance with and influence of a new in-car navigation system for trucks: Results of a field test. *Transport Policy, 23*(0), 42-49. doi:http://dx.doi.org/10.1016/j.tranpol.2012.06.011

Arthur, C. (2012). Text messages turns 20 – but are their best years behind them? Retrieved from http://www.guardian.co.uk/technology/2012/dec/02/text-messaging-turns-20#ixzz2UgEIYw9z

Asbridge, M., Brubacher, J. R., & Chan, H. (2013). Cell phone use and traffic crash risk: a culpability analysis. *International Journal of Epidemiology, 42*(1), 259-267.

Asif, A., & Boll, S. (2010). *Where to turn my car?: comparison of a tactile display and a conventional car navigation system under high load condition.* Paper presented at the Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications.

Atchley, P., Atwood, S., & Boulton, A. (2011). The choice to text and drive in younger drivers: Behavior may shape attitude. *Accident Analysis and Prevention, 43*(1), 134-142.

Atchley, P., & Chan, M. (2011). Potential benefits and costs of concurrent task engagement to maintain vigilance: A driving simulator investigation. *Human Factors, 53*(1), 3-12.

Atchley, P., & Warden, A. C. (2012). The need of young adults to text now: Using delay discounting to assess informational choice. *Journal of Applied Research in Memory and Cognition, 1*(4), 229-234. doi:http://dx.doi.org/10.1016/j.jarmac.2012.09.001

Axon, S., Speake, J., & Crawford, K. (2012). 'At the next junction, turn left': Attitudes towards Sat Nav use. *Area, 44*(2), 170-177.

Backer-Grøndahl, A., & Sagberg, F. (2011). Driving and telephoning: Relative accident risk when using hand-held and hands-free mobile phones. *Safety Science, 49*(2), 324-330.

Ball, K., Owsley, C., Stalvey, B., Roenker, D. L., Sloane, M. E., & Graves, M. (1998). Driving avoidance and functional impairment in older drivers. *Accident Analysis & Prevention, 30*(3), 313-322. doi:http://dx.doi.org/10.1016/S0001-4575(97)00102-4

Barón, A., & Green, P. (2006). *Safety and usability of speech interfaces for in-vehicle tasks while driving: A brief literature review* (UMTRI-2006-5). Retrieved from http:// citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.595.4580&rep=rep1&type=pdf

Basacik, D., Reed, N., & Robbins, R. (2012). *Smartphone use while driving - a simulator study* (PPR592). Retrieved from https://trl.co.uk/reports/PPR592

Basacik, D., & Stevens, A. (2008). *Scoping study of driver distraction.* Retrieved from https://trl.co.uk/reports/PPR345

Bayer, J. B., & Campbell, S. W. (2012). Texting while driving on automatic: Considering the frequency-independent side of habit. *Computers in Human Behavior, 28*(6), 2083-2090.

Beanland, V., Fitzharris, M., Young, K. L., & Lenné, M. G. (2013). Driver inattention and driver distraction in serious casualty crashes: Data from the Australian National Crash In-depth Study. *Accident Analysis & Prevention, 54*(0), 99-107. doi:http://dx.doi.org/10.1016/j.aap.2012.12.043

Becic, E., Dell, G. S., Bock, K., Garnsey, S. M., Kubose, T., & Kramer, A. F. (2010). Driving impairs talking. *Psychonomic Bulletin and Review, 17*(1), 15-21.

Bédard, M., Parkkari, M., Weaver, B., Riendeau, J., & Dahlquist, M. (2010). Assessment of driving performance using a simulator protocol: Validity and reproducibility. *The American Journal of Occupational Therapy, 64*(2), 336-340. doi:http://dx.doi.org/10.5014/ajot.64.2.336

Bella, F. (2008). Driving simulator for speed research on two-lane rural roads. *Accident Analysis and Prevention, 40*(3), 1078-1087. doi:http://dx.doi.org/10.1016/j.aap.2007.10.015

Benden, M. E., Smith, M. L., Henry, M., & Congleton, J. J. (2012). Reviewing Four Decades of Cell Phone Use while Driving Literature (1970-2010): An Emphasis on Texting Behaviors, Parental Perceptions, and Methods of Control. *Journal of Health Behavior and Public Health, 2*(2), 20-26.

Benedetto, A., Calvi, A., & D'Amico, F. (2012). Effects of mobile telephone tasks on driving performance: A driving simulator study. *Advances in Transportation Studies*(26), 29-44.

Billieux, J. (2012). Problematic use of the mobile phone: A literature review and a pathways model. *Current Psychiatry Reviews, 8*(4), 299-307. doi:http://dx.doi.org/10.2174/157340012803520522

Bittner, A., Simsek, O., Levison, W., & Campbell, J. (2002). On-road versus simulator data in driver model development driver performance model experience. *Transportation Research Record, 1803*(02-4103), 38-44. doi:http://dx.doi.org/10.3141/1803-06

Blaauw, G. J. (1980). Driving experience and task demands in simulator and instrumented car: A validation study. (IZF 1980-9).

Blaauw, G. J. (1982). Driving experience and task demands in simulator and instrumented car: A validation study. *Human Factors, 24*(4), 473-486.

Blana, E. (1997). *Driver simulator validation studies: A literature review*: University of Leeds, Institute for Transport Studies.

Bonnard, A., & Brusque, C. (2008). *Naturalistic Driving Observations to investigate distraction exposure and IVIS patterns of use: interests and constraints of the approach.* Paper presented at the HUMANIST, Lyon.

Brace, C. L., Young, K. L., & Regan, M. A. (2007). *Analysis of the literature: The use of mobile phones while driving*. Retrieved from http://www.nsc.org/DistractedDrivingDocuments/AnalysisLiterature-UseMobilePhonesWhileDriving.pdf

Braitman, K. A., & McCartt, A. T. (2010). National reported patterns of driver cell phone use in the United States. *Traffic Injury Prevention, 11*(6), 543-548.

Branzi, V., Domenichini, L., & La Torre, F. (2017). Drivers' speed behaviour in real and simulated urban roads – A validation study. *Transportation Research Part F: Traffic Psychology and Behaviour, 49* (Supplement C), 1-17. doi:https://doi.org/10.1016/j.trf.2017.06.001

Braver, E. R., Lund, A. K., & McCartt, A. T. (2009). Hands-free embedded cell phones and airbag-deployment crash rates: Letter to the editor. *Risk Analysis, 29*(8), 1069.

Briggs, G. F., Hole, G. J., & Land, M. F. (2011). Emotionally involving telephone conversations lead to driver error and visual tunnelling. *Transportation Research Part F: Traffic Psychology and Behaviour, 14*(4), 313-323. doi:http://dx.doi.org/10.1016/j.trf.2011.02.004

Brookhuis, K. A., De Vries, G., & De Waard, D. (1991). The effects of mobile telephoning on driving performance. *Accident Analysis and Prevention, 23*(4), 309-316.

Brookhuis, K. A., De Waard, D., & Janssen, W. H. (2001). Behavioural impacts of advanced driver assistance systems – an overview. *European Journal of Transport and Infrastructure Research., 1*(3), 245-253.

Brookhuis, K. A., & Dicke, M. (2009). The effects of travel information presentation through nomadic systems on driver behaviour. *European Transport Research Review, 1*(2), 67-74. doi:http://dx.doi.org/10.1007/s12544-009-0007-4

Brown, B., & Laurier, E. (2012). *The normal, natural troubles of driving with GPS*, Austin, TX.

Brown, T., Dow, B., Marshall, D., & Allen, S. (2007). *Validation of stopping and turning behavior for novice drivers in the National Advanced Driving Simulator*. Retrieved from https://www.nads-sc.uiowa.edu/bio_pub_pdf/Brown_et_al_-_Validation_of_stopping_and_turning_behavior.pdf

Brumby, D. P., & Seyedi, V. (2012). *An empirical investigation into how users adapt to mobile phone auto-locks in a multitask setting*.

Brumfield, R. M., & Pulugurtha, S. S. (2011) Effect of driver cell phone use on queue discharge patterns at signalized intersections. (pp. 71-79).

Bryden, K. J., Charlton, J., Oxley, J., & Lowndes, G. (2010). *Changes in wayfinding ability with age: use of wayfinding methods and attitudes towards GPS.* Paper presented at the Proceedings of the Australasian Road Safety Research, Policing and Education Conference, Clayton, VIC, Australia.

Buckwalter Jr, K. R. (2010). *Driving while distracted by a cell phone and/or texting device: Review of the literature and recommendations for Ohio*. Retrieved from http://docplayer.net/15153624-Driving-while-distracted-by-a-cell-phone-and-or-texting-device-review-of-the-literature-and-recommendations-for-ohio.html

Burge, R., & Chaparro, A. (2012). *The effects of texting and driving on hazard perception*.

Burnett, G. (1998). "Turn Right at the King's Head". Retrieved from http://www.ics.mq.edu.au/~coral/Papers/Baus/geb-phd.pdf

Burnett, G., & Joyner, S. (1993). *Investigation on the man machine interfaces to existing route guidance systems.* Paper presented at the Proceedings of the IEEE-IEE Vehicle Navigation and Informations Systems Conference, Ottawa, Ontario, Canada.

Burnett, G., & Joyner, S. (1996). Route guidance systems: Getting it right from the driver's perspective. *Journal of Navigation, 49*(2), 169-177.

Burnett, G., & Joyner, S. (1997). An assessment of moving map and symbol-based route guidance systems. In Y. I. Noy (Ed.), *Ergonomics and Safety of Intelligent Driver Interfaces* (Vol. 1, pp. 115-1137). Mahwah, NJ: Lawrence Erlbaum Associates.

Burnett, G., & Lee, K. (2005). The effect of vehicle navigation systems on the formation of cognitive maps. In G. Underwood (Ed.), *Traffic and Transport Psychology* (pp. 407-418): Elsevier.

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

Caird, J. K., & Horrey, W. J. (2011). Twelve Practical and Useful Questions About Driving Simulation. In D. L. Fisher, M. Rizzo, J. K. Caird, & J. D. Lee (Eds.), *Handbook of Driving Simulation for Engineering, Medicine, and Psychology*: CRC Press.

Caird, J. K., Johnston, K. A., Willness, C. R., Asbridge, M., & Steel, P. (2014). A meta-analysis of the effects of texting on driving. *Accident Analysis & Prevention, 71*(0), 311-318. doi:http://dx.doi.org/10.1016/j.aap.2014.06.005

Caird, J. K., Willness, C. R., Steel, P., & Scialfa, C. (2008). A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis and Prevention, 40*, 1282-1293.

Cao, S., & Liu, Y. (2013). Concurrent processing of vehicle lane keeping and speech comprehension tasks. *Accident Analysis & Prevention, 59*(0), 46-54. doi:http://dx.doi.org/10.1016/j.aap.2013.04.038

Carey, R. N., McDermott, D. T., & Sarma, K. M. (2013). The impact of threat appeals on fear arousal and driver behavior: A meta-analysis of experimental research 1990–2011. *PloS one, 8*(5), e62821.

Carsten, O. M. J. (2013). Early theories of behavioural adaptation. In C. Rudin-Brown & S. Jamson (Eds.), *Behavioural adaptation and road safety: Theory, evidence and action* (pp. 23-34): Taylor & Francis Group.

Carsten, O. M. J., & Brookhuis, K. A. (2005). Issues arising from the HASTE experiments. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2), 191-196.

Carsten, O. M. J., & Gallimore, S. (1996). The Leeds Driving Simulator: A new tool for research in driver behaviour. In A. G. Gale (Ed.), *Vision in Vehicles - V* (pp. 11-18). Amsterdam: Elsevier Science Publisher B. V. (North Holland).

Carsten, O. M. J., & Jamson, A. H. (2011). Driving simulators as research tool in traffic psychology. In B. E. Porter (Ed.), *Handbook of Traffic Psychology* (pp. 87-96). London: Academic Press.

Carsten, O. M. J., Kircher, K., & Jamson, S. (2013). Vehicle-based studies of driving in the real world: The hard truth? *Accident Analysis & Prevention, 58*(0), 162-174. doi:http://dx.doi.org/10.1016/j.aap.2013.06.006

CBR (2010). Navigatieapparatuur verplicht in examenauto. Retrieved from https://www.cbr.nl/312.pp?id=244

Cerbe, T. M., Kuhnert, A., & Strube, S. (2009). *Fuel saving potential of car navigation systems.* Paper presented at the 16th ITS World Congress 2009, Stockholm.

Chaloupka, C., & Risser, R. (1995). Don't wait for accidents -- possibilities to assess risk in traffic by applying the `Wiener Fahrprobe'. *Safety Science, 19*(2-3), 137-147.

Chang, J. C. (2010). *Cultural differences in navigation system destination entry.* Paper presented at the Science and Social Research (CSSR), 2010 International Conference on.

Chiang, D. P., Brooks, A. M., & Weir, D. H. (2004). On the highway measures of driver glance behavior with an example automobile navigation system. *Applied Ergonomics, 35*(3), 215-223.

Choi, J.-S., Kim, H.-S., Kang, D.-W., Choi, M.-H., Kim, H.-S., Hong, S.-P., . . . Chung, S.-C. (2013). The effects of disruption in attention on driving performance patterns: Analysis of jerk-cost function and vehicle control data. *Applied Ergonomics, 44*(4), 538-543. doi:http://dx.doi.org/10.1016/j.apergo.2012.11.004

Christoph, M. (2010). *Estimate of the safety effects of intelligent vehicle systems; A literature study*. Retrieved from http://www.swov.nl/rapport/R-2010-08.pdf

Christoph, M., Van der Kint, S., & Wesseling, S. (2017). *Interpolis Barometer 2017. Vragenlijst-studie mobiel telefoongebruik in het verkeer*

Christoph, M., Van Nes, N., Knapper, A., & Wesseling, S. (2013). *Naturalistic driving observations of manual interactions with navigation systems and mobile phones during driving.* Paper presented at the Transportation Research Board 92nd Annual Meeting, Washington, D.C.

Christoph, M., Van Nes, N., & Wesseling, S. (2012). *The effect of auditory route instructions of navigation systems on glance behaviour*. Paper presented at the Humanist Conference, Valencia.

