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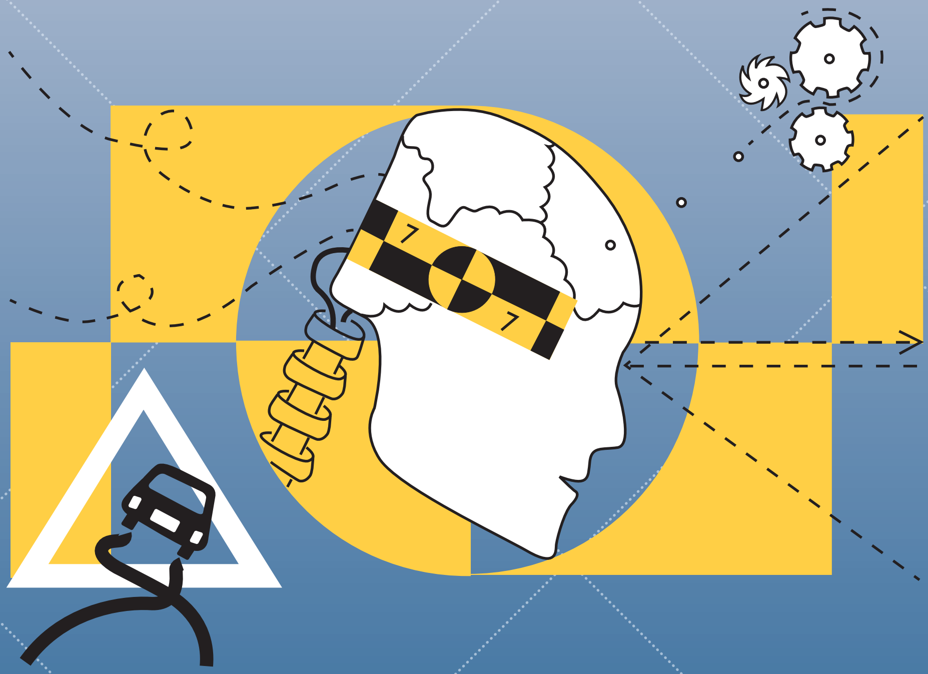

Driving Behaviour in Unexpected Situations

A study into drivers' compensation behaviour to safety-critical situations and the effects of mental workload, event urgency and task prioritization

DRIVING BEHAVIOUR IN UNEXPECTED SITUATIONS

A STUDY INTO DRIVERS' COMPENSATION BEHAVIOUR TO SAFETY-CRITICAL SITUATIONS AND THE EFFECTS OF MENTAL WORKLOAD, EVENT URGENCY AND TASK PRIORITIZATION

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Contents

INTRODUCTION **1**
1.1 Context 3
1.2 Research questions and scope 5
1.3 Scientific and societal relevance 8
1.3.1 Scientific relevance 8
1.3.2 Societal relevance 10
1.4 Outline of the thesis 11

THEORETICAL FRAMEWORK **13**
2.1 Complexity of the driving task 15
2.2 Descriptions of driving and drivers 17
2.2.1 Hierarchical model of the driving task (Michon, 1971, 1985) 19
2.2.2 Models related to Michon's (1971, 1985) hierarchical model of the driving task 22
2.2.3 Switching between automatized driving and conscious control 24
2.2.4 Models of risk handling 27
2.3 Traffic safety measures 29
2.4 Multi-tasking, distraction and mental workload while driving 32
2.4.1 Multi-tasking 32
2.4.2 Driver distraction 33
2.4.3 Mental workload 36
2.4.4 Distraction and mental workload: bearing resemblance but not the same 39
2.5 Situation awareness 41
2.6 Advanced Driver Assistance Systems and behavioural adaptation 43
2.6.1 Different types of ADA Systems 43
2.6.2 Behavioural adaptation 45
2.6.3 Human-centred design and development of ADA Systems 46
2.7 Framework 47

RESEARCH TOOLS **49**
3.1 Measuring driving behaviour 51
3.1.1 Instrumented vehicles: road and test tracks 52
3.1.2 Driving simulator 53
3.1.3 Self-report measures 54
3.2 Mental workload measurements 55
3.2.1 Primary task performance 55
3.2.2 Secondary task performance 57
3.2.3 Subjective measures 59
3.2.4 Physiological measures 59
3.2.5 Combining measures of mental workload 60
3.3 Driver characteristics 60
3.4 Research tools used in this thesis 61
3.4.1 Experimental tools 62
3.4.2 Calculation of variables from raw data 64
3.4.3 Statistical analysis for both experiments 65

EXPERIMENT 1: DRIVERS' REACTIONS TO UNEXPECTED EVENTS 67

4.1 Research tools 69
4.2 Participants 70
4.3 Experimental design 70
4.4 Procedure 74
4.5 Data registration and analysis 75
4.6 Results 75
4.6.1 Validation of research construct and setup 76
4.6.2 Differences between trials: within-subject effects on driving behaviour 84
4.6.3 Effects of between-subjects factor: mental workload conditions 86
4.6.4 Effects of the unexpected events: a closer look 88
4.7 Interpretation of results and additional hypotheses 97
4.7.1 Overview and interpretation of results 97
4.7.2 Hypotheses for final experiment 99
4.8 Consequences of current experimental setup for results and lessons learned 100
4.8.1 Layout of virtual environment 100
4.8.2 Programming of unexpected events 101
4.8.3 Programming of lead car's speed choice 101
4.8.4 Data recording 102
4.8.5 Modifications on experimental setup for final experiment - lessons learned 102

EXPERIMENT 2: EFFECTS OF UNEXPECTED BRAKING EVENTS UNDER VARYING MENTAL WORKLOAD CONDITIONS 105

5.1 Hypotheses 107
5.2 Research tools 107
5.3 Participants 108
5.4 Experimental design 109
5.5 Procedure 112
5.6 Results 113
5.6.1 Construct validity and setup 114
5.6.2 Effects of the braking event on driving behaviour 117
5.6.3 Effects of varying mental workload on driving behaviour 132
5.6.4 Interaction effects: braking, urgency and level of mental workload 136
5.7 Overview of results 142
5.8 Discussion of experimental setup 143
5.8.1 Criticality levels and number of unexpected events 143
5.8.2 Effect sizes 143
5.8.3 Motion sickness 144

DISCUSSION 145

6.1 Recapitulation: an overview of relevant results 147
6.1.1 Experiment 1: initial hypotheses 147
6.1.2 Experiment 2: additional hypotheses 148
6.1.3 Possible under- or overestimation of results 151
6.1.4 Differences explained 152
6.2 Interpretation of results 154
6.2.1 Mental workload and the driving task: dynamic vs steady-state situations 154
6.2.2 Michon's (1971, 1985) hierarchical model of the driving task 156
6.2.3 Task prioritization 159
6.2.4 Conscious control versus driving in an automatic fashion 160
6.2.5 Risk handling 162
6.3 Design considerations for ADA Systems 163

CONCLUSIONS **167**
7.1 Context and research questions 169
7.1.1 Research questions 169
7.1.2 Research approach 170
7.2 Findings: Reactions to unexpected, safety-critical events 170
7.2.1 Compensation behaviour and driving style 170
7.2.2 Task prioritization 171
7.2.3 Automatized driving versus conscious control over the driving task 172
7.3 Reflections on theoretical framework 172
7.3.1 Latent driver distraction and mental workload 172
7.3.2 The hierarchical model of the driving task 173
7.4 Human-centred design of ADA Systems 174
7.5 Recommendations for further research 175

REFERENCES **177**

APPENDICES **191**
A.1 Annotated code for the first experiment 193
A.2 Annotated code for the final experiment 195
B.1 Instructions for the first driving simulator experiment (in Dutch) 197
B.2 Instructions for the final driving simulator experiment (in Dutch) 198
C.1 Questionnaire for the first driving simulator experiment (in Dutch) 200
C.2 Questionnaire for the final driving simulator experiment (in Dutch) 202
D.1 Detailed results for the first driving simulator experiment 205
D.2 Detailed results for the final driving simulator experiment 207

DRIVING BEHAVIOUR IN UNEXPECTED SITUATIONS: SUMMARY **209**

RIJGEDRAG IN ONVERWACHTE SITUATIES: SAMENVATTING **215**

DANKWOORD **221**

ABOUT THE AUTHOR **225**

TRAIL THESIS SERIES **227**

Chapter 1

Introduction

Driving in urban areas can be challenging for drivers, especially when they are engaged in tasks outside their primary task of driving. The studies described in this thesis are concerned with drivers' responses to safety-critical situations in these demanding circumstances. The thesis relates switching from normal driving to compensating for a safety-critical event to the hierarchical model of the driving task, which was first presented by Michon in 1971. The current chapter describes the context of the research performed, points out the relevance of the results in the light of existing theories and gives an outline of the remainder of this thesis.

1.1 Context

Since cars were first introduced, the number of vehicles on the road has dramatically increased. In 1985 less than 4.5 million vehicles were registered in the Netherlands. By the beginning of 2010 this number had risen to 7.6 million (CBS, 2010). With this growing number of vehicles on the road and the corresponding increase in vehicle interaction, traffic safety has become an issue of growing concern. In addition to this concern with safety, we also want our transport system to be efficient, reliable and sustainable as well as having a high throughput and making both our cities and rural areas accessible. Whereas these characteristics may sometimes reinforce each other, at other times they compete for policy priority.