Cnossen, F., Rothengatter, T., & Meijman, T. (2000). Strategic changes in task performance in simulated car driving as an adaptive response to task demands. *Transportation Research Part F: Traffic Psychology and Behaviour, 3*(3), 123-140.

Cohen, L., Manion, L., & Morrison, K. (2013). *Research methods in education*: Routledge.

Collet, C., Guillot, A., & Petit, C. (2010a). Phoning while driving I: a review of epidemiological, psychological, behavioural and physiological studies. *Ergonomics, 53*(5), 589-601. doi:http://dx.doi.org/10.1080/00140131003672023

Collet, C., Guillot, A., & Petit, C. (2010b). Phoning while driving II: a review of driving conditions influence. *Ergonomics, 53*(5), 602-616. doi:10.1080/00140131003769092

Cook, J. L., & Jones, R. M. (2011). Texting and accessing the web while driving: Traffic citations and crashes among young adult drivers. *Traffic Injury Prevention, 12*(6), 545-549.

Cooper, J., Ragland, D., Ewald, K., Wasserman, L., & Murphy, C. (2012) Observational survey of cell phone use and texting by california drivers, 2011. (pp. 7-14).

Cooper, J. F., Ragland, D. R., Ewald, K., Wasserman, L., & Murphy, C. J. (2013). *Observational study of cell phone and texting use among California drivers 2012 and comparison to 2011 data*.

Cooper, J. M., Vladisavljevic, I., Medeiros-Ward, N., Martin, P. T., & Strayer, D. L. (2009). An investigation of driver distraction near the tipping point of traffic flow stability. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 51*(2), 261-268.

Cooper, J. M., Yager, C., & Chrysler, S. T. (2011). *An investigation of the effects of reading and writing text-based messages while driving*. Retrieved from https://static.tti.tamu.edu/swutc.tamu.edu/publications/technicalreports/476660-00024-1.pdf

Crandall, J. M., & Chaparro, A. (2012). Driver distraction: Effects of text entry methods on driving performance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56*(1), 1693-1697. doi:http:dx.doi.org/10.1177/1071181312561339

Creaser, J., & Manser, M. (2012). *Connected Vehicles Program: Driver performance and distraction evaluation for in-vehicle signing*. Retrieved from http://www.its.umn.edu/Publications/ResearchReports/pdfdownload.pl?id=1678

Crisler, M. C., Brooks, J. O., Ogle, J. H., Guirl, C. D., Alluri, P., & Dixon, K. K. (2008). Effect of wireless communication and entertainment devices on simulated driving performance. *Transportation Research Record: Journal of the Transportation Research Board, 2069*(1), 48-54.

Cuřín, J., Labský, M., Macek, T., Kleindienst, J., Young, H., Thyme-Gobbel, A., . . . König, L. (2011). *Dictating and editing short texts while driving: Distraction and task completion*, Salzburg.

Dalton, P., Agarwal, P., Fraenkel, N., Baichoo, J., & Masry, A. (2013). Driving with navigational instructions: Investigating user behaviour and performance. *Accident Analysis and Prevention, 50*(0), 298-303. doi:http://dx.doi.org/10.1016/j.aap.2012.05.002

Damasio, A. (1994). *Descartes' Error: Emotion, Reason, and the Human Brain*. New York: Putnam.

Davidse, R. J., Hagenzieker, M. P., Van Wolffelaar, P. C., & Brouwer, W. H. (2009). Effects of in-car support on mental workload and driving performance of older drivers. *Human Factors, 51*(4), 463-476. doi:http://dx.doi.org/10.1177/0018720809344977

De Waard, D. (1996). *The measurement of drivers' mental workload.* (PhD thesis), Rijksuniversiteit Groningen, Groningen. Retrieved from http://irs.ub.rug.nl/ppn/297329391

De Waard, D., Van der Hulst, M., Hoedemaeker, M., & Brookhuis, K. A. (1999a). Driver behavior in an emergency situation in the automated highway system. *Transportation Human Factors, 1*(1), 67-82.

De Waard, D., Van der Hulst, M., Hoedemaeker, M., & Brookhuis, K. A. (1999b). Reply to comments on "Driver behavior in an emergency situation in the automated highway system". *Transportation Human Factors, 1*(1), 87-89.

De Winter, J., De Groot, S., Mulder, M., Wieringa, P., Dankelman, J., & Mulder, J. (2009). Relationships between driving simulator performance and driving test results. *Ergonomics, 52*(2), 137-153.

Dingus, T. A., Guo, F., Lee, S., Antin, J. F., Perez, M., Buchanan-King, M., & Hankey, J. (2016). Driver crash risk factors and prevalence evaluation using naturalistic driving data. *Proceedings of the National Academy of Sciences, 113*(10), 2636-2641. doi:http://dx.doi.org/10.1073/pnas.1513271113

Dingus, T. A., Hulse, M. C., & Mollenhauer, M. A. (1997). Effects of age, system experience, and navigation technique on driving with an advanced traveler information system. *Occupational Health and Industrial Medicine, 37*(4), 156-156.

Dingus, T. A., Klauer, S. G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J. D., . . . Knipling, R. R. (2006a). The 100-Car Naturalistic Driving Study, Phase II - Results of the 100-Car Field Experiment., 422p.

Dingus, T. A., Klauer, S. G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J. D., . . . Knipling, R. R. (2006b). *The 100-Car Naturalistic Driving Study, phase II - Results of the 100-car field experiment.*

Domeyer, J. E., Cassavaugh, N. D., & Backs, R. W. (2013). The use of adaptation to reduce simulator sickness in driving assessment and research. *Accident Analysis & Prevention, 53*(0), 127-132. doi:http://dx.doi.org/10.1016/j.aap.2012.12.039

Dragutinovic, N., & Twisk, D. (2005). *Use of mobile phones while driving - effects on road safety*

Drews, F. A., Pasupathi, M., & Strayer, D. L. (2008). Passenger and cell phone conversations in simulated driving. *Journal of experimental psychology, 14*(4), 392-400.

Drews, F. A., Yazdani, H., Godfrey, C. N., Cooper, J. M., & Strayer, D. L. (2009). Text messaging during simulated driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 51*(5), 762-770. doi:10.1177/0018720809353319

Dula, C. S., Martin, B. A., Fox, R. T., & Leonard, R. L. (2011). Differing types of cellular phone conversations and dangerous driving. *Accident Analysis & Prevention, 43*(1), 187-193. doi:http://dx.doi.org/10.1016/j.aap.2010.08.008

Eby, D. W., & Vivoda, J. M. (2010). Driver hand-held cellular phone use in Minnesota, June and August, 2010. *Journal [serial on the Internet]*.

Eder, D. N., Lu, W., & Chen, F. (2009). *Assessment of cognitive engagement from heart rate dynamics during simulated driving with an in-vehicle information system*. Paper presented at the Driver Distraction and Inattention Conference 2009, Gothenburg. https://document.chalmers.se/download?docid=1648902304

Ege, E. S., Cetin, F., & Basdogan, C. (2011). *Vibrotactile feedback in steering wheel reduces navigation errors during GPS-guided car driving*, Istanbul.

Elvik, R. (2011). Effects of mobile phone use on accident risk. *Transportation Research Record: Journal of the Transportation Research Board, 2236*, 20-26. doi:http://dx.doi.org/10.3141/2236-03

Elvik, R., Christensen, P., & Amundsen, A. (2004). *Speed and road accidents. An evaluation of the Power Model.* . Retrieved from https://www.toi.no/getfile.php/131013/Publikasjoner/T%C3%98I%20rapporter/2004/740-2004/Repsumm.pdf

Emberson, L. L., Lupyan, G., Goldstein, M. H., & Spivey, M. J. (2010). Overheard cell-phone conversations when less speech is more distracting. *Psychological science, 21*(10), 1383-1388.

Emmerson, C., Guo, W., Blythe, P., Namdeo, A., & Edwards, S. (2013). Fork in the road: In-vehicle navigation systems and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 21*(0), 173-180. doi:http://dx.doi.org/10.1016/j.trf.2013.09.013

Endsley, M. R. (2000). Theoretical underpinnings of situation awareness: A critical review. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 3-32). Mahwah, NJ: Lawrence Erlbaum Associates.

Engström, J., Monk, C. A., Hanowski, R. J., Horrey, W. J., Lee, J. D., McGehee, D. V., . . . Yang, D. (2013). *A conceptual framework and taxonomy for understanding and categorizing driver inattention*. Retrieved from https://ec.europa.eu/digital-single-market/en/news/us-eu-inattention-taxonomy-report

ETSC (2010). *Minimising in-vehicle distraction: PRAISE (Preventing Road Accidents and Injuries for the Safety of Employees)*. Retrieved from http://www.etsc.eu/documents/PRAISE_Thematic_Report_Moving%20In%20Vehicle%20Distraction_22_December%202010.pdf

Evans, L. (1991). *Traffic safety and the driver*. New York: Van Nostrand Reinhold.

Evans, L. (2004). *Traffic safety* Bloomfield, MI: Science Serving Society.

Farber, E. I. (1999). Comments on "Driver behavior in an emergency situation in the automated highway system". *Transportation Human Factors, 1*(1), 83-85.

Farmer, C. M., Braitman, K. A., & Lund, A. K. (2010). Cell phone use while driving and attributable crash risk. *Traffic Injury Prevention, 11*(5), 466-470.

Feenstra, P. J., Hogema, J. H., & Vonk, T. (2008). Traffic safety effects of navigation systems. *2008 IEEE Intelligent Vehicles Symposium*, 1203-1208.

Fenech, E. P., Drews, F. A., & Bakdash, J. Z. (2010a). *The effects of acoustic turn-by-turn navigation on wayfinding.* Paper presented at the 54th Human Factors and Ergonomics Society Annual Meeting 2010, HFES 2010, San Francisco, CA.

Fenech, E. P., Drews, F. A., & Bakdash, J. Z. (2010b). *The effects of acoustic turn-by-turn navigation on wayfinding*, San Francisco, CA.

Fine, P. R., Heaton, K., Stavrinos, D., Hanowski, R., McGwin, G., Vance, D., . . . Franklin, C. (2012). *U33: Impact of distraction and health on commercial driving performance*.

Fisher, D., Pollatsek, A., & Horrey, W. (2011). Eye behaviors: How driving simulators can expand their role in science and engineering. *Handbook of Driving Simulation for Engineering, Medicine, and Psychology*: CRC Press.

Fitch, G. M., Grove, K., Hanowski, R. J., & Perez, M. A. (2014). Compensatory behavior of drivers when conversing on a cell phone. *Transportation Research Record: Journal of the Transportation Research Board, 2434*, 1-8. doi:http://dx.doi.org/doi:10.3141/2434-01

Fitch, G. M., Soccolich, S. A., Guo, F., McClafferty, J., Fang, Y., Olson, R. L., . . . Dingus, T. A. (2013). *The impact of hand-held and hands-free cell phone use on driving performance and safety-critical event risk*. Retrieved from DOT HS 811 757. Washington, DC

Forbes, N. L. (2009). *Behavioural adaptation to in-vehicle navigation systems.* University of Nottingham.

Forlizzi, J., Barley, W. C., & Seder, T. (2010). *Where should I turn? Moving from individual to collaborative navigation strategies to inform the interaction design of future navigation systems*. New York: Assoc Computing Machinery.

French, R. L. (1986). In-vehicle route guidance in the united states: 1910-1985. *IEE Conference Publication*: IEE.

Fuller, R. (1984). A conceptualization of driving behaviour as threat avoidance. *Ergonomics, 27*(11), 1139 - 1155.

Fuller, R. (2000). The Task-Capability Interface model of the driving process. *Recherche Transports Sécurité, 66*, 47-57.

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis and Prevention, 37*(3), 461-472.

Fuller, R. (2011). Driver control theory: From task difficulty homeostasis to risk allostasis. In B. E. Porter (Ed.), *Handbook of Traffic Psychology*. London: Academic Press.

Funkhouser, D., & Sayer, J. (2012). A naturalistic cell phone use census. *Transportation Research Record, 2321*, 1-6.

Garrison, T. M., & Williams, C. C. (2013). Impact of relevance and distraction on driving performance and visual attention in a simulated driving environment. *Applied Cognitive Psychology, 27*(3), 396-405.

GfK (2016a). Global smartphone sales hit a quarterly high in Q4 2015. Retrieved from http://www.gfk.com/insights/press-release/global-smartphone-sales-hit-a-quarterly-high-in-q4-2015/

GfK (2016b). *Trends in digitale media*. Retrieved from http://www.gfk.com/nl/insights/press-release/markt-mobiele-devices-volledig-verzadigd/

Gherri, E., & Eimer, M. (2011). Active listening impairs visual perception and selectivity: An ERP study of auditory dual-task costs on visual attention. *Journal of Cognitive Neuroscience, 23*(4), 832-844.

Ghosh, S., & Cowan, R. (2011). Analysis: Losing their way, PND makers in dash for new revenue. *Reuters*. Retrieved from http://www.reuters.com/article/2011/08/09/us-personalnavigationdevicemakers-idUSTRE7782WN20110809, June 18, 2012

Gibson , J. J., & Crooks, L. E. (1938). A theoretical field-analysis of automobile-driving. *The American Journal of Psychology, 11*(3).

Glendon, A. I. (2007). Driving violations observed: An Australian study. *Ergonomics, 50*(8), 1159-1182.

Godley, S. T., Triggs, T. J., & Fildes, B. N. (2002). Driving simulator validation for speed research. *Accident Analysis and Prevention, 34*, 589-600.

Godthelp, H., Milgram, P., & Blaauw, G. J. (1984). The development of a time-related measure to describe driving strategy. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 26*(3), 257-268. doi:http://dx.doi.org/10.1177/001872088402600302

Gordon, C. P. (2009). Crash studies of driver distraction. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver distraction: Theory, effects, and mitigation* (pp. 281). Boca Raton: CRC Press.

Graf, S., Spiessl, W., Schmidt, A., Winter, A., & Rigoll, G. (2008). *In-car interaction using search-based user interfaces.* Paper presented at the Proceedings of the twenty-sixth annual SIGCHI conference on Human factors in computing systems.

Graham, R., & Carter, C. (2001). Voice dialling can reduce the interference between concurrent tasks of driving and phoning. *International Journal of Vehicle Design, 26*(1 SPEC. ISS), 30-47.

Green, P. (2001). *Variations in task performance between younger and older drivers: UMTRI research on telematics.* Paper presented at the association for the advancement of automotive medicine conference on aging and driving.

Green, P. (2008). Driver interface safety and usability standards. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction* (pp. 445-461). Boca Raton: CRC Press.

Groeger, J. A., Carsten, O. M. J., Blana, E., & Jamson, H. (1999). Speed and distance estimation under simulated conditions. In A. G. Gale (Ed.), *Vision in Vehicles - VII* (pp. 291-299). Amsterdam: Elsevier Scientific (North Holland).

Haddington, P., & Rauniomaa, M. (2011). Technologies, Multitasking, and Driving: Attending to and Preparing for a Mobile Phone Conversation in a Car. *Human Communication Research, 37*(2), 223-254. doi:http://dx.doi.org/10.1111/j.1468-2958.2010.01400.x

Hagenzieker, M. P. (2015). "Dat paaltje had ook een kind kunnen zijn". Over verkeersveiligheid en gedrag van mensen in het verkeer. Inaugural lecture at Delft University of Technology.

Hale, A. R., Stoop, J., & Hommels, J. (1990). Human error models as predictors of accident scenarios for designers in road transport systems. *Ergonomics, 33*(10-11), 1377-1387. doi:http://dx.doi.org/10.1080/00140139008925339

Hallett, C., Lambert, A., & Regan, M. A. (2012). Text messaging amongst New Zealand drivers: Prevalence and risk perception. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(3), 261-271. doi:http://dx.doi.org/10.1016/j.trf.2011.12.002

Hallvig, D., Anund, A., Fors, C., Kecklund, G., Karlsson, J. G., Wahde, M., & Åkerstedt, T. (2013). Sleepy driving on the real road and in the simulator—A comparison. *Accident Analysis and Prevention, 50*, 44-50. doi:http://dx.doi.org/10.1016/j.aap.2012.09.033

Hancock, P. A., Mouloua, M., & Senders, J. W. (2009). On the philosophical foundations of the distracted driver and driving distraction. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver distraction: Theory, effects, and mitigation* (pp. 11-27). Boca Raton: CRC Press.

Hanley, P. F., & Sikka, N. (2012). Bias caused by self-reporting distraction and its impact on crash estimates. *Accident Analysis & Prevention, 49*(0), 360-365. doi:http://dx.doi.org/10.1016/j.aap.2012.02.008

Harbluk, J. L., Noy, Y. I., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident Analysis & Prevention, 39*(2), 372-379. doi:http://dx.doi.org/10.1016/j.aap.2006.08.013

Harms, I. M., & Dekker, G.-M. (2017). *ADAS: from owner to user*. Retrieved from https://connectingmobility.nl/PageByID.aspx?sectionID=112936&contentPageID=912643

Harms, I. M., Kuiken, M. J., & Fokkema, J. (2008). Analyses nadelige effecten navigatie-systemen op routekeuze.

Harms, L. (1996). Driving performance on a real road and in a drving simulator: results of a validation study. In A. G. Gale (Ed.), *Vision in Vehicles - V*. Amsterdam: Elsevier Science B. V. (North Holland).

Harms, L., & Patten, C. (2003). Peripheral detection as a measure of driver distraction. A study of memory-based versus system-based navigation in a built-up area. *Transportation Research Part F: Traffic Psychology and Behaviour, 6*(1), 23-36.

Harrison, M. A. (2011). College students' prevalence and perceptions of text messaging while driving. *Accident Analysis & Prevention, 43*(4), 1516-1520. doi:http://dx.doi.org/10.1016/j.aap.2011.03.003

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human Mental Workload*. Amsterdam: North Holland Press.

Haupt, J., van Nes, N., & Risser, R. (2015). Look where you have to go! A field study comparing looking behaviour at urban intersections using a navigation system or a printed route instruction. *Transportation Research Part F: Traffic Psychology and Behaviour, 34*, 122-140. doi:http://dx.doi.org/10.1016/j.trf.2015.07.018

Hayes, A. F., & Krippendorff, K. (2007). Answering the call for a standard reliability measure for coding data. *Communication methods and measures, 1*(1), 77-89.

Hickman, J. S., Hanowski, R. J., & Bocanegra, J. (2010). *Distraction in commercial trucks and buses: Assessing prevalence and risk in conjunction with crashes and near-crashes*.

Hills, B. L. (1980). Vision, visibility, and perception in driving. *Perception, 9*(2), 183-216.

Hislop, D. (2012). Hanging on the telephone: Mobile phone use patterns among UK-based business travellers on work-related journeys. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(2), 101-110. doi:http://dx.doi.org/10.1016/j.trf.2011.11.009

Hoffman, J. D., Lee, J. D., McGehee, D. V., Macias, M., & Gellatly, A. W. (2005). Visual sampling of in-vehicle text messages: Effects of number of lines, page presentation, and message control. *Transportation Research Record: Journal of the Transportation Research Board*(1937), pp 22-30.

Holland, C., & Rathod, V. (2013). Influence of personal mobile phone ringing and usual intention to answer on driver error. *Accident Analysis & Prevention, 50*(0), 793-800. doi:http://dx.doi.org/10.1016/j.aap.2012.07.004

Hoogendoorn, R. G. (2012). *Empirical research and modeling of longitudinal driving behaviour under adverse conditions.* (PhD thesis), Delft University of Technology, Delft.

Hoogendoorn, R. G., Van Arem, B., Hoogendoorn, S., Brookhuis, K. A., & Happee, R. (2012). Towards a stochastic model of driving behavior under adverse conditions. *Advances in Human Aspects of Road and Rail Transportation* (pp. 439-448): CRC Press.

Horrey, W. J., & Wickens, C. D. (2006). Examining the impact of cell phone conversations on driving using meta-analytic techniques. *Human Factors, 48*(1), 196-205.
Hosking, S. G., Young, K. L., & Regan, M. A. (2009). The effects of text messaging on young drivers. *Human Factors, 51*(4), 582-592.
Hoskins, A. H., & El-Gindy, M. (2006). Technical report: Literature survey on driving simulator validation studies. *International Journal for Heavy vehicle Systems, 13*(3), 241-252.
Hsieh, L., Seaman, S., & Young, R. (2010). *Effect of emotional speech tone on driving from lab to road: FMRI and ERP studies*, Pittsburgh, PA.
Hurts, K., Angell, L. S., & Perez, M. A. (2011). The distracted driver: Mechanisms, models and measurement. *Reviews of Human Factors and Ergonomics, 7*(3). doi:http://dx.doi.org/10.1177/1557234X11410387
Hydén, C. (1987). *The development of a method for traffic safety evaluation: The Swedish Traffic Conflicts Technique.* University of Lund, Lund, Sweden.
International Data Corporation. (2013). More smartphones were shipped in Q1 2013 than feature phones, and industry first according to IDC. Retrieved from http://www.zdnet.com/article/idc-more-smartphones-shipped-during-q1-than-feature-phones/
Interpolis. (2017). 'Dit kan jou ook gebeuren'. https://www.youtube.com/watch?v=V-WCzgjXqkA
Iqbal, S. T., Ju, Y.-C., & Horvitz, E. (2010). *Cars, calls, and cognition: Investigating driving and divided attention.* Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.
Itoh, N., Yamashita, A., & Kawakami, M. (2005). Effects of car-navigation display positioning on older drivers' visual search. In G. Costa, W. J. A. Goedhart, & J. Ilmarinen (Eds.), *International Congress Series* (Vol. 1280, pp. 184-189).
Jahn, G., Krems, J. F., & Gelau, C. (2009). Skill acquisition while operating in-vehicle information systems: Interface design determines the level of safety-relevant distractions. *Human Factors, 51*(2), 136-151.
Jahn, G., Oehme, A., Krems, J. F., & Gelau, C. (2005). Peripheral detection as a workload measure in driving: Effects of traffic complexity and route guidance system use in a driving study. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(3), 255-275.
James, W. (1890). The principles of psychology. Available online at http://psychclassics.yorku.lca/James/Principles/.
Jamson, S. L. (2013). What impact does legislation have on drivers' in-vehicle use of nomadic devices? *Transportation Research Part F: Traffic Psychology and Behaviour, 16*(0), 138-150. doi:http://dx.doi.org/10.1016/j.trf.2012.08.014
Jamson, S. L., & Jamson, A. H. (2010). The validity of a low-cost simulator for the assessment of the effects of in-vehicle information systems. *Safety Science, 48*(10), 1477.
Janssen, C. P., Brumby, D. P., & Garnett, R. (2010). *Natural break points: Utilizing motor cues when multitasking*, San Francisco, CA.
Jellentrup, N., Metz, B., & Rothe, S. (2011). *Can talking on the phone keep the driver awake? Results of a field-study using telephoning as a countermeasure against fatigue while driving.* Paper presented at the Proceedings of the 2nd International Conference on Driver Distraction and Inattention.
Jensen, B. S., Skov, M. B., & Thiruravichandran, N. (2010). *Studying driver attention and behaviour for three configurations of GPS navigation in real traffic driving*, Atlanta, GA.

Joksch, H. C. (1993). Velocity change and fatality risk in a crash—A rule of thumb. *Accident Analysis and Prevention, 25*(1), 103-104. doi:http://dx.doi.org/10.1016/0001-4575(93)90102-3

Jones, S. R. G. (1992). Was there a Hawthorne effect? *The American Journal of Sociology, 98*(3), 451-468.

Kahneman. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.

Kaptein, N. A., Theeuwes, J., & Van der Horst, R. (1996). Driving simulator validity: some considerations. *Transportation Research Record*(1550), 30-36.

Karlsson, I. C. M., Skoglund, T., Wallgren, P., Alonso, M., Guidotti, L., Martin, O., & May, A. (2015). Patterns of use, perceived benefits and reported effects of access to navigation support systems: an inter-European field operational test. *IET Intelligent Transport Systems, 9*(8), 802-809. doi:http://dx.doi.org/10.1049/iet-its.2014.0233

Karrer, K., Briest, S., Vöhringer-Kuhnt, T., T., B., & Schleicher, R. (2005). *Driving without awareness.* Paper presented at the Traffic and Transport Psychology, Proceedings of the ICTTP 2004, Nottingham, England.

Kern, D., Marshall, P., Hornecker, E., Rogers, Y., & Schmidt, A. (2009). Enhancing navigation information with tactile output embedded into the steering wheel. *Pervasive Computing, Proceedings, 5538*, 42-58.

Kidd, D. G., & McCartt, A. T. (2012). *Review of "Cell phone use and crash risk: Evidence for positive bias" by Richard A. Young*

KiM (2015). Navigatiesystemen: Wie, wanneer en waarom? The Hague: Kennisinstituut voor Mobiliteitsbeleid.

Kim, S., Hong, J. H., Li, K. A., Forlizzi, J., & Dey, A. K. (2012) Route guidance modality for elder driver navigation. *10th International Conference on Pervasive Computing, Pervasive 2012: Vol. 7319 LNCS* (pp. 179-196). Newcastle.

Kircher, K., Patten, C., & Ahlström, C. (2011). *Mobile telephones and other communication devices and their impact on traffic safety - A review of the literature*

Klauer, S. G., Guo, F., Simons-Morton, B. G., Ouimet, M. C., Lee, S. E., & Dingus, T. A. (2014). Distracted driving and risk of road crashes among novice and experienced Drivers. *New England Journal of Medicine, 370*(1), 54-59. doi:doi:10.1056/NEJMsa1204142

Klauer, S. G., Guo, F., Sudweeks, J. D., & Dingus, T. A. (2010). *An analysis of driver inattention using a case-crossover approach on 100-car data: Final report*

Klee, H., Bauer, C., Radwan, E., & Al-Deek, H. (1999). Preliminary validation of driving simulator based on forward speed. *Transportation Research Record*(1689), 33-39. doi:http://dx.doi.org/10.3141/1689-05

Klunder, G. A., Malone, K., Mak, J., Wilmink, I. R., Schirokoff, A., Sihvola, N., . . . Kosmatopoulos, E. (2009). *Impact of ICT on energy efficiency in road transport* Retrieved from http://repository.tudelft.nl/view/tno/uuid%3A2a2c6c59-0ddd-4a93-91b2-0ca7d363918c/

Knapper, A. S. (2013). *Effects of handheld mobile conversation on experienced phone users' simulated driving performance*. Paper presented at the Young Researchers Seminar, Lyon.

Knapper, A. S., Hagenzieker, M. P., & Brookhuis, K. A. (2010). *Three ways of observing drivers using navigation systems*. Paper presented at the 11th TRAIL Congress, Rotterdam. http://rstrail.nl/new/wp-content/uploads/2015/02/Knapper_0.pdf

Kujala, T., & Saariluoma, P. (2011). Effects of menu structure and touch screen scrolling style on the variability of glance durations during in-vehicle visual search tasks. *Ergonomics, 54*(8), 716-732.

Kun, A. L., Paek, T., Medenica, Ž., Memarović, N., & Palinko, O. (2009). *Glancing at personal navigation devices can affect driving: Experimental results and design implications*, Essen.

Laberge-Nadeau, C., Maag, U., Bellavance, F., Lapierre, S. D., Desjardins, D., Messier, S., & Saïdi, A. (2003). Wireless telephones and the risk of road crashes. *Accident Analysis & Prevention, 35*(5), 649-660. doi:http://dx.doi.org/10.1016/s0001-4575(02)00043-x

Lajunen, T., Parker, D., & Summala, H. (2004). The Manchester Driver Behaviour Questionnaire: A cross-cultural study. *Accident Analysis & Prevention, 36*, 231-238.