While researchers, governments and others concerned with transport systems are facing the challenge of dealing with conflicting goals and assigning priority to different aims, so do the actual people driving the cars that make up the system. They can even have conflicting roles to play while driving. For instance, is a mother with a crying baby in the back seat of her car a driver, or firstly a mom? Is the man with a sudden heart attack a driver, or primarily a patient? And the entrepreneur who is on his way to a crucial meeting on a huge merger, what is his primary role? An interesting discussion on a number of such philosophical questions related to drivers' roles and responsibilities is presented by Hancock, Mouloua and Senders (2008).

With innovation and technology advancing, a variety of Advanced Driver Assistance (ADA) Systems, such as collision avoidance systems, congestion assistants or curve speed warning systems, have been developed to assist in performing the complex driving task. Until these ADA Systems have developed into fully automated Autonomous Driving Systems, the human driver remains the determining element in transport systems and with that an important topic in traffic research.

As early as 1962 Sir Frederik Bartlett predicted that the increasing influence of Information Technology and development in human skills would greatly change our daily lives (Bartlett, 1962). More recently, Brookhuis (2008) asserted that in the coming years the increase in information availability will increasingly dominate and change our world, especially so in the transport system (Brookhuis, 2008). A thorough study of human drivers and the peculiarities of their driving behaviour is needed in support of further developments. This thesis focuses on a part of such a study. That is, the way in which drivers react to unexpected and risky situations and how various characteristics of the driver and the environment influence such reactions.

This thesis is focused on the subject of driving behaviour and its link with traffic safety. For the purpose of this thesis an urban environment was chosen to study driver behaviour because of the complexity of the driving task in such an environment. Cities pose numerous challenges such as high traffic complexity, low air quality, increasing congestion and reduced safety, due to the complexity of the infrastructure and the large density and variety of road users and their varying speeds.

Over the last few years, the development of ADA Systems has gained strong momentum, partly due to the increased availability of new technologies and the further development of existing systems, including more sensitive sensors, smaller and more powerful computer chips and more advanced communication technology. The systems that are currently being developed range from fully autonomous to communicating and cooperating systems, such as automated highway systems (for automatically creating platoons on highways) to navigation for recreational routes or emissions reduction and warning systems for obstacles outside the driver's direct line of sight. Whereas the development of ADA Systems is being pushed by rapid technological developments, it is very important to look at what the driver actually needs. Results from different studies indicate that drivers do not always respond in a predictable way to the introduction of new systems in their vehicles (e.g., Adell, Várhelyi & Dalla Fontana, 2011; Dragutinovic, Brookhuis, Hagenzieker & Marchau, 2005). An expert group of the Organisation for Economic Cooperation and Development defined behavioural adaptation as "*those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change*" (OECD, 1990, p.23). Drivers have indeed been shown to alter parts of their driving actions in response to the changed driving task. The changes associated with this adaptation depend on the type of support given, the supported task, and the hierarchical level (strategic, tactical or operational) at which this task is situated (Saad, 2006). Among the concerns in research into behavioural adaptation are drivers' limited abilities to take control for the tasks that are not supported (Saad, 2006). This advocates an integrated design of ADA Systems. It is important to look at driver's needs and normal driving behaviour to understand how ADA Systems can make driving safer, more comfortable and more environmentally friendly.

This thesis studies the execution of the driving task in safety-critical situations in an urban environment. The model of the driving task that Michon developed in 1971 and elaborated upon in 1985 is used as basis for studying and interpreting driving behaviour. The model breaks down the driving task into three hierarchically ordered levels. At the highest level, the strategic level, the driver plans the trip in terms of itinerary, time of arrival, etc. One level below, the tactical level, deals with choices and actions related to the interaction with the road and other road users, such as keeping distance, taking a turn and changing lanes. The lowest operational level involves the interaction with the vehicle controls and the perception of the environment. Subtasks such as turning the steering wheel, pushing the throttle and looking at a road sign are included in this operational level. In Michon's (1971) model the three task levels are strongly linked. Choices are made top-down in normal driving behaviour: actions at a higher level dictate the kind of information that enters the adjacent lower level, and determine if and how the actions at that level should be undertaken.

However, this top-down interaction does not always dictate driving behaviour. In unexpected situations a driver sometimes needs to compensate in order to return to a safe or desired situation. Take the example of driving on a slippery road. In normal, top-down driver behaviour, the desired speed determines the angle at which the throttle is pushed downward. On a slippery road however, the direction of the vehicle might deviate from the desired direction. The driver has to act quickly to stay on the road, regardless of the itinerary, desired speed and other elements on the strategic level. This compensation behaviour is directed bottom-up, resulting in a temporary directional switch in task level interaction.

Driving behaviour is determined by the characteristics of the driving task and by a variety of external factors. One important factor is mental workload. A number of different definitions of mental workload exist, some of which will be discussed in more detail in Chapter 2. Throughout this thesis the definition as proposed by De Waard (1996) is used. This definition reads: "*Mental workload is the specification of the amount of information processing capacity that is used for task performance*". De Waard (1996) describes how mental workload depends on the combination of task demands (what does the driver need to do), the available information processing capacities (how much can the driver handle), and the effort invested (how much energy is the driver willing to invest in task performance). Mental workload is highly related to driving behaviour and the driving task through these aspects. Firstly, task demands can increase or decrease according to the situation and the pursued goals, and this change can even present itself in a time frame of milliseconds. Or as others have put it: "Driving is hours and hours of boredom intermixed with moments of terror" (Boudreau, 2009). Although this statement is a somewhat exaggerated representation of reality, it does illustrate how quickly task demands can change. During long stretches of time, driving can consist of sequences of well-learned actions that can be performed almost automatically. But these situations can suddenly, sometimes without warning, turn into events that require the driver's full attention and quick compensation in order to avoid serious conflicts or even accidents. Whereas the latter situation can bring about a high level of mental workload, automatically performed action patterns may have very low task demands, leading to situations in which it may be difficult to sustain a high level of attention. This is related to the second aspect determining mental workload: human information processing capacities. These capacities are different according to the driver's state. For example, after a good night of sleep drivers are generally more alert with the capability of handling a higher task load than after a night of dancing and drinking. Finally, the driver can invest more energy in performing the task at hand, leading to a sustained task performance at the cost of increased workload.

1.2 Research questions and scope

This thesis deals with driving in unexpected, safety-critical situations and the related possible switch from normal top-down influence to bottom-up influence between driving task levels. It also examines whether and how the severity of the situation influences this directional change in task level interaction. Does a more severe situation for instance lead to faster, stronger or more prolonged compensational behaviour? This research furthermore aims to determine to what extent the hierarchical model of the driving task (Michon, 1971, 1985) could also be used as a predictive tool, describing the actions of drivers in specific situations. For practical reasons, related to the discrepancy between studying naturalistic choices regarding trips goals, trip mode and route on the one hand, and controlling or even repeating certain safety-critical events that may occur during driving on the other hand, we focus only on the operational and tactical levels of Michon's model. Chapters 3 and 4 will elaborate on these decisions regarding research tools and experimental setup.

Moreover, the influence of elevated mental workload on driving behaviour in these unexpected situations is examined. Will an increase in mental workload bring along a more intense or a longer-lasting reaction of the compensatory behaviour after such an event? Or could there be a threshold above which bringing the situation to a safe end demands so much attention that attentive compensation decreases? The effects of drivers' basic demographic characteristics (age, gender) and driving experience on the aforementioned results are also examined.

Finally, some ambiguity sometimes occurs in studies focussing on mental workload and/ or driver distraction, two distinct concepts that appear to have some resembling features. This thesis describes the similarities and distinctions between the two concepts in an attempt to clarify the relationship between driver distraction and mental workload.

The hypotheses which are at the basis of the studies described in this thesis are derived from the hierarchical model of the driving task as was first described by Michon (1971), and later adapted by the same author (Michon, 1985). This hierarchical model states that the driving task is comprised of multiple subtasks which can be categorized into three task levels. When a journey is planned and executed, drivers execute subtasks of driving at the different task levels from the upper, strategic level, through the middle tactical level down to the operational level, successively. Figure 1.1 shows this hierarchical interaction, which is presumed to take place in normal driving.