Lansdown, T. C. (2012). Individual differences and propensity to engage with in-vehicle distractions – A self-report survey. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(1), 1-8. doi:http://dx.doi.org/10.1016/j.trf.2011.09.001

Lansdown, T. C., & Stephens, A. N. (2013). Couples, contentious conversations, mobile telephone use and driving. *Accident Analysis & Prevention, 50*(0), 416-422. doi:http://dx.doi.org/10.1016/j.aap.2012.05.015

Lansdown, T. C., Stephens, A. N., & Walker, G. H. (2015). Multiple driver distractions: a systemic transport problem. *Accid Anal Prev, 74*, 360-367. doi:http://dx.doi.org/10.1016/j.aap.2014.07.006

Lee, H. C., Cameron, D., & Lee, A. H. (2003). Assessing the driving performance of older adult drivers: on-road versus simulated driving. *Accident Analysis and Prevention, 35*(5), 797-803. doi:http://dx.doi.org/10.1016/s0001-4575(02)00083-0

Lee, H. C., Falkmer, T., Rosenwax, L., Cordell, R., Granger, A., Vieira, B., & Lee, A. (2007). Validity of driving simulator in assessing drivers with Parkinson's disease. *Advances in Transportation Studies*.

Lee, H. C., & Lee, A. H. (2005). Identifying older drivers at risk of traffic violations by using a driving simulator: A 3-year longitudinal study. *The American Journal of Occupational Therapy, 59*(1), 97-100.

Lee, J., Forlizzi, J., & Hudson, S. E. (2008). Iterative design of MOVE: A situationally appropriate vehicle navigation system. *International Journal of Human-Computer Studies, 66*(3), 198-215. doi:http://dx.doi.org/10.1016/j.ijhcs.2007.01.004

Lee, J. D. (2014). Dynamics of Driver Distraction: The process of engaging and disengaging. *Annals of Advances in Automotive Medicine, 58*, 24-32.

Lee, J. D., McGehee, D., Brown, J., Richard, C., Ahmad, O., Ward, N., . . . Lee, J. (2011). Matching simulator characteristics to highway design problems. *Transportation Research Record: Journal of the Transportation Research Board*(2248), 53-60. doi:http://dx.doi.org/10.3141/2248-07

Lee, J. D., Young, K. L., & Regan, M. A. (2009). Defining driver distraction. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction - Theory, effects & mitigation* (pp. 31-40). Boca Ration: Taylor & Francis Group.

Lee, W.-C., & Cheng, B.-W. (2008). Effects of using a portable navigation system and paper map in real driving. *Accident Analysis & Prevention, 40*(1), 303-308.

Lee, W.-C., & Cheng, B.-W. (2010). Comparison of portable and onboard navigation system for the effects in real driving *Safety Science, 48*, 1421-1426.

Leshed, G., Velden, T., Rieger, O., Kot, B., & Sengers, P. (2008). *In-car gps navigation: engagement with and disengagement from the environment.* Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2010). That's close enough - A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. *Accident Analysis & Prevention, 42*, 1926-1933.

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2011). Speed maintenance under cognitive load – Implications for theories of driver behaviour. *Accident Analysis & Prevention, 43*(4), 1497-1507. doi:http://dx.doi.org/10.1016/j.aap.2011.02.030

Libby, D., & Chaparro, A. (2009). *Text messaging versus talking on a cell phone: A comparison of their effects on driving performance*, San Antonio, TX.

Liu, Y. C. (2001). Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveler information systems. *Ergonomics, 44*(4), 425-442.

Llerena, L. E., Aronow, K. V., Macleod, J., Bard, M., Salzman, S., Greene, W., . . . Schupper, A. (2015). An evidence-based review: distracted driver. *J Trauma Acute Care Surg, 78*(1), 147-152. doi:https://doi.org/10.1097/TA.0000000000000487

Lo, V. E. W., Green, P. A., & Franzblau, A. (2011). Where do people drive? Navigation system use by typical drivers and auto experts. *Journal of Navigation, 64*(2), 357-373. doi:http://dx.doi.org/10.1017/s0373463310000561

Ma, R., & Kaber, D. B. (2007a). Situation awareness and driving performance in a simulated navigation task. *Ergonomics, 50*(8), 1351-1364. doi:http://dx.doi.org/10.1080/00140130701318913

Ma, R. Q., & Kaber, D. B. (2007b). Effects of in-vehicle navigation assistance and performance on driver trust and vehicle control. *International Journal of Industrial Ergonomics, 37*(8), 665-673. doi:10.1016/j.ergon.2007.04.005

Maciej, J., Nitsch, M., & Vollrath, M. (2011). Conversing while driving: The importance of visual information for conversation modulation. *Transportation Research Part F: Traffic Psychology and Behaviour, 14*(6), 512-524. doi:http://dx.doi.org/10.1016/j.trf.2011.05.001

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

Maclure, M., & Mittleman, M. A. (1997). Editorial - Cautions about car telephones and collisions. *New England Journal of Medicine, 336*(7), 501-502.

Malta, L., L., A. M., Faber, F., B., M., P., S. P., Benmimoun, M., & Schäfer, R. (2012). *Impacts on traffic safety. Final results from the EuroFOT project*.

Mattes, S. (2003). The lane-change-task as a tool for driver distraction evaluation. *Quality of Work and Products in Enterprises of the Future*, 57-60.

May, A., & Ross, T. (2006a). Presence and quality of navigational landmarks: Effect on driver performance and implications for design. *Human Factors, 48*(2), 346-361.

May, A., Ross, T., & Osman, Z. (2005). The design of next generation in-vehicle navigation systems for the older driver. *Interacting with Computers, 17*(6), 643-659.

May, A. J., & Ross, T. (2006b). Presence and quality of navigational landmarks: Effect on driver performance and implications for design. *Human Factors, 48*(2), 346-361.

Mayhew, D. R., Simpson, H. M., Wood, K. M., Lonero, L., Clinton, K. M., & Johnson, A. G. (2011). On-road and simulated driving: Concurrent and discriminant validation. *Journal of Safety Research, 42*(4), 267-275. doi:http://dx.doi.org/10.1016/j.jsr.2011.06.004

McAvoy, D. S., Schattler, K. L., & Datta, T. K. (2007). *Driving simulator validation for nighttime construction work zone devices.* Paper presented at the 86th Annual Meeting of the Transportation Research Board, Washington, DC.

McCartt, A. T., Hellinga, L. A., & Bratiman, K. A. (2006). Cell phones and driving: Review of research. *Traffic Injury Prevention, 7*(2), 89-106. doi:http://dx.doi.org/10.1080/15389580600651103

McCormick, I. A., Walkey, F. H., & Green, D. E. (1986). Comparative perceptions of driver ability— A confirmation and expansion. *Accident Analysis & Prevention, 18*(3), 205-208. doi:http://dx.doi.org/10.1016/0001-4575(86)90004-7

McEvoy, S. P., & Stevenson, M. R. (2009). Measuring exposure to driver distraction. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction - Theory, effects & mitigation* (pp. 73-83). Boca Raton: Taylor & Francis Group.

McEvoy, S. P., Stevenson, M. R., McCartt, A. T., Woodward, M., Haworth, C., Palamara, P., & Cercarelli, R. (2005). Role of mobile phones in motor vehicle crashes resulting in hospital attendance: a case-crossover study. *BMJ Publishing Group Ltd.*

McEvoy, S. P., Stevenson, M. R., & Woodward, M. (2012). Cell phone use and crash risk: To the editor. *Epidemiology, 23*(4), 648 doi:http://dx.doi.org/10.1097/EDE.0b013e3182594053

McKenna, F. P. (1988). What role should the concept of risk play in theories of accident involvement? *Ergonomics, 31*(4), 469-484. doi:http://dx.doi.org/10.1080/00140138808966692

McRuer, D. T., & Klein, R. H. (1976). Comparison of driver dynamics with actual and simulated visual displays. *Transportation Research Record*(611), 46-48.

Medeiros-Ward, N., Cooper, J. M., Doxon, A. J., Strayer, D. L., & Provancher, W. R. (2010). *Bypassing the bottleneck: The advantage of fingertip shear feedback for navigational cues*, San Francisco, CA.

Merat, N., Anttila, V., & Luoma, J. (2005). Comparing the driving performance of average and older drivers: The effect of surrogate in-vehicle information systems. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2 SPEC. ISS.), 147-166.

Mesken, J., Hagenzieker, M. P., Rothengatter, T., & De Waard, D. (2007). Frequency, determinants, and consequences of different drivers' emotions: An on-the-road study using self-reports, (observed) behaviour, and physiology. *Transportation Research Part F: Traffic Psychology and Behaviour, 10*(6), 458-475. doi:http://dx.doi.org/10.1016/j.trf.2007.05.001

Metz, B., Schoch, S., Just, M., & Kuhn, F. (2014). How do drivers interact with navigation systems in real life conditions?: Results of a field-operational-test on navigation systems. *Transportation Research Part F: Traffic Psychology and Behaviour, 24*(0), 146-157. doi:http://dx.doi.org/10.1016/j.trf.2014.04.011

Metz, B., Schomig, N., & Kruger, H. P. (2011). Attention during visual secondary tasks in driving: Adaptation to the demands of the driving task. *Transportation Research Part F-Traffic Psychology and Behaviour, 14*(5), 369-380. doi:http://dx.doi.org/10.1016/j.trf.2011.04.004

Michon, J. A. (1985). A critical view of driver behavior models: What do we know, what should we do? In L. Evans & R. C. Schwing (Eds.), *Human behavior and traffic safety* (pp. 485–520). New York: Plenum Press.

Minister of Transport and Water. (1990). *Reglement verkeersregels en verkeerstekens*. Retrieved from http://wetten.overheid.nl/jci1.3:c:BWBR0004825&hoofdstuk=II&paragraaf=30&artikel=61a&z=2017-07-01&g=2017-07-01

Mittleman, M. A., Maclure, M., & Mostofsky, E. (2012). Cell phone use and crash risk. *Epidemiology, 23*(4), 647-648 doi:http://dx.doi.org/10.1097/EDE.0b013e3182583cdf

Mora, P. V., Tontsch, A., & Montoro, I. (2012). Effects of manually entering navigator destinations while driving in a simulator. *Intelligent Transport Systems, IET, 6*(4), 397-403.

Morgan, J. F. (2008). *Hysteresis effects in driving.* (PhD thesis) University of Central Florida. Retrieved from http://stars.library.ucf.edu/etd/3753.

Morgan, J. F., Trimble, T. E., Bowman, D. S., Baker, S., Pickett, R., Murray, D., & Bergoffen, G. (2011). *Synthesis of literature relating to cellular telephone/personal digital assistant use in commercial truck and bus operations*.

Mouloua, M., Ahern, A., Rinalducci, E., Alberti, P., Brill, J. C., & Quevedo, A. (2010). *The effects of text messaging on driver distraction: A bio-behavioral analysis.* Paper presented at the 54th Human Factors and Ergonomics Society Annual Meeting 2010, San Francisco, CA.

Mullen, N., Charlton, J., Devlin, A., & Bédard, M. (2011). Simulator validity: Behaviors oberved on the simulator and on the road. In D. L. Fisher, M. Rizzo, J. K. Caird, & J. D. Lee (Eds.), *Handbook of driving simulation for engineering, medicine, and psychology*: CRC Press.

Näätänen, R., & Summala, H. (1974). A model for the role of motivational factors in drivers' decisionmaking. *Accident Analysis & Prevention, 6*, 243-261.

Nemme, H. E., & White, K. M. (2010). Texting while driving: Psychosocial influences on young people's texting intentions and behaviour. *Accident Analysis & Prevention, 42*(4), 1257-1265. doi:http://dx.doi.org/10.1016/j.aap.2010.01.019

Neurauter, M. L., Hankey, J. M., Schalk, T. B., & Wallace, G. (2012). Outbound texting comparison of speech-based approach and handheld touch-screen equivalent. *Transportation Research Record*(2321), 23-30. doi:http://dx.doi.org/10.3141/2321-04

NHTSA (2011) Driver electronic device use in 2010. (pp. 8p): National Center for Statistics and Analysis.

NHTSA (2013). *Visual-manual NHTSA driver distraction guidelines for in-vehicle electronic devices*. Federal Register Retrieved from http://www.gpo.gov/fdsys/pkg/FR-2013-04-26/pdf/2013-09883.pdf.

Nielsen, J. (1993). *Usability Engineering*: Morgan Kaufmann Publishers Inc.

Noel, E., Nonnecke, B., & Trick, L. (2005). *Evaluating first-time and infrequent use of in-car navigation devices.* Paper presented at the International Driving Symposium on human factors in driver assessment, training and vehicle design.

Nowakowski, C., & Green, P. (2001). *Prediction of menu selection times parked and while driving using the SAE J2365 method*

Nowakowski, C., Green, P., & Tsimhoni, O. (2003). *Common automotive navigation system usability problems and a standard test protocol to identify them.* Paper presented at the ITS-America 2003 Annual Meeting.

Nowakowski, C., Utsui, Y., & Green, P. (2000). *Navigation system destination entry: The effects of driver workload and input devices, and implications for SAE recommended practice*

NSC (2010). *Understanding the distracted brain. Why driving while using hands-free cell phones is risky behaviour*. Retrieved from https://www.nsc.org/road-safety/safety-topics/distracted-driving/distracted-brain/

O'Brien, N. P., Goodwin, A. H., & Foss, R. D. (2010). Talking and texting among teenage drivers: A glass half empty or half full? *Traffic Injury Prevention, 11*(6), 549-554.

O'Connor, S. S., Whitehill, J. M., King, K. M., Kernic, M. A., Boyle, L. N., Bresnahan, B. W., . . . Ebel, B. E. (2013). Compulsive cell phone use and history of motor vehicle crash. *Journal of Adolescent Health, 53*(4). doi:http://dx.doi.org/10.1016/j.jadohealth.2013.05.015

OECD (1990). *Behavioural adaptations to changes in the road transport system*

Oei, H. L. (2003). Mogelijke veiligheidseffecten van navigatiesystemen. Een literatuurstudie, enkele eenvoudige effectberekeningen en resultaten van een enquete. *R-2002-30*(R-2002-30).

Ogle, J., Guensler, R., Bachman, W., Koutsak, M., & Wolf, J. (2002). Accuracy of global positioning system for determining driver performance parameters *Transportation Research Record* (pp. 12-24).