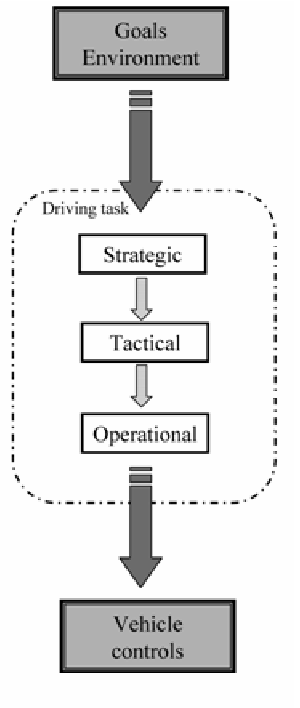

Figure 1.1 Hierarchical model of the driving task, as proposed by Michon (1971); the three levels of the driving task are hierarchically ordered with top-down level interactions

In 1985, Michon hypothesized that not only the top-down interaction between the hierarchically ordered levels could be present in driving, but that bottom-up influence might also be possible, as “goals may occasionally be adapted to fit the outcome of certain maneuvers” (Michon, 1985, p. 490). In other words, bottom-up influence between task levels is an option in unexpected situations requiring compensation. Such situations could for instance be: driving on a slippery road (compensation needed on operational level); a road block (compensation needed on tactical level); or an unexpected manoeuvre from another road user (compensation needed on either the tactical or the operational level, depending on the type of compensation needed). Figure 1.2 shows the hierarchical model with the extension of bottom-up interaction between the three levels. It should be noted here that task levels also have internal feedback loops: tasks at the three levels are continuously adjusted and controlled according to cues from the environment.

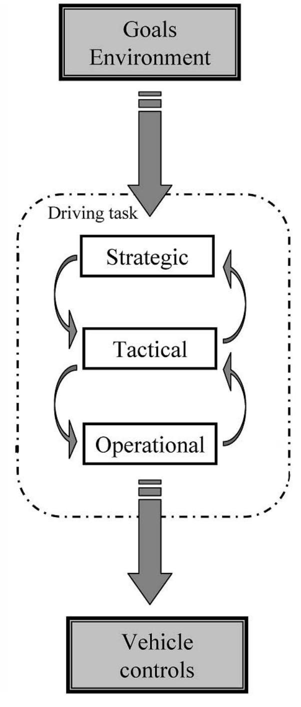

Figure 1.2 Directional change from top-down to bottom-up influence between the operational and tactical level of the driving task - it is presumed that this directional change happens in unexpected situations requiring compensation (adapted from Michon, 1985)

The research described here aims to increase the understanding of driving in safety-critical situations in an urban environment. The research questions are as follows:

- How do drivers respond to unexpected, safety-critical events while driving in an urban environment?
- How do the results relate to the framework presented by the hierarchical model of the driving task (Michon, 1971, 1985)?
- To what extent does the urgency of the event influence this response?
- To what extent does the level of mental workload exert an influence on this reaction?
- To what extent do drivers' basic demographic characteristics, such as gender or age, influence this reaction?
- What is the relationship between the findings in our studies and previous studies done into driver distraction, mental workload, risk handling and other human factors in driving?
- What is the relationship between mental workload and driver distraction?
- Which recommendations can be made for the development of safe ADA Systems?

As with any other study, the scope of this research is limited:

- Only passenger cars were studied. Passenger cars make up for the largest part of the traffic population, with 7.6 million Dutch passenger cars (CBS, 2010) accounting for almost 75% of all vehicle kilometres driven on Dutch roads in 2010 (KiM, 2011). Furthermore, passenger cars were involved in 81% of the accidents on Dutch roads in 2005 (SWOV, 2010).
- The scope of our research is furthermore limited by the fact that the drivers were not supported by any support system while driving. We focus on unsupported driving behaviour, and will discuss the implications of the findings for the development of driver support systems at the conclusion of this work.
- The focus of the research is on driving at urban intersections. These are complex situations which are very demanding for drivers, and at which all three levels of the driving task are relevant simultaneously (see also Sections 2.1 and 2.2.1). We imposed a simplified set of traffic rules for the experimental setting, including a speed limit of 50 km/h for all urban areas and right of way for traffic coming from the right.
- We studied driving behaviour of experienced, regular drivers. This excludes drivers who had their driver’s licence for less than five years (novice drivers), drivers over 60 years of age (elderly drivers), and drivers without an appropriate share of on-road experience (inexperienced drivers). These groups have their own characteristics, challenges and behaviours, and including these characteristics does not necessarily comply with answering our research questions.

1.3 Scientific and societal relevance

The research presented in this thesis contributes to the existing knowledge of driving behaviour in risky situations, and the influence of mental workload and event circumstances. The main contributions can be summarized as follows.

1.3.1 Scientific relevance

This thesis describes driving behaviour in risky situations in urban environments. It relates drivers’ behaviour in these situations to the hierarchical model of the driving task by Michon (1971, 1985). This link between (theoretical) task description and (practical) task execution gives insight into both theoretical and actual goal management of drivers, and into task execution in different circumstances.

The hierarchical model of the driving task has been presented a few decades ago and has been adopted widely among human factors researchers and modellers since to represent the driving task (e.g., Bekiaris, Amiditis & Panou, 2003; Fuller, 2005; Van der Molen & Botticher, 1988; Ranney, 1994). Michon (1985) proposed to use the model as a framework for a comprehensive driver model that would incorporate cognition through knowledge and rules and would be capable of dealing with a wide variety of realistic, complex situations (Michon, 1985). Few researchers have tried to test the implications of this framework for human task execution in real driving situations. Specifically the supposed switch between top-down task level interactions to bottom-up interactions has remained underexposed in both literature and experimental settings. Some researchers suggest that there is no such thing as a directional switch between top-down and bottom-up interaction but more so a distinction between feedback and feed-forward control, and that goals and intentions are continuously revised (e.g., Hollnagel & Woods, 2005). However, the overall framework and the proposed switch between the two directions of influence between task levels has, to our knowledge, not been put to the test of actual driving behaviour.

On the one hand, this thesis tries to explore the boundaries of the possible applications of the hierarchical model of the driving task. On the other hand, it also aims to broaden the knowledge of driving behaviour and the ways in which different circumstances influence goal management in drivers.

The research specifically focuses on driving at urban intersections. Driving in this demanding and complex traffic situation is different from highway driving in a number of ways. First, multiple task levels are relevant simultaneously, leading to a complex situation of competing tasks and goals. Second, certain aspects of urban infrastructure are more complex than in highway situations, adding to task demands. For instance, there are intersections, at which different roads cross each other, different traffic lanes for different types of road users (e.g., bike lanes, bus lanes), and the many side streets lead to more options for route choice than on most highways. And finally, rural roads and especially motorways carry rather homogenous traffic flows consisting mainly of motor vehicles. However, urban roads have a large variety of road users such as cars, trucks, cyclists, motorcyclists, and pedestrians, all sharing the road especially at intersections. This mixed equipage and mixed user group demands focussed attention, anticipation and a high level of situation awareness. To add to these demanding circumstances, we presented safety-critical situations to drivers, and measured their driving performance and behavioural reactions to these situations. Insight into drivers' reactions in these especially demanding situations gives insight into task prioritization, goal management, effort investment, and risk handling. These are all abstract but highly relevant concepts, which need to be considered when studying driving behaviour. The results from the present study provide new insights into task prioritization in demanding circumstances. They furthermore add to the existing theories of risk handling by determining how drivers respond to changing risk levels in multi-task conditions.

Moreover, the thesis reflects on the relationship between driver distraction and mental workload. These are two constructs that are closely related, but that are affected by different aspects of the driving situation and may also have different effects on driving performance. Since their effects on driving performance are potentially very different, it is important to know what to measure when, and how to explain the effects found. We contribute to this debate with a discussion of the differences and similarities between the two concepts of driver distraction and mental workload. The thesis introduces the concept of latent driver distraction, a form of driver distraction that does not materialize in measurably unsafe driving behaviour, but that does impair being able to respond adequately to upcoming safety-critical situations. It furthermore brings up the practice that evidence for increased mental workload is often used as a direct indication of all types of driver distraction. However, measurements should focus on the type of driver distraction that is measured, instead of translating an increase in one of the constructs into a supposed increase in the other construct. Therefore, the relationship between mental workload and driver distraction is also made explicit.

Finally, the research presented in this thesis is related to the human centred design of Advanced Driver Assistance (ADA) Systems. ADA Systems represent a promising way to support drivers in their task, and might bring about important changes in the approach to traffic safety issues. They can furthermore relieve the driver of parts of the relevant tasks from the driver, increasing comfort or safety. The development process of ADA Systems can have different starting points. One could start from available technology, from what drivers want, or from what drivers need. This study focuses on the latter starting point, the human-centred, behaviour based design of ADA Systems. Such behaviour based design not only entails complying with ergonomic design principles, it also means keeping track of the relevant issues that drivers encounter while driving, and thus of driver needs. This study seeks to bridge the knowledge of cognitive and psychological processes and technological advancements. Before truly human-centred design is a viable option, more knowledge and understanding of driver needs and the effects of cognitive aspects of driving on task performance is needed. This thesis adds new knowledge to this developing field of research by giving insight into task prioritization, driver distraction effects and risk handling in situations when ADA Systems are most needed: safety-critical driving situations.

1.3.2 Societal relevance

This thesis adds new knowledge to human factors research, specifically on the topic of driver distraction and mental workload. In 2004 nearly 600 serious injuries or fatalities could have been prevented on Dutch roads if the traffic participants involved would not have used their mobile phones while driving (Dragutinovic & Twisk, 2005). This shows the relative risk of distracted driving. Understanding and quantifying the risks involved with distracted driving are important steps in countering these risks.

Furthermore, the driving simulator studies were concerned with driving behaviour in risky situations. Normal driving situations can easily turn into conflict situations, as multiple actors have multiple, possibly conflicting goals in difficult situations in which task demands often fluctuate. And as easily as normal situations can turn into conflicts, so easily can these conflicts also turn into accidents, resulting in damage, injury or even death. Knowledge about ways to counter drivers' unsafe reactions to conflict situations can help prevent the occurrence of those situations which might turn into accidents.

Moreover, this thesis focuses specifically on urban driving behaviour. Not only did more than 30% of all traffic accidents in the Netherlands in 2010 leading to injuries occur at urban intersections (SWOV, 2011), but these intersections are also the bottlenecks of the urban road network when focusing on capacity and traffic flow. Congestion in turn leads to increased emissions and reduces the local air quality. Knowledge of driving behaviour in these situations may be a first step in countering these challenges.

Finally, the development of ADA Systems has burgeoned over the past years. ADA Systems can support the driver in demanding situations and can increase driver comfort, traffic safety or reduce congestion or emissions. Based on our results, recommendations for the development of a new promising direction for ADA Systems are made. A new type of system could monitor the driver's state, maintain safe margins around the vehicle, and adaptively change these margins based on the driver's state. This proposed group of systems could have the generic name DAISy (Distraction Avoidance Integrated System). With the guidelines in this thesis taken into account, DAISy could adaptively assist the driver in one of the most demanding driving situations: distracted driving in an urban setting.

1.4 Outline of the thesis

This thesis is structured such that Chapter 2 describes the theoretical framework of the research. The topics discussed in this theoretical framework include the structure of the driving task, models of risk handling, situation awareness, mental workload and distraction during driving. The structure of the driving task is used as a frame for the studies described in this thesis. We specifically focus on the change from top-down interaction to bottom-up interaction between the levels of the driving task. Mental workload, driver distraction and situation awareness are topics that are all closely related to multi-tasking, and as driving is a multi-tasking activity by nature, a number of sections elaborate this aspect of driving. The final section of Chapter 2 describes different aspects of ADA Systems for urban intersection driving.

Chapter 3 gives an overview of research tools that may be used to study driving behaviour. Among the tools described are driving simulators, Field Operational Tests (FOT's), questionnaires, and measurements of mental workload during driving. The final section of Chapter 3 describes the research tools that we used during our studies.

The first experiment, conducted to provide more insight into the directions of interaction between the operational and tactical levels of the driving task, is described in Chapter 4. This experiment was conducted in a fixed-base driving simulator, and studied drivers' reactions to unexpected and safety-critical situations. Chapter 4 describes the aim, setup, results and conclusions from this experiment. The chapter is concluded with the formulation of four hypotheses that have been used for the final experiment.

This final experiment is described in Chapter 5. The four hypotheses that were formulated in Chapter 4 are tested against the data from the final experiment, and the generalizability and scope of the results are briefly discussed.

Chapter 6 discusses the complete set of results and places them in the perspective of earlier research and existing theories of risk handling, task prioritization and driving in dual-task conditions. The findings of both experiments are compared and the most prominent differences explained. Furthermore, the implications for the human-centred design of ADA Systems are discussed with respect to (avoiding) distracted driving.

Finally, Chapter 7 concludes this thesis with an overview of conclusions and a number of recommendations for further research.

Chapter 2

Theoretical framework

Car driving is a complex task, comprised of many different subtasks which simultaneously demand attention from drivers. Besides getting safely from one location to another, drivers also want to accomplish other goals, such as feeling comfortable and being time-efficient, and these goals are not always compatible. Among the most challenging driving situations are urban intersections, at which different subtasks have to be executed simultaneously while interacting with different types of road users. In order to develop possible solutions for the many challenges that drivers face, an understanding of the driving task and the influence of the most prominent internal and external factors is needed. This chapter describes the different factors influencing driving behaviour and performance, and the driver models which have been developed until now. It concludes by giving an overview of Advanced Driver Assistance (ADA) Systems with a specific focus on urban intersection driving.

2.1 Complexity of the driving task

Driving a car is a complex and safety-critical task (Groeger, 2000). The complexity of the driving task has three main causes. First of all, driving requires the driver to use a number of functional abilities simultaneously (Peters & Nillson, 2007): perceptual abilities, cognitive abilities, and motor abilities. Drivers need to see, hear and feel what's going on in and around the vehicle, use their decision making skills, attention and memory to make appropriate and timely decisions and supervise the driving task, and touch, press and control the vehicle's physical interfaces. Although most of these actions can be trained into well-developed skills, they still have to be performed simultaneously[1] and in a timely and efficient manner. The match between the driver's capabilities and the demands of the driving task largely determines the level of safety of the resulting behaviour. This is described by Fuller (2000, 2005) as the task-capability interface, which will be elaborated upon later in this chapter. Second, drivers have to be able to adapt to quickly changing circumstances. Because situations can turn from safe to safety-critical within (fractions of) seconds, either because of a personal error, or due to a situation occurring outside the driver's control (e.g., Klauer, Dingus, Neale, Sudweeks & Ramsey, 2006; Staubach, 2009), drivers constantly need to be alert and ready to respond to changing situations. This means that the demands placed on the driver can change from very low to very high (and back) within short time periods. Varying levels of alertness can have an influence on reaction times and the ability to assess the situation (e.g., Klauer et al, 2006; Mohebbi, Gray & Tan, 2009; Philip, Taillard, Quera-Salva, Bioulac & Åkerstedt, 1999) and therefore on the ability to make safe and efficient decisions in real-time. And third, different goals underlie the driving task, and these goals can vary between drives, between individual drivers, and within individual drivers over time. The main goal for driving is generally getting from one location to another in a safe manner within given time constraints. In addition, other goals such as feeling comfortable, enjoying the landscape, and being cost-efficient can be important to drivers (e.g., Rumar, 1990; Cnossen, Meijman & Rothengatter, 2004). During driving, these goals have to be monitored and balanced in real-time, although different goals may conflict or require different actions. Goal management is therefore an important but complicating aspect of the driving task.

Besides these aspects which complicate the driving task, characteristics of individual drivers also play an important role in driving. Driving style, age and gender may influence how drivers perceive their world, their task and the risk of their actions. This leads to many differences between and within drivers and driving situations, complicating studies of driving behaviour. Hole (2007) gives an overview of studies reporting differences between men and women and between different age groups for driving.

One situation in particular is both complex and safety-critical for drivers: urban intersections. This thesis focuses on driving behaviour in these demanding situations. Not only did more than 30% of all Dutch injury traffic accidents in the year 2010 occur at urban intersections (SWOV, 2011), but these intersections are also the bottlenecks of the urban road network

[1] Although there is indeed a simultaneous demand for attention from multiple subtasks when driving in demanding situations, people actually switch the focus of their attention between different tasks in the practice of multi-tasking. Delbridge defines multi-tasking as performing "*multiple task goals in the same time period by engaging in frequent switches between individual tasks*" (Delbridge, 2000). Obviously, certain tasks do not require continuous active attention, specifically routine tasks where are automatized, such as standing or walking. A high number of control level tasks is often automatized in experienced drivers. Section 2.2 elaborates on driving task automation and driving experience.

when focusing on capacity and traffic flow. Congestion in turn leads to increased emissions, reducing the local air quality. Drivers face many concurrent decisions in this situation, involving route choice, speed choice, interaction with other road users, and complex road designs. Finally, traffic is composed of more categories of road users with mixed equipage in urban areas than in other areas, and this also poses challenges for drivers.

The main driving challenges which are relevant at a certain point in time are determined by three factors: the driver, the vehicle, and the road environment (including other road users, rules and regulations), together making up the (dynamic) DVE interaction (DVE for Driver, Vehicle, and Environment). For instance, drivers might become distracted by an event occurring outside the vehicle, they can temporarily be impaired due to fatigue, or they may experience a malfunctioning car. Intentions can change for individual drivers and over time, as a result of changing subjective norms, emotions or beliefs. Drivers can be highly alert or become drowsy or distracted, which has its influence on their information processing and decision making capacities. Both the vehicle and the systems built into it can be designed in a way that influences the driving task demands and can have different characteristics, such as maximum possible speed. Infrastructural aspects can also influence driving behaviour and the DVE interaction. On the one hand, drivers might understand directly what to do if the road environment is designed in a 'self-explaining' manner (Theeuwes & Godthelp, 1995; Matena et al., 2008). On the other hand, they might become confused in situations where other road users behave unexpectedly or where the physical road environment is distracting in itself due to distracting objects on the road side (e.g., Hoedemaeker, Hogema & Pauwelussen, 2010). This distraction in turn might have an effect on the driver's decisions and actions. These factors are summarized in a combined behavioural model of the factors that influence driving behaviour, given in Figure 2.1 (after Van der Horst, 1998).