Olson, R. L., Hanowski, R. J., Hickman, J. S., & Bocanegra, J. (2009). *Driver distraction in commercial vehicle operations.*

Openbaar Ministerie. (2017). Telefoneren. Retrieved from https://www.om.nl/onderwerpen/verkeer/handhaving-verkeer/telefoneren/

Osborne, J. W. (2008). *Bringing balance and technical accuracy to reporting odds ratios and the results of logistic regression analyses*: Sage Publications: Thousand Oaks, CA, USA.

Owens, J. M., McLaughlin, S. B., & Sudweeks, J. (2011). Driver performance while text messaging using handheld and in-vehicle systems. *Accident Analysis & Prevention, 43*(3), 939-947. doi:http://dx.doi.org/10.1016/j.aap.2010.11.019

Pacejka, H. B., & Bakker, E. (1992). The magic formula tyre model. *Vehicle System Dynamics, 21*(sup001), 1-18. doi:http://dx.doi.org/10.1080/00423119208969994

Park, A., Salsbury, J., Corbett, K., & Aiello, J. (2013). The effects of text messaging during dual-task driving simulation on cardiovascular and respiratory responses and reaction time. *Ohio Journal of Science, 111*(2-5), 42-44.

Parkes, A. M., Ashby, M. C., & Fairclough, S. H. (1991). The effects of different in-vehicle route information displays on driver behaviour. *SAE Technical Papers*.

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2016). Exploring the mechanisms of distraction from in-vehicle technology: The development of the PARRC model. *Safety Science, 87*, 25-37. doi:http://dx.doi.org/10.1016/j.ssci.2016.03.014

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2017). What's the law got to do with it? Legislation regarding in-vehicle technology use and its impact on driver distraction. *Accident Analysis & Prevention, 100*, 1-14. doi:http://dx.doi.org/10.1016/j.aap.2016.12.015

Patten, C. J. D., Kircher, A., Östlund, J., & Nilsson, L. (2004). Using mobile telephones: cognitive workload and attention resource allocation. *Accident Analysis & Prevention, 36*(3), 341-350. doi:http://dx.doi.org/10.1016/s0001-4575(03)00014-9

Pereira, M., Hamama, H., Bruyas, M.-P., & Simoes, A. (2008). *Effect of additional tasks in driving performance: Comparison among three groups of drivers.* Paper presented at the European Conference on Human Centred Design for Intelligent Transport Systems, Lyon, France.

Pettitt, M. A., Burnett, G., Bayer, S., & Stevens, A. (2006). Assessment of the occlusion technique as a means for evaluating the distraction potential of driver support systems. *IEE Proceedings: Intelligent Transport Systems, 153*(4).

Phillips, R. O., Ulleberg, P., & Vaa, T. (2011). Meta-analysis of the effect of road safety campaigns on accidents. *Accident Analysis & Prevention, 43*(3), 1204-1218. doi:http://dx.doi.org/10.1016/j.aap.2011.01.002

Poushter, J. (2016). Smartphone ownership and internet usage continues to climb in emerging economies. Retrieved from http://www.pewglobal.org/2016/02/22/smartphone-ownership-and-internet-usage-continues-to-climb-in-emerging-economies/

Pradhan, A., Simons-Morton, B., Lee, S., & Klauer, S. (2011). *Hazard perception and distraction in novice drivers: Effects of 12 months driving experience*.

Raad voor de Rechtspraak (2018). Meervoudig arrest. Wat is de reikwijdte van artikel 61a van het RVV 1990? http://deeplink.rechtspraak.nl/uitspraak?id=ECLI:NL:GHARL:2018:2186

Rakauskas, M. E., Gugerty, L. J., & Ward, N. J. (2004). Effects of naturalistic cell phone conversations on driving performance. *Journal of Safety Research, 35*(4), 453-464. doi:http://dx.doi.org/10.1016/j.jsr.2004.06.003

Rakauskas, M. E., Ward, N., Bernat, E., Cadwallade, M., & De Waard, D. (2005). *Driving performance during cell phone conversations and common in-vehicle tasks while sober and drunk*

Ranney, T. A. (1994). Models of driving behavior: A review of their evolution. *Accident Analysis & Prevention, 26*(6), 733-750.

Ranney, T. A., Baldwin, G. H. S., Parmer, E., Martin, J., & Mazzae, E. N. (2011). *Distraction effects of manual number and text entry while driving*. Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/811510.pdf

Ranney, T. A., Baldwin, G. H. S., Parmer, E., Martin, J., & Mazzae, E. N. (2012). *Distraction effects of in-vehicle tasks requiring number and text entry using Auto Alliance's principle 2.1B verification procedure*. Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/811571.pdf

Ranney, T. A., Baldwin, G. H. S., Smith, L. A., Martin, J., & Mazzae, E. N. (2013). *Driver behavior during visual-manual secondary task performance: Occlusion method versus simulated driving*

Ranney, T. A., Mazzae, E., Garrott, R., & Goodman, M. J. (2000). *NHTSA driver distraction research: Past, present, and future*. Retrieved from http://www-nrd.nhtsa.dot.gov/departments/Human%20Factors/driver-distraction/PDF/233.PDF

Rasmussen, J., Duncan, K., & Leplat, J. (1988). *New technology and human error*. Chichester: John Wiley & Sons.

Rauniomaa, M., & Haddington, P. (2012). Driven by a social and interactional routine: Responding to a mobile phone summons in a car. *International Journal of Cyber Behavior, Psychology and Learning (IJCBPL), 2*(3), 39-58.

Reagan, I., & Baldwin, C. L. (2006). Facilitating route memory with auditory route guidance systems. *Journal of Environmental Psychology, 26*(2), 146-155.

Reason, J. (1990). *Human Error*. New York: Cambridge University Press.

Reason, J., Manstead, A., Stradling, S., Baxter, J., & Campbell, K. (1990). Errors and violations on the roads: a real distinction? *Ergonomics, 33*(10-11), 1315-1332. doi:http://dx.doi.org/10.1080/00140139008925335

Redelmeier, D. A., & Tibshirani, R. J. (1997). Association between cellular-telephone calls and motor vehicle collisions. *New England Journal of Medicine, 336*(7), 453-458. doi:http://dx.doi.org/10.1056/NEJM199702133360701

Reed, M. P., & Green, P. A. (1999). Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task. *Ergonomics, 42*(8), 1015-1037.

Reed, N., & Robbins, R. (2008) The effect of text messaging on driver behaviour: a simulator study. (pp. R367): TRL.

Reimer, B., D'Ambrosio, L. A., Coughlin, J. F., Kafrissen, M. E., & Biederman, J. (2006). Using self-reported data to assess the validity of driving simulation data. *Behavior Research Methods, 38*(2), 314-324.

Reimer, B., Mehler, B., Coughlin, J. F., Roy, N., & Dusek, J. A. (2011). The impact of a naturalistic hands-free cellular phone task on heart rate and simulated driving performance in two age groups. *Transportation Research Part F: Traffic Psychology and Behaviour, 14*(1), 13-25. doi:http://dx.doi.org/10.1016/j.trf.2010.09.002

Reimer, B., Mehler, B., Donmez, B., Pala, S., Wang, Y., Zaho, N., . . . Coughlin, J. F. (2012). A driving simulator study examining phone dialing with an iPhone vs. a button style flip-phone. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56*(1), 2191-2195. doi:http://dx.doi.org/10.1177/1071181312561462

Reimer, B., Mehler, B., Wang, Y., Mehler, A., McAnulty, H., McKissick, E., . . . Greve, G. (2012). *An exploratory study on the impact of typeface design in a text rich user interface on off-road glance behavior*.

Reinhardt, W., & Jendrzok, M. (2009). *Final report of the EC eSafety Nomadic Device Forum* Retrieved from http://www.imobilitysupport.eu/library/imobility-forum/working-groups/concluded/nomadic-device-forum-ndf/reports-8/2037-final-report-full/file

Richards, C. (2015). *GfK Retail Reports (in Dutch)*. Retrieved from http://www.gfk.com/nl/news-and-events/press-room/Documents/Retail%20Reports%20-%20Q4%20-%20Telecom.pdf

Rijksoverheid. (2016). *Interdepartementaal beleidsonderzoek verkeershandhaving*. Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2017/01/17/tk-bijlage-ibo-verkeershandhaving-eindrapport

Ross, T., & Brade, S. (1995). *Empirical study to determine guidelines for optimum timing of route guidance instructions.* Paper presented at the IEE Colloquium (Digest), London, UK.

Ross, T., & Burnett, G. (2001). Evaluating the human-machine interface to vehicle navigation systems as an example of ubiquitous computing. *International Journal of Human-Computer Studies, 55*(4), 661-674.

Rossi, R., Gastaldi, M., Biondi, F., & Mulatti, C. (2012). Evaluating the impact of processing spoken words on driving experiments with driving simulator. *Transportation Research Record*(2321), 66-72. doi:10.3141/2321-09

Rothengatter, T. (1988). Risk and the absence of pleasure: a motivational approach to modelling road user behaviour. *Ergonomics, 31*(4), 599-607. doi:http://dx.doi.org/10.1080/00140138808966702

Rothengatter, T., Alm, H., Kuiken, M. J., Michon, J. A., & Verwey, W. B. (1993). The driver. In J. A. Michon (Ed.), *Generic Intelligent Driver Support: A comprehensive report on GIDS*. London & Washington DC: Taylor & Francis.

Rozario, M., Lewis, I., & Kartherine White, M. (2010). An examination of the factors that influence drivers' willingness to use hand-held mobile phones. *Transportation Research Part F: Psychology and Behaviour*(13), 365-376.

Rudin-Brown, C. M., Young, K. L., Patten, C., Lenné, M. G., & Ceci, R. (2012). Driver distraction in an unusual environment: Effects of text-messaging in tunnels. *Accident Analysis and Prevention*. doi:http://dx.doi.org/10.1016/j.aap.2012.04.002

Saad, F., Hjälmdahl, M., Cañas, J., Alonso, M., Garayo, P., Macchi, L., . . . Panou, M. (2004). Literature review of behavioural effects. *AIDE, Deliverable D1_2_1*.

Salmon, P. M., Lenné, M. G., Stanton, N. A., Jenkins, D. P., & Walker, G. H. (2010). Managing error on the open road: The contribution of human error models and methods. *Safety Science, 48*, 1225-1235.

Salmon, P. M., Regan, M. A., & Johnston, I. (2005). *Human error and road transport: Phase one - A framework for an error tolerant road transport system*

Samuel, S., Pollatsek, A., & Fisher, D. (2011). *Texting while driving: Evaluation of glance distributions for frequent/infrequent texters and keypad/touchpad texters.* Paper presented at the Proceedings of the Sixth International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design.

Sanghavi, P. (2013a). Commentary: Culpability analysis won't help us understand crash risk due to cell phones. *International Journal of Epidemiology, 42*(1), 267-269.
Sanghavi, P. (2013b). Using culpability analysis to infer crash risk requires unrealistic assumptions Author's response to: Culpability Analysis is Still a Valuable Technique. *International Journal of Epidemiology*, dyt146.
Santos, J., Merat, N., Mouta, S., Brookhuis, K., & De Waard, D. (2005). The interaction between driving and in-vehicle information systems: Comparison of results from laboratory, simulator and real-world studies. *Transportation Research Part F, 8*, 135-146.
Savolainen, P. T., Das, A., Gates, T. J., & Datta, T. K. (2011). *Cell Phone Use and Crash Patterns Among Michigan Drivers*.
Sayer, J. R., Bao, S., & Funkhouser, D. (2013). *Effects of cell phone conversations and device manipulation on objective measures of driving performance*. Paper presented at the 3rd International Conferennce on Driver Distraction and Inattention, Gothenburg, Sweden.
Schlehofer, M. M., Thompson, S. C., Ting, S., Ostermann, S., Nierman, A., & Skenderian, J. (2010). Psychological predictors of college students' cell phone use while driving. *Accident Analysis & Prevention, 42*(4), 1107-1112. doi:http://dx.doi.org/10.1016/j.aap.2009.12.024
Schweizer, T. A., Kan, K., Hung, Y., Tam, F., Naglie, G., & Graham, S. (2013). Brain activity during driving with distraction: an immersive fMRI study. *Frontiers in Human Neuroscience, 7*. doi:http://dx.doi.org/10.3389/fnhum.2013.00053
Shechtman, O. (2010). Validation of driving simulators. *Advances in Transportation Studies*(SPEC. ISSUE), 53-62. doi:http://dx.doi.org/10.4399/97888548416596
Shechtman, O., Classen, S., Awadzi, K., & Mann, W. (2009). Comparison of driving errors between on-the-road and simulated driving assessment: A validation study. *Traffic Injury Prevention, 10*(4), 379 - 385.
Sheridan, T. B. (2004). Driver distraction from a control theory perspective. *Human Factors, 46*(4), 587-599.
Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Reviews, 84*, 127-190.
Shinar, D., & Ronen, A. (2007). Validation of speed perception and production in a single screen simulator. *Advances in Transportation Studies*.
Shinar, D., Tractinsky, N., & Compton, R. (2005). Effects of practice, age, and task demands, on interference from a phone task while driving. *Accident Analysis & Prevention, 37*(2), 315-326. doi:http://dx.doi.org/10.1016/j.aap.2004.09.007
Silberzahn, R., & Uhlmann, E. L. (2015). Crowdsourced research: Many hands make tight work. *Nature, 526*, 189-191.
Srinivasan, R. (1997). Effect of selected in-vehicle route guidance systems on driver reaction times. *Human Factors, 39*(2), 200-215.
Stapel, D. (2012). *Ontsporing*. Amsterdam: Prometheus.
Stavrinos, D., Jones, J. L., Garner, A. A., Griffin, R., Franklin, C. A., Ball, D., . . . Fine, P. R. (2013). Impact of distracted driving on safety and traffic flow. *Accident Analysis & Prevention*(0). doi:http://dx.doi.org/10.1016/j.aap.2013.02.003
Stelling, A., & Hagenzieker, M. P. (2012). *Distraction in traffic; A literature review*. Retrieved from http://www.swov.nl/rapport/R-2012-04.pdf
Stelling, A., & Hagenzieker, M. P. (2015). *Estimated number of road fatalities due to distraction; an update (in Dutch)*

Stoner, H. A., Fisher, D. L., & Mollenhauer, M. A. (2011). Simulator and scenario factors influencing simulator sickness. In D. L. Fisher, J. K. Caird, M. Rizzo, & J. D. Lee (Eds.), *Handbook of driving simulation for engineering, medicine, and psychology: An overview* (pp. 14.11 - 14.20). Boca Raton: CRC Press, Taylor & Francis Group.