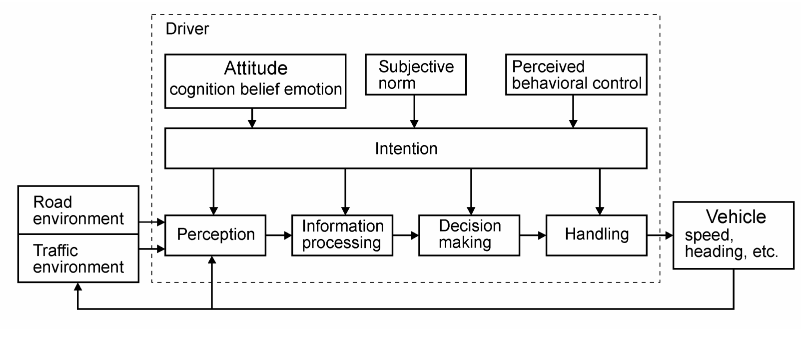

Figure 2.1 Combined behavioural model to indicate factors that influence driver behaviour (after Van der Horst, 1998)

Each of these factors (driver, vehicle and road environment) can be supported or simplified by means of support systems or infrastructural changes. For urban intersections, a number of intelligent transport systems have been studied. Advanced Driver Assistance (ADA) Systems specifically support drivers in performing their driving task, either by informing the driver, by supporting part of the driving task, or by taking over (part of) the driving task completely.

Unfortunately, many technological developments do not result from a study of drivers' task performance, but from a combination of available technology and deducted user needs based on accident statistics. As will be explained later in this chapter, accident statistics give only limited insight into the actual conflicts that happen on the road, let alone within driving tasks that drivers need support for. This means that relying on accident statistics for insight into driver needs can leave many aspects of the driving task and the driver unexposed.

The development of ADA Systems should be based on driver needs also for another reason. A change in task demands will most probably lead to behavioural adaptation (Verwey, Brookhuis & Janssen, 1996). Behavioural adaptation is an important factor in the overall effects of ADA Systems, and is therefore not to be ignored in studies concerning ADA Systems development. The development of ADA Systems, and behavioural adaptation to these support systems, is discussed in Section 2.6. But before anything can be said about behavioural adaptation in specific situations, or even about the execution of the driving task in normal circumstances, we have to understand what the structure of the driving task is, how subtasks are executed and prioritized, and which factors influence the execution of the driving task, in general and for specific driver types. The first step is therefore to take a look at the existing descriptions of drivers, the driving task, and the intentions drivers have in taking up this complex task.

The following sections focus on different aspects of information processing in general, as well as during driving. In the first case, the text will refer to the human information processor as the *operator,* whereas where the text concerns driving specifically, it will read *driver*. This distinction will be used throughout the remainder of this thesis.

2.2 Descriptions of driving and drivers

In order to gain insight into driving behaviour in certain circumstances, it is necessary to have a description of the driver, driving performance and the different goals and factors underlying driving. A number of models have been developed in the past with this aim, but so far, no all-purpose and comprehensive model of driving behaviour has been developed (Ranney, 1994; Cody & Gordon, 2007; Lewis-Evans & Rothengatter, 2009). This is, among other things, due to the fact that different driver models are often designed with different applications and different aims in mind. Different models can focus on specific aspects of driver behaviour, for example, on classifying driver characteristics for accident causation, on predicting or describing behavioural adaptation, or on normative task descriptions. Michon (1985) proposed a generic classification of driver models, using a two-dimensional classification (see Table 2.1). He distinguished between input-output (behavioural) models and psychological models in the first dimension, and between functional and taxonomic models in the second. According to Michon, input-output models (or stimulus-response models, or behavioural models) describe the relationships between actions (either desired or actual behaviour) and the driving situation, without referencing to the driver's internal state. Psychological models, on the other hand, describe driving behaviour as a result of psychological variables and driver state. This latter category is oriented towards drivers' "motivations for moving" (Michon, 1985). Michon's second distinction is between taxonomic models and functional models. The main difference between these two categories of models is the presence or absence of dynamic interactions between components. Taxonomic models contain inventories of facts or data, which have static relationships that can be described in terms of order and hierarchy and which are defined by their frequencies or probabilities (Michon, 1985, 1989). This type of model does not describe dynamic relations. Functional models, on the other hand, are more dynamic models that describe behavioural and/ or cognitive processes.

Table 2.1 Two-dimensional classification of driver models (after Michon, 1985)

	Taxonomic models	**Functional models**
Input-output models (behavioural)	Task analysis	Mechanistic models Adaptive control models
Psychological models (internal state)	Trait models	Motivational models Cognitive process models

We will give a general description and some examples of at least one of the model types in each cell of the matrix.

i. Taxonomic behavioural models

The main type of model of the driving task in the taxonomic and input-output-based cell of the model matrix is task analysis. As the name already reveals, this model provides an analysis of the subtasks which make up driving and the performance objectives of those tasks. A well-known task analysis was published by McKnight and Adams (1970). They made an exhaustive overview of requirements and objectives, which included 45 subtasks consisting of more than 1,700 elementary actions in total. Although the analysis is very complete and gives a good overview of the different subtasks which are included in the driving task, it does not include temporal relationships or cognitive or psychological aspects of driving. For this reason, the task analysis does not provide a suitable way to get insight into actual driving behaviour in dynamic circumstances.

ii. Taxonomic psychological models

Trait models are taxonomic inventories which are related to the psychological, internal state of drivers. They describe psychological aspects of the driver with a relation to driving behaviour or the execution of the driving task. A trait model can predict driving skills or attitudes but does not give insight into actual driving behaviour in specific situations, and does not include the dynamic character of the driving task. Michon (1985) mentions two distinct types of trait models. The first is the factorial model for perceptual, cognitive and motor skills developed by Fleischman (1967, 1975). This model describes how skills arise from basic operator traits such as reaction speed, and how practice changes the level of performance from ‘knowing that’, at which level the operator can verbalize the actions, to ‘knowing how’, at which point automaticity can be reached for certain skills (Fleischman, 1967, in Michon, 1985). Although this approach offers no insight into the actual processing that takes place when driving or performing another complex task, it does give some insight into the factors involved in learning processes. The second type of trait model discussed by Michon consists of observations of accident frequencies for different driver groups. These types of observations link personal traits, such as level of stress, driving style or other factors to intervals between successive incidents. These observations can help to give some insight into driver characteristics and their influence of drivers’ accident-proneness.

iii. Functional behavioural models

As opposed to taxonomic models, functional models describe processes which take place within the driver or during driving. There are two main types of functional input-output models. On the one hand, mechanistic models describe the actions of drivers based on the functions of the driving task. An example could be a model which describes the driver as a part of a traffic system and does not incorporate any motives or psychological aspects, such as a car-following model without an (internal or motivational) explanation for the behaviour shown. These types of models are not very intelligible with regard to drivers' intentions and motives, nor do they deal with the (adaptive) prioritizing of subtasks. When assumptions about motivational aspects of driving are introduced, models no longer fit in the category of mechanistic models (Michon, 1985). On the other hand, adaptive control models deal with information flow and decision making. According to these models, the driving task can be seen as a continuous task requiring visual tracking, information processing, basic skills such as lane keeping and maintaining an appropriate speed, and object avoidance. Adaptive control models describe the way in which information flows are used in these subtasks and/ or in the execution of the overall driving task. Subtask prioritization, information processing from perception to action, and internal factors can therefore be included in this type of model.

iv. Functional psychological models

Functional psychological models are related to mental abilities, beliefs, motivations, emotions and other cognitive processes that play a part in driving. There are two main types of functional psychological models: motivational models and cognitive process models. Cognitive process models represent the processes underlying driving behaviour and choices. They relate actions with cognitive processes such as perception, stimulus selection, decision making, and goal management. Motivational models deal with beliefs, attitudes and their relationship with actual (driving) behaviour, such as the theory of planned behaviour (Ajzen, 1985). A large proportion of these motivational models describe drivers' risk handling and risk avoidance behaviour, such as Näätänen and Summala's (1976) zero-risk theory, Wilde's (1982) risk homeostasis theory, and Fuller's Task-Capability-Interface (Fuller, 2000; Fuller, McHugh & Pender, 2008). These types of motivational models are elaborated in a separate section, as it is highly related to the way in which drivers handle safety-critical situations.

First we present Michon's (1971, 1985) hierarchical model, providing a description of the driving task which embraces normal driving and unexpected circumstances, and the prioritization of subtasks. Michon presented this model, a description of subtask types, their hierarchical classification and their (hierarchical) interaction, as a framework for the development of a comprehensive driver model (Michon, 1985). Such a comprehensive model of driving, which includes cognition and motivations as well as dynamic relations between (the handling of) subtasks, transcends the classification scheme as proposed by Michon himself, since multiple aspects of both dimensions are part of the final model. In the current state, the proposed framework fits best in the category of functional behavioural models, since it describes dynamic relations, but does not (yet) include motivations or cognition.

2.2.1 Hierarchical model of the driving task (Michon, 1971, 1985)

The driving task can be seen as a three-layered hierarchical task with a strategic, a tactical, and an operational level (Michon, 1971, 1985; Janssen, 1979). At the strategic (navigation) level, the journey is planned, taking into account current location and proposed destination. Subtasks at this level are for instance determining destination and desired arrival time, choosing the mode of transport that best fits the wishes for the trip, and determining the route to be taken. The strategic level is also where the driver sets his/ her overall goals for the trip, such as hurrying or enjoying the ride. The tactical (manoeuvring) level is where the driver tries to attain these goals by manoeuvring the vehicle. Here, interaction with other road users and the road layout takes place – for example, when passing a vehicle. The tactical level contains subtasks such as taking a turn, keeping the appropriate distance to the surrounding vehicles, and keeping the correct position on the road. On the operational (control) level, the driver directly controls the vehicle. This includes subtasks such as steering, handling the clutch and other interactions with the vehicle controls. The three task levels also have internal feedback loops: tasks at the three levels are continuously adjusted and controlled according to cues from the environment. The three task levels (strategic, tactical and operational) are hierarchical in the sense that they influence each other in a top-down way; however, control mechanisms have not been specified. The hierarchical model of the driving task (Michon, 1971) is depicted in Figure 2.2.

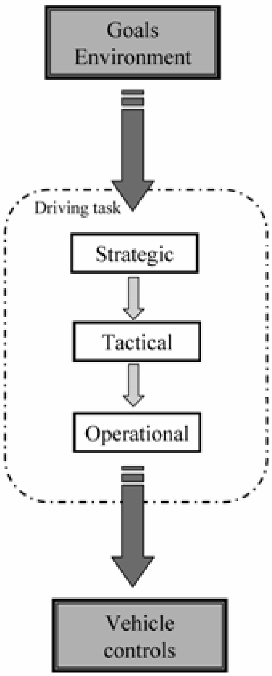

Figure 2.2 Hierarchical model of the driving task (based on Michon, 1971)

The interaction between task levels is especially present at urban intersections, where all three levels simultaneously become active. A graphical representation of top-down task level influence during normal driving at urban intersections is given in Figure 2.3 (after Van der Horst, 1977). At the strategic level, drivers decide on their route choice based on infrastructural aspects and route information. Choices about the route directly influence lane choice, interaction with other road users, speed choice, and which way the driver turns at an intersection, and this finally dictates the angle of the steering wheel and the pressure put on the gas pedal.

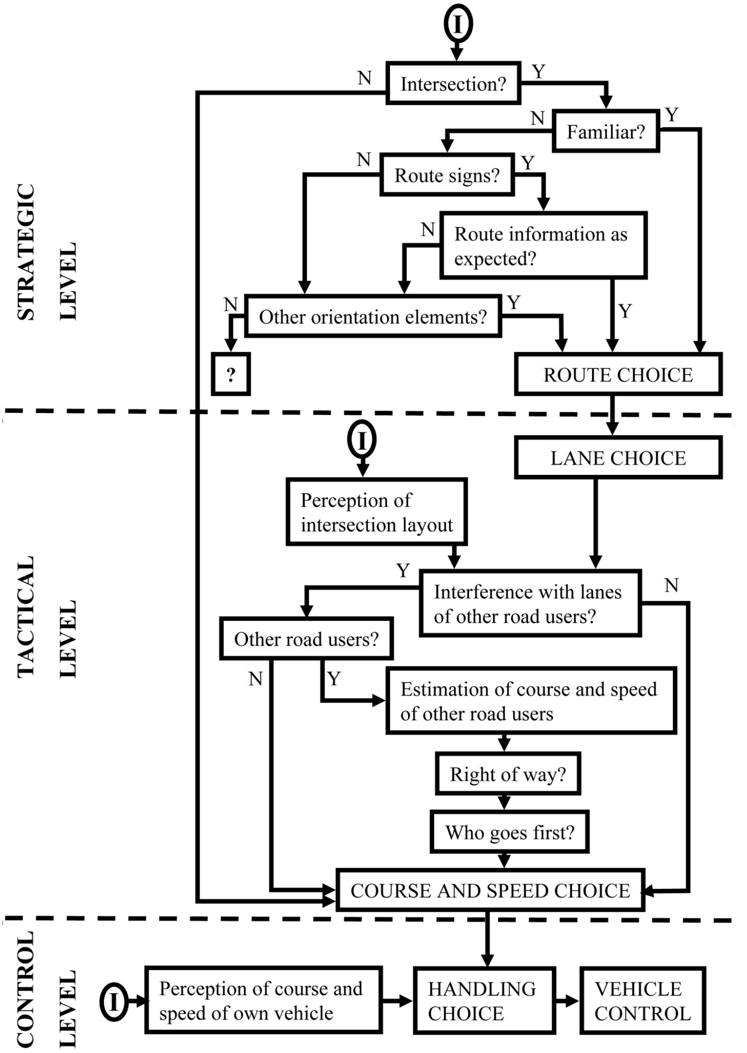

Figure 2.3 Interaction of the three levels of the driving task when negotiating an intersection (after Van der Horst, 1977)

The hierarchy in this control model therefore lies in the fact that the outcome of behaviour at certain task levels almost always dictates the tasks at the nearest lower level, at least in normal driving behaviour conditions. However, it is expected that bottom-up influence is also possible in specific circumstances. When an interruption of the normal driving task changes the driving situation unexpectedly, lower task levels could dictate that something should be done or decided and prioritized at higher task levels. An example might help here. Drivers wanting to turn left at a blocked intersection will notice the road block and register the situation as requiring a change in behaviour. They will change their route accordingly. The tactical task level is concerned with the action of turning left and the interaction with the road, and compensation behaviour at this level now dictates that different choices regarding route need to be made at a higher level. At the operational level, this type of compensation and bottom-up influence could for instance occur when the road is slippery and the car does not react to the steering wheel movements normally. The influence (goals, intentions, chosen route, desired speed) from the higher levels is then neglected, and tasks at the operational level take over in regaining control over the vehicle. To our knowledge, research into this bottom-up influence between levels of the driving task is infrequent. Figure 2.4 depicts the complete interaction between the three levels of the driving tasks, as is hypothesized based on Michon (1971, 1985).

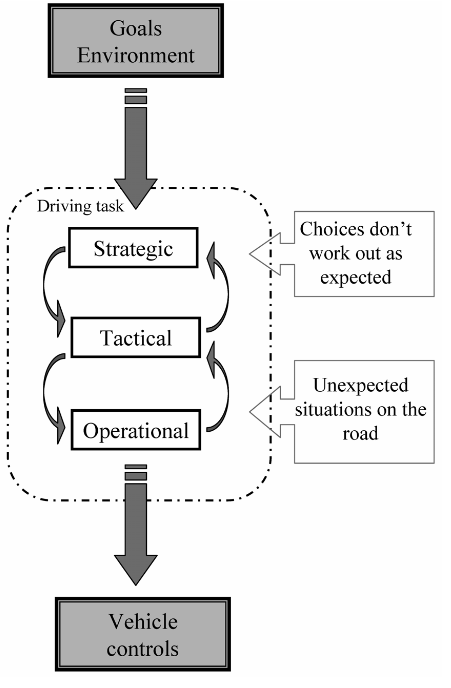

Figure 2.4 Interaction between the three levels of the driving task, including types of situations which could invoke bottom-up influence (after Michon, 1985)

2.2.2 Models related to Michon's (1971, 1985) hierarchical model of the driving task

Rasmussen (1987) describes structural aspects of human performance in another hierarchical behaviour model, which can also be applied to driving behaviour. His taxonomy distinguishes skill-based, rule-based and knowledge-based behaviour. This refers to the level of skill and automatic execution (or conscious control) with which the task is performed. Skill-based performance means that the task is fully learned, and that human operators no longer need to think consciously about task execution. Behaviour at the rule-based level is executed by consciously selecting a set of rules relating to a specific subtask, after which this subtask is performed automatically. In knowledge-based behaviour, every action is thought about in a

conscious manner. After a certain amount of practice, performance on tasks moves from the knowledge-based level to the rule-based level, and possibly on to the skill-based level.
Together, these two hierarchies of the driving task have been put into a matrix by Hale, Stoop and Hommels (1990), with an example of related driving behaviour for each cell. This matrix is reproduced in Figure 2.5.

	Strategic	**Tactical (Manoeuvring)**	**Operational (Control)**
Knowledge-based	Navigating in unfamiliar area	Controlling skid	Novice on first lesson
Rule-based	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
Skill-based	Route used for daily commute	Negotiating familiar intersection	Vehicle handling on curves

Figure 2.5 Classification of selected driving tasks by Michon's (1971, 1985) control hierarchy and Rasmussen's (1987) skill-rule-knowledge framework (after Hale et al., 1990, Figure 1, p. 1383)

Finally, three stages of information processing can be distinguished for the driving task: selection, processing and action (Theeuwes, 1993). Wickens' (1984) multiple resource theory (MRT) model of information processing furthermore states that human operators do not have one single resource for information processing, but rather multiple resources that can be used simultaneously. These three stages of information processing also interact with the other level distinctions mentioned earlier. The level of automation changes the importance and type of information processing, because a more automatically executed task does not need as much conscious thought as a task performed at the knowledge-based level. On the other hand, all three stages of information processing do occur at all the hierarchical levels of the driving task, and the type of task defines the type of information processing required. This further shows the complexity of the task of driving on urban intersections: all three task and performance dimensions are relevant and influence each other in this situation. Figure 2.6 shows a 3-dimensional matrix of the road user task (after Theeuwes, 1993).