Stradling, S., Broughton, P., Kinnear, N., O'Dolan, C., Fuller, R., Bates, H., . . . Hannigan, B. (2008). Understanding inappropriate high speed: A quantitative analysis. *Road Safety Research Report, 93*.

Strayer, D. L., Cooper, J., & Drews, F. (2011). Profiles in cell phone-induced driver distraction. In D. L. Fisher, M. Rizzo, J. K. Caird, & J. D. Lee (Eds.), *Handbook of Driving Simulation for Engineering, Medicine, and Psychology*: CRC Press.

Strayer, D. L., Cooper, J., Turril, J., Coleman, J., & Hopman, R. (2015). *The smartphone and the driver's cognitive workload: A comparison of Apple, Google, and Microsoft's intelligent personal assistants*

Strayer, D. L., Cooper, J., Turrill, J., Coleman, J., Medeiros-Ward, N., & Biondi, F. (2013). *Measuring cognitive distraction in the automobile*. Retrieved from https://aaafoundation.org/measuring-cognitive-distraction-automobile/

Strayer, D. L., Cooper, J. M., Goethe, R. M., McCarty, M. M., Getty, D., & Biondi, F. (2017). *Visual and cognitive demands of using in-vehicle infotainment systems*

Strayer, D. L., & Drews, F. A. (2007). Cell-phone-induced driver distraction. *Current directions in psychological science, 16*(3), 128-131.

Sullman, M. J. M. (2012). An observational study of driver distraction in England. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(3), 272-278. doi:http://dx.doi.org/10.1016/j.trf.2012.01.001

Summala, H. (1988). Risk control is not risk adjustment: the zero-risk theory of driver behaviour and its implications. *Ergonomics, 31*(4), 491-506.

Summala, H. (2005). Traffic psychology theories: Towards understanding driving behaviour and safety efforts. In G. Underwood (Ed.), *Traffic and transport psychology* (pp. 383-395). Amsterdam: Elsevier B.V.

Svenson, O. (1981). Are we all less risky and more skillful than our fellow drivers? *Acta Psychologica, 47*(2), 143-148. doi:https://doi.org/10.1016/0001-6918(81)90005-6

Svenson, O., & Patten, C. D. (2005). Mobile phones and driving: a review of contemporary research. *Cognition, Technology & Work, 7*(3), 182-197. doi:http://dx.doi.org/10.1007/s10111-005-0185-3

SWOV (2010). *Factsheet: Safety effects of navigation systems*. Retrieved from https://www.swov.nl/publicatie/safety-effects-navigation-systems

SWOV (2016). Cijfers - slachtoffers, bestuurders en ongevallen. Retrieved from https://www.swov.nl/NL/Research/cijfers/Cijfers_Ongevallen.htm

SWOV (2017). *Progressieve sanctiesystemen in het verkeer*. Retrieved from https://www.swov.nl/feiten-cijfers/factsheet/progressieve-sanctiesystemen-het-verkeer

Takayama, L., & Nass, C. (2008). Driver safety and information from afar: An experimental driving simulator study of wireless vs. in-car information services. *International Journal of Human-Computer Studies, 66*, 173-184.

Taylor, D. H. (1964). Drivers' galvanic skin response and the risk of accident. *Ergonomics, 7*(4), 439-451. doi:http://dx.doi.org/10.1080/00140136408930761

Tijerina, L., Johnston, S., Palmer, E., & Winterbottom, M. D. (2000). Driver distraction with wireless telecommunications and route guidance systems. . (DOT HS 809-069).

Tijerina, L., Parmer, E., & Goodman, M. J. (1998). *Driver workload assessment of route guidance system destination entry while driving: a test track study.* Paper presented at the Proceedings of the 5th ITS World Congress, Seoul, Korea.

Tivesten, E., & Dozza, M. (2015). Driving context influences drivers' decision to engage in visual–manual phone tasks: Evidence from a naturalistic driving study. *Journal of Safety Research, 53*(0), 87-96. doi:http://dx.doi.org/10.1016/j.jsr.2015.03.010

TNO (2008). Independent research proves the positive influence of satellite navigation devices on driving and traffic safety.

Toole, L. M., Hanowski, R. J., Smith-Jackson, T. L., & Winchester, W. W. (2013). *Towards understanding mobile device use in commercial motor vehicle drivers: Do drivers interact as a drowsiness countermeasure?* Paper presented at the 3rd International Conferennce on Driver Distraction and Inattention, Gothenburg, Sweden.

Törnros, J. (1998). Driving behaviour in a real and a simulated road tunnel—a validation study. *Accident Analysis and Prevention, 30*(4), 497-503. doi:http://dx.doi.org/10.1016/s0001-4575(97)00099-7

Törnros, J. E. B., & Bolling, A. K. (2005). Mobile phone use—Effects of handheld and handsfree phones on driving performance. *Accident Analysis & Prevention, 37*(5), 902-909. doi:http://dx.doi.org/10.1016/j.aap.2005.04.007

Tractinsky, N., Ram, E. S., & Shinar, D. (2013). To call or not to call–that is the question (while driving). *Accident Analysis & Prevention, 56*, 59-70.

Trick, L. M., Toxopeus, R., & Wilson, D. (2010). The effects of visibility conditions, traffic density, and navigational challenge on speed compensation and driving performance in older adults. *Accident Analysis & Prevention, 42*(6), 1661-1671.

Trigoso, J., Areal, A., & Pires, C. (2016). *Distraction & fatigue. ESRA thematic report no. 3*.

TRL, TNO, & RappTrans (2015). *Study on good practices for reducing road safety risk casued by road user distractions - final report*.

Tsimhoni, O., Smith, D., & Green, P. (2004). Address entry while driving: Speech recognition versus a touch-screen keyboard. *Human Factors, 46*(4), 600-610.

Turetschek, C. (2009). *Effects of ISA-like IST, Dissertation.* Vienna University, Vienna. Retrieved from http://othes.univie.ac.at/8042/1/2009-11-25_9502860.pdf

Vaa, T. (2001). *Cognition and emotion in driver behaviour models: Some critical viewpoints*. Paper presented at the 14th ICTCT workshop: car drivers.

Vaa, T. (2007). Modelling driver behaviour on basis of emotions and feelings: Intelligent Transport Systems and behavioural adaptations. In P. C. Cacciabue (Ed.), *Modelling Driver Behaviour in Automotive Environments* (pp. 208-232): Springer London.

Van Erp, J. B. F., & Van Veen, H. A. H. C. (2004). Vibrotactile in-vehicle navigation system. *Transportation Research Part F: Traffic Psychology and Behaviour, 7*(4-5), 247-256.

Van Wolffelaar, P. C., & Van Winsum, W. (1992, 2-4 Sep 1992). *A new driving simulator including an interactive intelligent traffic environment.* Paper presented at the Proceedings of the 3rd International Conference on Vehicle Navigation and Information Systems,1992.

Veldstra, J., Bosker, W., De Waard, D., Ramaekers, J., & Brookhuis, K. A. (2015). Comparing treatment effects of oral THC on simulated and on-the-road driving performance: testing the validity of driving simulator drug research. *Psychopharmacology, 232*, 2911-2919.

Vera-López, J. D., Pérez-Núñez, R., Híjar, M., Hidalgo-Solórzano, E., Lunnen, J. C., Chandran, A., & Hyder, A. A. (2013). Distracted driving: Mobile phone use while driving in three Mexican cities. *Injury prevention, 19*(4), 276-279.

Verwey, W. B. (1993). *Further evidence for benefits of verbal route guidance instructions over symbolic spatial guidance instructions.* Paper presented at the Proceedings of the IEEE-IEE Vehicle Navigation and Informations Systems Conference, Ottawa, Ont, Can.

Victor, T. (2005). *Keeping eye and mind on the road.* (PhD Doctoral), Uppsala University, Uppsala.

Victor, T., Dozza, M., Bärgman, J., Boda, C.-N., Engström, J., Flannagan, C., . . . Markkula, G. (2015). *Analysis of naturalistic driving study data: Safer glances, driver inattention, and crash risk* (No. SHRP 2 Report S2-S08A-RW-1. 2015.)

Victor, T. W., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2), 167-190. doi:10.1016/j.trf.2005.04.014

Vrkljan, B. H., & Polgar, J. M. (2007). Driving, navigation, and vehicular technology: Experiences of older drivers and their co-pilots. *Traffic Injury Prevention, 8*(4), 403-410.

Waddell, L. P., & Wiener, K. K. K. (2014). What's driving illegal mobile phone use? Psychosocial influences on drivers' intentions to use hand-held mobile phones. *Transportation Research Part F: Traffic Psychology and Behaviour, 22*(0), 1-11. doi:http://dx.doi.org/10.1016/j.trf.2013.10.008

Wang, Y., Mehler, B., Reimer, B., Lammers, V., D'Ambrosio, L. A., & Coughlin, J. F. (2010). The validity of driving simulation for assessing differences between in-vehicle informational interfaces: A comparison with field testing. *Ergonomics, 53*(3), 404-420. doi:http://dx.doi.org/10.1080/00140130903464358

Warffemius, P. (2013). *De maatschappelijke waarde van kortere en betrouwbaardere reistijden*

Watson, J. M., & Strayer, D. L. (2010). Supertaskers: Profiles in extraordinary multitasking ability. *Psychonomic Bulletin and Review, 17*(4), 479-485. doi:http://dx.doi.org/10.1037/a0013119

Waugh, J. D., Glumm, M. M., Kilduff, P. W., Tauson, R. A., Smyth, C. C., & Pillalamarri, R. S. (2000, July 1, 2000). *Cognitive workload while driving and talking on a cellular phone or to a passenger.* Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2000. Prentice Hall, New Jersey.

Wegenverkeerswet par 1. art. 6. (1994). Retrieved from http://wetten.overheid.nl/BWBR0006622/2017-07-12#HoofdstukII_Paragraaf1_Artikel6

Wegman, F. C. M., & Aarts, L. T. (2006). *Advancing sustainable safety: National road safety outlook for 2005-2020*. Den Haag: SWOV

Westlake, E. J., & Boyle, L. N. (2012). Perceptions of driver distraction among teenage drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(6), 644-653.

White, K. M., Hyde, M. K., Walsh, S. P., & Watson, B. (2010). Mobile phone use while driving: An investigation of the beliefs influencing drivers' hands-free and hand-held mobile phone use. *Transportation Research Part F: Traffic Psychology and Behaviour, 13*(1), 9-20. doi:http://dx.doi.org/10.1016/j.trf.2009.09.004

WHO (2011). *Mobile phone use: A growing problem of driver distraction*. Retrieved from http://www.who.int/violence_injury_prevention/publications/road_traffic/distracted_driving/en/index.html.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical issues in ergonomics science, 3*(2), 159-177.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors, 50*(3), 449-455.

Wickens, C. D., Dixon, S., & Chang, D. (2003). *Using interference models to predict performance in a multiple-task UAV environment-2 UAVs*

Wickens, C. D., & Holland, J. G. (2000). *Engineering psychology and human performance, 3rd edition*. Upper Saddel River, NJ: Prentice-Hall 3.
Wickens, C. D., & Horrey, W. J. (2009). Models of attention, distraction, and highway hazard avoidance. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction - Theory, effects & mitigation* (pp. 57-67). Boca Raton: Taylor & Francis Group.
Wikipedia. (2015). Speedometer. Retrieved from http://en.wikipedia.org/wiki/Speedometer
Wilde, G. J. S. (1982). The Theory of Risk Homeostasis: Implications for Safety and Health. *Risk Analysis, 2*(4), 209-225. doi:http://dx.doi.org/10.1111/j.1539-6924.1982.tb01384.x
Wilde, G. J. S. (1988). Risk homeostasis theory and traffic accidents: propositions, deductions and discussion of dissension in recent reactions. *Ergonomics, 31*(4), 441-468. doi:http://dx.doi.org/10.1080/00140138808966691
Wilde, G. J. S. (1994). *Target Risk: Dealing with the danger of death, disease and damage in everyday decisions*. Toronto: PDE Publications.
Wilfinger, D., Murer, M., & Tscheligi, M. (2012). *Are 5 buttons enough: Destination input on touchscreen keyboards*, Portsmouth, NH.
Willis, K. S., Hölscher, C., Wilbertz, G., & Li, C. (2009). A comparison of spatial knowledge acquisition with maps and mobile maps. *Computers, Environment and Urban Systems, 33*(2), 100-110. doi:http://dx.doi.org/10.1016/j.compenvurbsys.2009.01.004
Witte, T. H., & Wilson, A. M. (2004). Accuracy of non-differential GPS for the determination of speed over ground. *Journal of Biomechanics, 37*(12), 1891-1898. doi:http://dx.doi.org/10.1016/j.jbiomech.2004.02.031
Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011). *The aligned rank transform for nonparametric factorial analyses using only anova procedures*. Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Vancouver, BC, Canada.
Wu, C. F., Huang, W. F., & Wu, T. C. (2009). A Study on the design of voice vavigation of car navigation system. In J. A. Jacko (Ed.), *Human-Computer Interaction, Pt Iii* (Vol. 5612, pp. 141-150). Berlin: Springer-Verlag Berlin.
Yan, X., Abdel-Aty, M., Radwan, E., Wang, X., & Chilakapati, P. (2008). Validating a driving simulator using surrogate safety measures. *Accident Analysis and Prevention, 40*(1), 274-288. doi:http://dx.doi.org/10.1016/j.aap.2007.06.007
Yanko, M. R., & Spalek, T. M. (2013). Route familiarity breeds inattention: A driving simulator study. *Accident Analysis & Prevention, 57*(0), 80-86. doi:http://dx.doi.org/10.1016/j.aap.2013.04.003
Young, K. L., & Regan, M. A. (2007). Driver distraction: A review of the literature. In I. J. Faulks, M. A. Regan, M. Stevenson, J. Brown, A. Porter, & J. D. Irwin (Eds.), *Distracted driving* (pp. 379-405). Sydney, NSW: Australasian College of Road Safety.
Young, K. L., & Regan, M. A. (2013). Defining the relationship between behavioural adaptation and driver distraction. In C. Rudin-Brown & S. Jamson (Eds.), *Behavioural adaptation and road safety: Theory, evidence and action* (pp. 207-225): Taylor & Francis Group.
Young, K. L., Regan, M. A., & Lee, J. D. (2009a). Factors moderating the impact of distraction on driving performance and safety. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver distraction - Theory, effects & mitigation* (pp. 335-351). Boca Raton: Taylor & Francis Group.
Young, K. L., Regan, M. A., & Lee, J. D. (2009b). Measuring the effects of driver distraction: Direct driving performance methods and measures. In M. A. Regan, J. D. Lee, & K.