The levels of each dimension interact frequently and the links between cells at the three dimensions are not strictly fixed (Cody & Gordon, 2007). For instance, tactical tasks can be performed at either skill, rule, or knowledge based performance level, depending on the exact task and the level of experience. However, tasks at the operational level, such as pressing the gas pedal or turning the steering wheel, will often be performed in a skill-based manner by experienced drivers. Furthermore, most regular situations in normal driving in which tasks at different levels interact, such as translating a route into a left turn at a specific location, will be executed at a rule-based level by most experienced drivers. After all, the more frequent the execution of a subtask, and the easier it is, the sooner its execution will move to a more efficient performance level, to rule-based and finally skill-based execution. On the other hand, when an unexpected situation occurs, disrupting the normal rule-based behaviour and top-down interaction between the task levels, bottom-up compensation on task control is required. In these cases, knowledge-based task performance is needed to handle the situation. As most of the driving actions are performed in a skill-based or rule-based manner for experienced drivers, average drivers will not even be conscious of their actions until they need to solve problems at a knowledge-based level (Wagenaar, 1992).

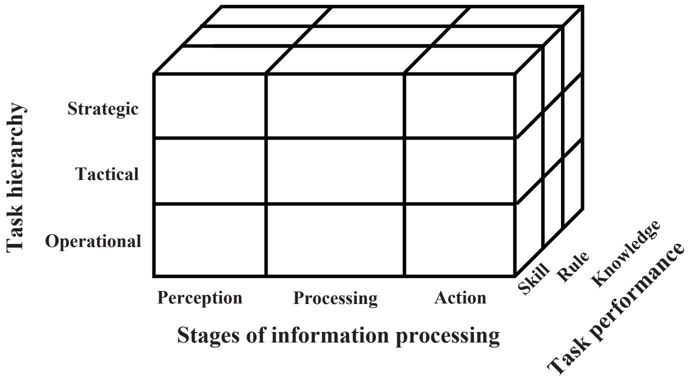

Figure 2.6 Structure of the road user task in three dimensions (after Theeuwes, 1993)

2.2.3 Switching between automatized driving and conscious control

As was mentioned in the previous paragraph, Rasmussen's hierarchical SRK-model describes the three levels (skill-based, rule-based and knowledge-based) at which tasks can be executed (Rasmussen, 1987). The terms skill-, rule- and knowledge-based information processing refer to the degree of conscious control of the operator over the activities performed. With experience, operators can move from one level of task execution to the next; knowledge-based performance can thus grow into rule-based and finally skill-based performance. The level of conscious control over the tasks performed can decrease with growing automation and skill-level, and execution may become increasingly effortless. Many tasks can become automatic with enough practice. Shiffrin and Schneider (1977) showed that the process of looking for a specific group of letters in a set of other distracter letters could be trained into automatic performance with sufficient practice if the target letters and distracters were in the same groups consistently. However, if letters were switched from being targets to distracters, automaticity did not occur despite much practice. In other words, many tasks can be trained into becoming automatic, and relearning these tasks with the aim of changing them into a different habit is very difficult. A similar effect was found in highly learned components of the driving task. Korteling (1994) performed an experiment in which drivers had to reverse the polarity of their actions (i.e. turn the wheel right when they wanted to go left and vice versa). Steering was so strongly automatic that the participants could not unlearn it in the course of the experiment, and kept going 'off road' in the driving simulator.

Automaticity can be decomposed into many different aspects, such as the operator's level of attention, control and awareness; the goal dependency of the task; and the level of efficiency of task performance (for an extensive overview of automaticity features, please refer to Moors & De Houwer, 2006). These authors suggest that most of the features are relative, i.e. they can be compared to a relative standard (Moors & De Houwer, 2006). Research on driving behaviour and automaticity (Young & Stanton, 2007) supports this suggestion that automaticity lies on a continuum. Young and Stanton (2007) furthermore state that automaticity is resource-based, since it was found that driving performance of skill-based subtasks for highly skilled drivers was still affected by mental workload levels.

Training and experience are not the only factors that determine the level of conscious control an operator needs to exert. The situation that the operator encounters also determines the way in which the operator needs to act. Reason (1990) proposed the Generic Error Modelling System (GEMS) as an extension of the SRK-framework (Rasmussen, 1987). The system describes how the performance level (skill-based, rule-based or knowledge-based) is partly determined by the situation encountered. For instance, when an operator encounters an unexpected situation while performing a task in an automatic fashion, s/he enters into rule-based performance in order to return to the normal situation. In this case, the optimal response to the unexpected situation is not part of the task which is performed at the skill-based performance level, and the task is thus executed at the nearest lower level possible, i.e. rule-based.

Driving is a task in which both automatic performance of subtasks and conscious task execution play a role. Such learned automatic (sub)tasks can allow drivers to save attentional resources, as skill-level and mental workload are inversely related (Young & Stanton, 2007). Skill-level and the level of conscious control, or automaticity (Anderson, 1995), are related, as the SKR-framework by Rasmussen (1987) also implies. When fewer resources are invested, less conscious control will be exerted, and tasks will be executed in a more automatized or habitual fashion. The time needed to move from one skill-level to the next depends on the task difficulty and the amount of practice; operational driving tasks can be performed on a skill-based level after as little as one month practice (Young & Stanton, 2007). It has been found that even with very little driving experience (as can be seen in novice or inexperienced drivers), mental workload can decrease when the operational levels of the driving task become more and more automatized (Verwey, 2000).

When drivers drive in an automatic fashion and thus do not exert conscious control over every single subtask, their ‘habitual’ behaviour can show in different ways. On the operational level, for instance, drivers can approach an intersection or bend without decelerating at the normal level, which points to a less active pedal control. Other tasks at the operational level, such as steering (lane keeping) and checking the mirror, can also be performed in an automatized fashion. Automatized performance of tactical level subtasks can also occur, for instance when drivers come nearer to a decelerating lead vehicle by postponing their response or by compensating. In a situation where the safety margins around the vehicle are large enough and the other road user behaves as expected, this could lead to an efficient use of cognitive resources without compromising safety. Since high levels of mental workload can have adverse effects on driving performance and a certain amount of automaticity can reduce these levels of mental workload, this can in certain cases be beneficiary to safety.

As was already described, the change from knowledge- and rule-based performance to skill-based performance (or from conscious driving performance to a more automatic driving mode) is based on experience and training. Driving modes can also change back from a state of driving in an automatic fashion to a state of conscious control over the driving task. This mode switch can have a number of causes or reasons. Drivers may switch from automatic to conscious task execution when an unexpected situation occurs that needs to be countered by the driver (for instance when countering a risky situation by braking or steering away), they can actively choose to switch to driving in a conscious manner (for instance when taking an unusual route home), or they can be startled by a situation. In all three situations, the driving mode switches from habitual, automatic driving into conscious, attentive driving. For example, when a child suddenly runs into the road in front of a car, the driver has to apply emergency braking immediately in order to come to a full stop. Not only will this task itself be performed consciously, the driver might also be more conscious of the complete driving task or the environment for some time after this event. Even when a startling situation is not safety-critical and/ or does not require a conscious response from the driver (for instance when a vehicle creating the startling situation responds adequately), it can still cause the driver to drive in a more conscious fashion for a certain amount of time.

Habitual performance can become subject to error in situations that do not comply with the original (trained) scenario. A classic (but usually not safety-critical) example is when drivers plan to take an unusual route home so that they can pick up something from a shop on the way (Trick, Enns, Mills & Vavrik, 2004). When they get inattentive or distracted, they might find themselves driving their usual route despite their initial intentions: the well-trained subtask of finding the usual route has taken over. In the situation described, the goal (pick up something from the shop) would have been reached if the drivers would have adaptively switched from automatic driving mode to a mode of conscious control. Habits can indeed even create risky situations. For instance, when drivers do not get feedback from their environment that maintaining an appropriate distance to a lead vehicle is necessary, they might omit to create this safe habit and instead create a new habit of driving (too) close to another vehicle. Duncan, Williams and Brown (1991) compared the driving performance of three groups: novice drivers (less than one year experience), experienced drivers (at least 5 years experience), and expert drivers (veteran drivers who had passed a very difficult driving course). Novices, still not experienced enough to have developed many habits or to be driving in an automatic driving mode, were more likely to brake at a safe distance from an intersection than the other groups, and were also better in leaving an appropriate distance when following another car. Duncan, Williams and Brown (1991) concluded that the driving environment is too forgiving to give good feedback in the form of reward and punishment, thus training drivers in the differences between correct and incorrect behaviour. Drivers may speed and drive too close to another vehicle on a daily basis and still avoid collisions. If there are no negative consequences, the incorrect actions could be repeated and may become automatic. They may even suppress and override correct habits (for instance, those taught in driver training) when practiced more often.

Overreliance and complacency on intelligent systems supporting the driver in part of the driving task can also bring about an automatic driving state that is not always appropriate for the situation (for more information on behavioural adaptation to Advanced Driver Assistance Systems, please refer to Section 2.6). Some of these systems still require active and conscious control in the form of supervision, and, in certain cases, even active involvement of the driver. However, drivers do not always respond adequately in these situations, even when it is clearly their task to control the vehicle in these situations (e.g., De Waard, Brookhuis, Fabriek & Van Wolffelaar, 2004; De Waard, Van der Hulst, Hoedemaeker & Brookhuis, 1999). In these cases, it seems as though they drive in an automatic manner, instead of consciously paying attention to the state of the device and the driving situation.