L. Young (Eds.), *Driver Distraction - Theory, effects & mitigation* (pp. 85-105). Boca Raton: Taylor & Francis Group.

Young, K. L., Rudin-Brown, C. M., & Lenné, M. G. (2010). Look who's talking! a roadside survey of drivers' cell phone use. *Traffic Injury Prevention, 11*(6), 555-560.

Young, R. A. (2012a). The author responds. *Epidemiology, 23*(4), 649-650.

Young, R. A. (2012b). Cell phone use and crash risk: Evidence for positive bias. *Epidemiology, 23*(1), 116-118.

Young, R. A., & Schreiner, C. (2009a). Real-world personal conversations using a hands-free embedded wireless device while driving: Effect on airbag-deployment crash rates. *Risk Analysis, 29*(2), 187-204. doi:http://dx.doi.org/10.1111/j.1539-6924.2008.01146.x

Young, R. A., & Schreiner, C. (2009b). Response to Braver et al.: Response. *Risk Analysis, 29*(8), 1070-1071.

Zaidel, D. M., & Noy, Y. I. (1997). Automatic versus interactive vehicle navigation aids. *Ergonomics and safety of intelligent driver interfaces.* (pp. 287-307). Hillsdale, NJ England: Lawrence Erlbaum Associates, Inc.

Zajdel, R., Zajdel, J., Śmigielski, J., & Nowak, D. (2013). Cell phone ringtone, but not landline phone ringtone, affects complex reaction time. *International Journal of Occupational Medicine and Environmental Health, 26*(1), 102-112.

Zajdel, R., Zajdel, J., Zwolińska, A., Śmigielski, J., Beling, P., Cegliński, T., & Nowak, D. (2012). The sound of a mobile phone ringing affects the complex reaction time of its owner. *Archives of Medical Science, 8*(5), 892-898.

Zhao, N., Reimer, B., Mehler, B., D'Ambrosio, L. A., & Coughlin, J. F. (2013). Self-reported and observed risky driving behaviors among frequent and infrequent cell phone users. *Accident Analysis & Prevention, 61*, 71-77. doi:http://dx.doi.org/10.1016/j.aap.2012.07.019

Zijlstra, F. R. H. (1993). *Efficiency in work behaviour. A design approach for modern tools.* (PhD), PhD Thesis. Delft University of Technology, Delft.

Zijlstra, F. R. H., & Van Doorn, L. (1985). *The construction of a scale to measure perceived effort*

Samenvatting

De effecten van het gebruik van mobiele telefoons en navigatiesystemen tijdens het rijden

Autorijden is misschien wel de meest complexe taak die velen iedere dag uitvoeren. Bestuurders van auto's moeten letten op andere auto's, fietsers en voetgangers, tussen de "lijntjes" rijden en tegelijk zorgen dat ze op veilige afstand van hun voorligger blijven. Diverse factoren die te maken hebben met menselijk gedrag hebben invloed op de ongevalskans. Volgens de WHO (2015) zijn de belangrijkste risicofactoren snelheid, rijden onder invloed van alcohol, motorhelmen, autogordels en kinderzitjes, en afleiding in het verkeer. In veel landen is afleiding in het verkeer al benoemd tot beleidsprioriteit voor de komende jaren. Hoeveel deze afleiding precies de ongevalskansen vergroot is niet precies bekend, schattingen variëren van 10 tot 30% (TRL et al., 2015).

Dit proefschrift gaat in op afleiding als gevolg van het gebruik van mobiele telefoon of navigatiesysteem tijdens het rijden, en hoe dat de kwaliteit van rijden beïnvloedt. Vrijwel alle mobiele telefoons zijn tegenwoordig smartphones, met touchscreens, apps en e-mail. In de westerse wereld heeft vrijwel iedere automobilist een mobiele telefoon. Navigatiesystemen geven de autobestuurder aanwijzingen over hoe hij moet rijden om zijn bestemming te bereiken, wat leidt tot zowel efficiënte routes als een relatief comfortabele rit. Veel mensen gebruiken een navigatiesysteem, twee derde van de Nederlandse huishoudens bezit een draagbaar exemplaar (KiM, 2015).
De hoofdvraag van dit proefschrift is als volgt:
<u>Wat zijn de verkeersveiligheids- en efficiëntie-effecten van het gebruik van mobiele telefoons en navigatiesystemen tijdens het rijden?</u>

Een uitgebreid literatuuronderzoek gaf inzicht in de mogelijke classificaties, theorieën, methoden en maten die kunnen helpen bij het beantwoorden van de hoofdvraag. Het bleek bijvoorbeeld belangrijk om helder onderscheid te maken tussen verscheidene subtaken die horen bij het gebruiken van mobiele telefoons en navigatiesystemen, en de rijtaak zelf. Zo bestaan taken die horen bij mobiele telefoons en navigatiesystemen uit verschillende afleidingscategorieën: visueel, manueel, cognitief en auditief (zie bijvoorbeeld Ranney, Mazzae, Garrott & Goodman, 2000). Van visuele afleiding is bijvoorbeeld sprake wanneer een automobilist niet op de weg naar het verkeer kijkt, maar naar een vogel naast de weg of naar een boodschap op zijn telefoon. Manuele (of fysieke) afleiding ontstaat bijvoorbeeld wanneer de chauffeur iets uit het handschoenkastje pakt. Een autobestuurder is cognitief afgeleid als hij niet zijn aandacht bij het verkeer maar bij een telefoongesprek heeft, of wanneer hij dagdroomt. Auditieve afleiding kan te maken hebben met waarschuwingsgeluiden, zoals de melding van een bijna lege tank of een inkomend facebookbericht. Dit soort geluiden zijn moeilijk om te negeren. Ook hebben de categorieën veel met elkaar te maken. Het is bijvoorbeeld heel moeilijk om bij een waarschuwingsgeluid niet naar de bron van de melding te kijken om erachter te komen waar de melding voor was. Dit proefschrift onderscheidt daarom vier taken, die zich op verschillende manier verhouden tot de afleidingscategorieën: Het bedienen van de telefoon, het voeren van telefoongesprekken, het bedienen van het navigatiesysteem en het volgen van de routebegeleiding.

In theorie is het besturen van een auto een complexe taak, die veel inspanning vereist maar gemakkelijker wordt door ervaring. Operationeel is autorijden zoiets als voortdurend een bepaalde afstand houden tot objecten tijdens het bewegen in longitudinale en laterale richting. De bestuurder moet goed opletten en alle relevante binnenkomende informatie verwerken, en er op de juiste manier op reageren. Hoe goed iemand die taak uitvoert hangt volgens de theorie van Fuller (2005) af van de moeilijkheid van de taak en de capaciteiten van de bestuurder zelf. Zo kunnen mensen maar een bepaalde hoeveelheid informatie tegelijk verwerken, hoewel de één dat veel beter kan dan de ander, bijvoorbeeld doordat hij beter zijn best doet of door ervaring. Een belangrijke motivator voor sommige automobilisten is een zekere angst voor onverwachte gebeurtenissen, daarom zullen ze die angst binnen bepaalde grenzen willen houden. Dat heeft tot gevolg dat sommige bestuurders bereid zijn bepaalde afleidende taken te verrichten tijdens het rijden, terwijl anderen daar verre van blijven. Het voor dit proefschrift meest bruikbare theoretisch model was het zogenaamde taak-capaciteit-interferentie-model. Dit model beschrijft de interactie tussen de capaciteiten en motivaties van autobestuurders en de complexiteit van de rijtaak en de omgeving (Fuller, 2005). Het model houdt hierbij rekening met verschillende niveaus van taakuitvoering (strategisch, tactisch en operationeel, cf. Michon, 1985) en laat ruimte om afleiding door taken die naast de primaire rijtaak bestaan mee te nemen, door de moeilijkheid te verhogen.

Uit de literatuur blijkt een groot aantal methoden en maten die bruikbaar zijn en gebruikt worden om afleiding van de autorijtaak te bestuderen, ieder met zijn voor- en nadelen. De conclusie is dat er niet één perfecte methode bestaat, zoals anderen ook al opmerkten (bijvoorbeeld Carsten, Kircher & Jamson, 2013). De op te nemen maten hangen eigenlijk vooral af van de beschikbare budgetten en methoden. Maar ook van technische mogelijkheden, want het is bijvoorbeeld jammer genoeg niet goed mogelijk om in kaart te brengen wat de bestuurder precies denkt.

Uit de literatuur blijkt in het algemeen dat visuele afleidingen tijdens het rijden, bijvoorbeeld het kijken naar en bedienen van een telefoon of navigatie-systeem, vooral het sturen, i.e. de laterale controle aantasten. Cognitieve afleidingen, zoals het voeren van een telefoongesprek, hebben invloed op de reactietijd en afstand tot de voorligger, dus de meer longitudinale controle. Het afgelopen decennium is in de literatuur veel gediscussieerd over de effecten van telefoongesprekken op daadwerkelijke ongevalsrisico's. Hoewel de meeste mensen inzien dat het bedienen van apparatuur tijdens het rijden niet veilig is, doen veel automobilisten het toch.

Het vervolg van het proefschrift bestaat uit drie onderzoeken, waarin telkens dezelfde groep deelnemers terugkwam: 1. Een onderzoek in de rijsimulator waarin de effecten van de vier genoemde subtaken op het uitvoeren van de rijtaak centraal staan, 2. een validatiestudie die ingaat op de validiteit van de rijsimulator wat betreft de gekozen snelheid tijdens afgeleid rijden, en 3. een onderzoek dat middels de methode van *naturalistic driving* in kaart brengt hoe de deelnemers het navigatiesysteem gebruiken tijdens normale ritten.

In de rijsimulatorstudie namen 20 automobilisten deel die ervaring hadden met het gebruiken van mobiele telefoon en navigatiesysteem tijdens het rijden. De deelnemers reden twee keer in een rijk aangeklede gesimuleerde omgeving, terwijl ze al dan niet secondaire taken met betrekking tot de mobiele telefoon en het navigatiesysteem uitvoerden. De resultaten laten zien dat de meeste secondaire taken leiden tot een verlaging van de snelheid en dat de visueel-manuele taken (bedienen van telefoon en navigatiesysteem) daarnaast de blik van de weg haalden, met als gevolg een verslechterde laterale taakuitvoering. De resultaten van de telefoongesprekken lijken te suggereren dat bestuurders, door zorgvuldig te plannen, zouden kunnen compenseren voor de afleidende gevolgen van het gesprek door langzamer te gaan rijden. Een aanwijzing hiervoor is het feit dat zij op de weg kunnen blijven kijken, hoewel ze nog steeds bijvoorbeeld belangrijke verkeersborden kunnen missen. De studie gaf nauwelijks verschil tussen het rijden met een papieren kaart en het volgen van aanwijzingen van het navigatiesystem, hoewel de deelnemers aangaven zich minder in te spannen tijdens de taak met het navigatiesysteem.

De validatiestudie betrof de relatieve en absolute validiteit van de rijsimulator voor wat betreft de gemiddelde snelheid en de variatie van snelheid tijdens afleidende taken. Zestien deelnemers (van de eerdere twintig) reden twee keer een bepaalde route in het echt en dezelfde route ook twee keer nagemaakt in de rijsimulator. Tijdens het rijden voerden ze routetaken uit (met een papieren of een navigatiesysteem), en voerden ze telefoon-gesprekken. Het rijden tijdens deze taken en zonder de taken werd vergeleken voor zowel de rijsimulator als op de echte weg. Er was geen sprake van absolute validiteit, dat wil zeggen dat de metingen van gemiddelde snelheid zowel als de variatie in snelheid in de simulator niet dezelfde waarden gaven als op de echte weg. Wel was de richting van de effecten in alle experimentele condities telkens gelijk, wat duidt op relatieve validiteit. Dat betekent dat een verandering in de rijtaakuitvoering waar het gaat om de gereden snelheid tijdens afleidende taken goed met behulp van een rijsimulator onderzocht kan worden.

Aan de studie op de echte weg (naturalistic driving) namen 21 mensen deel. Deze zeven vrouwelijke en veertien mannelijke deelnemers waren ervaren gebruikers van een navigatiesysteem. Ze kregen voor ongeveer een maand lang een speciale auto mee. Hun ritten met die auto werden opgenomen door vier camera's, GPS en andere sensoren. De resultaten laten zien dat het navigatiesysteem in ongeveer 23% van de ritten aan stond, voornamelijk op de wat langere ritten die gedurende het onderzoek niet vaker werden gereden. Uit de cijfers bleken geen verschillen tussen ritten met en zonder navigatiesysteem in het percentage van de tijd dat boven de snelheidslimiet werd gereden. Tijdens ritten waarin het systeem aan stond interacteerden de bestuurders ongeveer 5% van de tijd met het navigatiesysteem, wat neerkwam op ongeveer 1% van de totale tijd van de ritten. Van de interacties vond 40% plaats in de eerste 10% van de duur van de rit, en tijdens ongeveer 35% van de interacties stond men stil of was de snelheid zeer laag (0-10 km/h). Dat suggereert dat hoewel de deelnemers het gebruik van het navigatiesysteem tot op zekere hoogte reguleerden, ze wel regelmatig risicovolle taken uitvoerden tijdens het rijden.

Alles overziend betekenen de resultaten dat

- Het bedienen van een mobiele telefoon of navigatiesysteem tijdens het autorijden de rijkwaliteit en voertuigcontrole verslechteren, wat leidt tot een grotere kans op een ongeval.
- De belangrijkste oorzaak van de verslechtering ligt in het feit dat de bestuurder fysiek niet in staat is om zowel op de weg als naar het apparaat te kijken.
- Het regelmatig voor komt voor dat automobilisten apparaten bedienen tijdens het rijden, en dit neemt toe.
- Het volgen van de route-instructies van het navigatiesysteem in het algemeen veilig en efficiënt is. Maar niet als het systeem ook tijdens het rijden bediend wordt.
- Een telefoongesprek tijdens het rijden negatieve effecten heeft op de rijkwaliteit (hogere taakbelasting, minder stabiele snelheid, lagere reactiesnelheid). Aan de andere kant passen bestuurders soms hun gedrag aan in de positieve zin (lagere snelheid, blik op de weg), wat tot op zekere hoogte kan compenseren voor de negatieve effecten.
- De kansen op een ongeval tijdens het al rijdend voeren van een telefoongesprek zijn groter dan tijdens gewoon rijden, maar vergelijkbaar met ongevalskansen tijdens bijvoorbeeld het bedienen van de klimaatregeling. Hiermee zijn de kansen van belang voor de wetenschap, maar mogelijk minder relevant in de praktijk en voor beleid.

Vanuit een verkeersveiligheidsperspectief zou met name iedere vorm van afleiding die de blik van de weg haalt moeten verminderen. Ook het gegeven dat voor de meeste telefoongesprekken een vorm van bedienen plaats moet vinden, vooral bij uitgaande gesprekken, en het feit dat stembediening nog niet perfect is, maakt het aanbevelenswaardig om ook telefoongesprekken tijdens het rijden te vermijden. Er zijn diverse manieren om te proberen het gedrag van automobilisten te veranderen, die vallen onder communicatie, wetgeving en handhaving, en technologie.

Voor de automobilist speelt naast veiligheid waarschijnlijk ook efficiëntie een rol. Dat leidt ertoe dat zij zich niet altijd aan de regels rond afleiding zullen houden, ondanks de inzet van de autoriteiten om het gedrag te veranderen. Dat is bijvoorbeeld ook te zien bij de enigszins vergelijkbare problematiek van rijden onder invloed; het mag sterk zijn afgenomen de afgelopen dertig jaar, maar het is zeker niet naar nul gedaald. Daarom, en naast het algemene advies om zich niet af te laten leiden, zouden bestuurders die toch hun telefoon of navigatiesysteem willen bedienen tijdens het rijden dat het beste kunnen doen als zij

- zoveel mogelijk op de weg (kunnen) blijven kijken
- in drukke en onvoorspelbare omstandigheden zo weinig mogelijk andere activiteiten hoeven te ondernemen
- het bij inkomende telefoongesprekken houden
- telefoongesprekken simpel kort houden.

Ook fabrikanten kunnen hier een grote rol in hebben. Om de prevalentie (en de risico's) van afleidende taken tijdens het rijden te beperken moeten die taken zo weinig en zo kort mogelijk zijn.

Summary

The effects of using mobile phones and navigation systems during driving
Driving might be the most complex task that many engage in on a daily basis. Drivers need to pay attention to other vehicles, cyclists and pedestrians, while keeping the car safely between the road markings and at an appropriate distance from any vehicle in front. Several factors relating to human behaviour affect the likelihood of someone being involved in a crash. The WHO (2015) distinguishes speed, drink driving, motorcycle helmets, seatbelts and child restraints, and distracted driving as the key risk factors. Many countries have put distraction as one of their policy priorities for the coming years. The precise impact of distracted driving on crash likelihood is not known yet. Estimates of road user distraction being a contributory factor in accidents range from 10 to 30% (TRL, TNO, & RappTrans, 2015).

This thesis focuses on drivers being distracted from mobile phones and navigation systems, and how their driving performance is affected. Mobile phones are predominantly smartphones nowadays, with touchscreens, downloadable apps and e-mail. Most drivers in Western countries own a mobile phone. Navigation systems may help the driver navigate, providing both efficient routes and comfort. Navigation systems are widely used, for instance in the Netherlands two third of all Dutch households own a portable navigation system in 2015 (KiM, 2015).
The general question overarching this dissertation is:
<u>What are the road safety and efficiency effects of using a mobile phone or a navigation system while driving?</u>

The literature was assessed elaborately in order to identify classifications, theories, methods and measures that may aid answering this question. It appeared important to disentangle the several different tasks involved in mobile phones, navigation systems, and the driving task itself. The mobile phone and conversation tasks consist of several distraction categories: visual, manual, cognitive and auditory (see e.g. Ranney et al., 2000). Drivers are visually distracted when they are not monitoring traffic, for instance when looking at their phone, or watching a bird next to the road. Manual (or biomechanical) distractions occur for instance when grabbing something from the glove department. Drivers may be cognitively distracted in case of a phone conversation, or simple daydreaming. Auditory distractions may stem from a warning sound (i.e. an empty fuel tank warning or a Facebook update beep), that is difficult to ignore. The categories are closely connected. An empty fuel tank warning sound may well be followed by a glance at the dashboard to assess what the sound was for. Therefore, this thesis distinguishes four main tasks, each relating to a set of distraction categories: Operating mobile phones, having phone conversations, operating the navigation system and following the navigation system's instructions.

The theory argues that driving a car is a complex task, that requires a lot of effort but becomes easier with experience. Operationally, driving may be described as keeping a certain distance from objects while making both longitudinal and lateral movements. The driver needs to be aware of the situation and he should process all relevant incoming information and react accordingly. How the driver performs the driving task depends on both the task difficulty and the driver's capabilities (Fuller, 2005). That is, most drivers can only process so much information at a time, but some perform better than others, for instance because of experience or exerted effort. Drivers may even by and large be motivated by feelings of fear for inadvertent events. They may try to maintain their feelings of risk within certain limits, which makes some drivers perform certain distracting activities while driving, while others refrain from doing so. The theoretical model that appeared most useful for the topic of this thesis was Fullers Task-Capability Interference model (2005). This model describes the interaction between drivers' capabilities and motivations as well as the complexity of the driving task and the environment. Furthermore, the model incorporates different levels (i.e., the strategic, tactical and operational, cf. Michon, 1985) and is able to involve distractions from tasks secondary (or tertiary) to the driving task thereby increasing the difficulty.

From assessing the literature for the best method to apply and measures to record when studying driver distraction, it became clear that a large variety of methods and many measurements may be used and have been applied. Each method has its pros and cons, and the conclusion is that no single perfect method exists, as noted by others (i.e., Carsten et al., 2013). When it comes to measures, the measures one should record depend heavily on the resources available as well as the method chosen. Unfortunately, it remains impossible to validly assess what the driver is thinking.

The literature showed that in general, visually distracting tasks, such as operating mobile phones and navigation systems, affect steering and lateral control. Cognitive distractions, including phone conversations, affect longitudinal control, in terms of reaction time and keeping distance to the car ahead. In the last decade, the effects of having phone conversations during driving have been the topic of widespread discussion. Although most people do realise that most of the time it is unsafe to operate devices while driving, still many drivers continue to do so.

Next, three studies were conducted that all included the same participants: 1. A driving simulator study that assessed the effects of the four subtasks identified on driving performance, 2. a validation study that assessed the validity of the driving simulator regarding distracted driving speed, and 3. a naturalistic driving study, that assessed how and when the participants used their navigation system in real driving.

The driving simulator study was used to investigate how experienced user's driving behaviour is affected by performing other tasks. 20 participants drove twice in a rich simulated traffic environment while performing secondary, i.e. mobile phone and navigation system tasks. The results indicate that most secondary tasks lead to a decrease in driving speed, while visual-manual tasks (i.e., operating either the navigation system or a mobile phone) additionally takes drivers' eyes of the road, deteriorating lateral performance. Regarding the results of the mobile phone conversations per se, it seems reasonable to suggest that drivers, through careful planning, may well be able to compensate for the distracting effects of the conversation by slowing down. The fact that they are able to keep their eyes on the road may be indicative of this, though the fact that distraction prevents them from noticing relevant signs is looming continually. The study revealed hardly any differences regarding driving with a paper map or with a navigation system, except for a lower rating in effort for driving with the navigation system.

The relative and absolute validity of the driving simulator were assessed regarding effects on mean speed and speed variation during distracting secondary tasks, and normal driving. Sixteen participants drove the same route four times, twice simulated, in the driving simulator and twice in the real world. They performed way finding tasks, using either a paper map or a route guidance system, and mobile phone conversation tasks. Furthermore, driving without secondary tasks on other road segments in the two methods was compared. As both mean speed and standard deviations of speed were not equivalent, absolute validity could not be established. However, as effects found in the experimental conditions varied in the same directions, evidence for relative validity was provided. It was concluded that driving performance regarding speed under distracting conditions may validly be investigated in the driving simulator employed.

In the naturalistic driving study, 21 experienced users of navigation systems, seven female and fourteen male, were provided with a specially equipped vehicle for approximately one month. Their trips were recorded using four cameras, GPS data and other sensor data. The results show that the navigation system was activated for 23% of trips, predominantly on longer and unique trips. Analyses of the percentage of time for which the speed limit was exceeded showed no evidence of differences between trips for which the navigation system was used or not used. On trips for which the navigation system was activated, participants spent about 5% of trip time interacting with the device, for total trip time this was 1%. About 40% of interacting behaviour took place in the first 10% of the trip time, and about 35% took place while the car was standing still or moving at a very low speed, i.e. 0-10 km/h. The results suggest that although drivers regulate their use of such systems to some extent, they regularly perform risky tasks while driving.

Overall, the results imply that

- Operating any device during driving deteriorates driving performance considerably in terms of vehicle control, thus increasing the risk of crashing.
- The main cause for this deterioration is the fact that the driver is physically unable to watch both a device and the road simultaneously.
- It is not uncommon, henceforth increasingly common that drivers operate devices during driving.
- Following route guidance advice by a navigation system is generally safe and efficient. However, the route should not be programmed or altered while driving.
- Having a phone conversation during driving negatively affects driving performance (higher task demand, less stable speed keeping, reduced reaction time). However, drivers may also adapt their behaviour positively (lower speed, more on-road glancing), which to some extent may compensate the negative effects.
- Odds ratios for talking on the phone while driving, though increasing risk, were comparable to effects of operating the in-vehicle climate control (Dingus et al., 2016), hence they are scientifically important, but for policy and practice probably less relevant.

From a road safety perspective it would be best to try to diminish distracted driving that involves glancing off road in the first place. Considering the fact that phone conversations often require some manual operating, particularly in case of outgoing calls, and voice control does not (yet) overcome all troubles, it seems recommendable to include phone conversations in the attempt to avoid distraction. Driver behaviour may be changed using several instruments, ranging from technology to communication, legislation, and enforcement.

From a driver's perspective, efficiency may remain an motivation, which implies that they still disregard the rules regarding distracted driving in spite of authorities' attempts to change drivers' behaviour. After all, the comparable act of drunk driving may have diminished in the past 30 years, but certainly not to zero. Therefore, next to the general advice not to engage in distractions while driving, drivers who choose to operate phones or navigation systems or have phone conversations would be better off if they

- Try and keep their eyes on the road as much as possible
- Try and refrain from distracting activities in unpredictable traffic situations such as built-up areas
- Try and keep phone conversations limited to incoming calls only.

Manufacturers could also play an important role to avoid distraction. In order to minimise prevalence (and thus risk), the non-task related activities that drivers perform during driving should be as few and as short as possible.

About the author

Allert Sake Knapper was born in Assen on June 18th in 1983. He went to school in Assen and later in Groningen, where he obtained his athenaeum diploma from Gomarus College in 2001. He studied psychology at the University of Groningen, graduating in 2008.

Since 2009, Allert has been affiliated with Delft University of Technology, with the Transport and Logistics group at the Faculty of Technology, Policy and Management, and later also with the Transport and Planning department of the Faculty of Civil Engineering and Geosciences, conducting his PhD research. In 2010, Allert was detached to SWOV, to collaborate on the European project INTERACTION, in order to synergise with his own PhD research. Allert has been involved in several teaching activities and was a member of the TRAIL PhD Council.

In 2013, he started at the Ministry of Social Affairs and Employment, as a financial policy officer. Since 2018 he works at the Ministry of Finance, where he now leads the project www.Rijksfinancien.nl and is still involved in scientific research, but now related to public finance .

SWOV-Dissertatiereeks

In deze reeks zijn eerder verschenen:

Jolieke Mesken (2006). *Determinants and consequences of drivers' emotions.*

Ragnhild Davidse (2007). *Assisting the older driver: Intersection design and in-car devices to improve the safety of the older driver.*

Maura Houtenbos (2008). *Expecting the unexpected: A study of interaction behaviour at intersections.*

Frits Bijleveld (2008). *Time series analysis in road safety research using state space methods.*

Saskia de Craen (2010). *The X-factor; A longitudinal study of calibration in young novice drivers.*

Atze Dijkstra (2011). *En route to safer roads; How road structure and road classification can affect road safety.*

Charlotte Bax (2011). *Processes and patterns; The utilisation of knowledge in Dutch road safety policy*.

Willem Vlakveld (2011). *Hazard anticipation of young novice drivers; Assessing and enhancing the capabilities of young novice drivers to anticipate latent hazards in road and traffic situations.*

Sjoerd Houwing (2013). *Estimating the risk of driving under the influence of psychoactive substances.*

Henk Stipdonk (2013). *Road safety in bits and pieces; for a better understanding of the development of the number of road fatalities.*

Paul Schepers (2013). *A safer road environment for cyclists.*

Divera Twisk (2014). *Protecting pre-license teens from road risk; Identifying risk contributing factors and quantifying effects of intervention strategies.*

Dafne Piersma (2018). *Fitness to drive of older drivers with cognitive impairments.*

Agnieszka Stelling-Kończak (2018). *Cycling safe and sound; The impact of quiet electric cars, listening to music and conversing on the phone on cyclists' auditory perception and cycling safety*.