When handling the driving task as an automatic, almost supervisory task, performance deterioration is a risk. If the need to respond to environmental stimuli decreases and actively using the available attentional resources is not required, these resources might be allocated elsewhere and drivers can become inattentive. On the rare occasions when drivers then do need to respond or compensate for a safety-critical situation, they will experience impoverished situational awareness, the disorientation that has been called the “out of the loop” effect (Endsley, 1995). Section 2.5 discusses Situation Awareness in more detail.

The hierarchical model of the driving task, as proposed by Michon (1971, 1985), and specifically the directional change of task level interaction from top-down (normal driving behaviour) to bottom-up (compensation to an unexpected situation), will be a key concept in this research. The research will also focus on the behavioural adaptation and compensation to unexpected events, either by switching to conscious control or by changing driving behaviour to accommodate for a change in external situations. This behavioural compensation could be related to the way in which drivers handle risky situations. The following section describes four motivational models dealing with risk handling during driving.

2.2.4 Models of risk handling

As mentioned earlier, a large proportion of the motivational models of driving behaviour focuses on drivers' risk handling and the behavioural adaptation resulting from it. Lewis-Evans, de Waard and Brookhuis (2011) propose a distinction between two types of risk-handling theories: monitoring theories and threshold theories. We use this distinction here. Four influential and well-known models of risk handling in human factors research are the Risk Homeostasis Theory by Wilde (1982), Näätänen and Summala's (1976) zero-risk model, the Threat Avoidance Theory (Fuller, 1984) and the Task-Capability-Interface (Fuller, 2000). They describe the behavioural adaptation that drivers show to situations that they perceive as risky and the reasons for this behavioural adaptation. Risk Homeostasis (Wilde, 1982) is an example of a monitoring theory whereas the zero-risk model (Näätänen & Summala, 1976) and the Threat Avoidance Theory (Fuller, 1984) are examples of threshold theories (Lewis-Evans, De Waard & Brookhuis, 2011). The Task-Capability Interface (Fuller, 2000) combines threshold theory and monitoring theory.

i. Risk Homeostasis Theory

Homeostasis refers to a dynamic process which regulates a system's internal environment and aims to maintain a stable target level through regulation mechanisms and equilibrium adjustments. In 1982, Wilde presented the Risk Homeostasis Theory (RHT). This theory is based on two assumptions. The first assumption in RHT is that drivers have a personal acceptable level of risk which they try to attain throughout all driving situations. In situations in which the perceived level of risk is different from their personal acceptable risk level, drivers will show a behavioural change, mode change or even trip decision change in the direction of their personal acceptable risk level. The level of risk that is accepted is based on the notion of utility, so on the costs and benefits of both risky and cautious behaviour. It is important to note here that the personal acceptable risk level is not completely fixed for one person, but can fluctuate based on either long term characteristics such as age and personality, or short-term aspects such as individual trips and goals. The second assumption Wilde (1982) makes is that this individual risk homeostasis, by which drivers maintain a fixed risk level, leads to an aggregated risk homeostasis for the complete traffic system, so for all road users together.

An implication of the first assumption is that drivers will show an increase in risky behaviour when traffic safety measures are implemented; for instance, drivers might adopt higher speeds after the introduction of seatbelts (this specific example was indeed confirmed in an instrumented vehicle study performed by Janssen [1994]). The assumption furthermore implicate that both the personal and the aggregated risk level can be calculated; however, this is impossible, both conceptually and practically. Finally, an implication of the combination of the two assumptions is that the way to create safer traffic situations might not be by changing the situation or circumstances, but by implementing measures that decrease drivers' personal acceptable risk level. Although the total effect of safety measures will not always be completely neutralized by behavioural adaptation to the safer circumstances, it has been shown that interventions can sometimes lead to negative behavioural adaptation (OECD, 1990).

ii. Zero-risk model

The plausibility of RHT has been challenged in many studies (for an overview of criticisms see Evans, 1991). Some authors do not believe that drivers are capable of calculating a real-time risk level (e.g., Wagenaar, 1992; Summala & Näätänen, 1988). Others state that drivers, instead of adapting their behaviour to reach a largely fixed personal level of risk, seek to prefer situations which either objectively have zero risk, or which subjectively feel like safe situations. This is the main principle for the second risk-related theory, Näätänen and Summala's Zero-risk theory (1976). A basic assumption in zero-risk theory is that drivers judge a traffic situation to have no risk at all as long as the perceived level of risk is below the threshold of the acceptable level of risk. This perception of zero-risk results from a feeling of being in control and being able to respond adequately to a potentially upcoming safety-critical situation. According to the theory, drivers' self confidence increases with their experience, and with this process the perceived level of risk diminishes to zero. Experienced drivers therefore generally do not perceive any risk during driving, and intend to travel in a way in which this remains the case. Continuous monitoring of both the situational risk and the subjective accepted level of risk is therefore not necessary.

When the situation is perceived as being safety-critical, i.e. having a risk larger than the threshold, drivers adjust their behaviour by means of control mechanisms. These mechanisms will lead to deceleration, thus decreasing the risk level to below the threshold, and back to a zero-risk situation. In 1988, the authors elaborated on their theory (Summala & Näätänen, 1988), putting the focus on maintaining safety-margins, defined as the distance between the driver and a hazard. Drivers do not continuously make ongoing risk assessments but operate under zero-risk circumstances by control of safety margins (Summala & Näätänen, 1988). Concluding, drivers do not adjust risk levels, but they adjust their safety margins when they perceive that a situation is safety-critical rather than contain zero risk.

iii. Threat Avoidance Theory

In 1984, Fuller proposed another motivational approach to risk compensation and driving behaviour (Fuller, 1984). His Threat Avoidance Theory described how drivers have conflicting aims: on the one hand getting to a chosen destination and on the other avoiding hazards on the way there. According to Fuller, drivers learn through experience how to avoid risks by anticipatory responses to upcoming hazards instead of reacting by delayed responses. They learn which (types of) situations are risk-prone, and only show behavioural adaptation in these (types of) situations. So instead of adjusting their behaviour to risk reactively, they avoid the risk in an anticipatory or selective way. Since the road environment is forgiving and objectively risky driving (for instance speeding) does not always lead to safety-critical situations, traffic situations with objective risk and perceptions of subjective risk are not always connected.

iv. Task-Capability Theory

In 2000, Fuller presented an elaborate version of his theory, the Task-Capability-Interface (TCI; Fuller, 2000). In this paper, Fuller suggested that under typical circumstances, drivers perceive situations to be zero risk, but under pressure they may knowingly accept some degree of a hazard because the combined utility of continuing the same driving style outweighs the alternative, slowing down or compensating for their perceived risk. Fuller stressed that there is a difference between the notion of risk as perceived by drivers, and the determination of risk level as made by statisticians. This level of perceived risk is defined by the combination of the task difficulty and the driver's capabilities, and can be either zero (the safe feeling of being in control) or one (temporary loss of control). Task difficulty is determined by - in descending importance - driving speed, road position and trajectory, whereas capability is determined by a combination of drivers' competence and the temporary ability to use this competence. This ability can be constrained by variables such as distraction and motivation. The drivers' main task is to manage task difficulty so that their capabilities can handle these demands, while also satisfying other goals. Drivers can counter a situation in which task demands exceed capability either by decreasing the task demands (e.g., lowering speed) or by increasing capability (e.g., increasing the invested effort) (Fuller, 2000). Since driving is mostly a self-paced task, lowering speed gives the driver more time to perceive possible hazards and make adequate decisions, therefore decreasing task difficulty. Investing more effort, on the other hand, allows the driver to handle the task at hand better by increasing the capability. A risky situation can arise through active sensation seeking (testing the limits) or through the prolonged absence of 'negative feedback' to aspects of their driving behaviour (giving drivers the idea that their capabilities are higher than they actually are as compared to the relative task difficulty) (Fuller, 2000). The ratio of task difficulty and ability can reach a limit as a result of unexpected changes in task demand, for instance arising from the unexpected behaviour of other road users. The impact on safety of such a sudden increase in task demand will be the more significant the closer the driver is to the critical threshold of difficulty-capability ratio. Finally, a limit also occurs where capability is overestimated.

More recently, Fuller, McHugh and Pender (2008) tested three hypotheses arising from the TCI model in a series of experiments. Firstly, perceived difficulty should be systematically related to speed ceteris paribus (i.e. all other things remaining equal); secondly, ratings of risk would be independent of speed until the task demands approached the driver's capability; thirdly, feelings of risk should be stable and around zero until a threshold level of speed pushed the task demands close enough to the driver's capability. Although these hypotheses were indeed supported by the experimental results, the implicit assumption that risk ratings were similar to subjective estimates of collision was not met. Apparently, drivers focus more on maintaining control than on possible consequences of the loss of control, such as a collision. Fuller, McHugh and Pender (2008) therefore stated that up to the speed at which drivers feel comfortable, the perceived risk is a direct expression of task difficulty and has no relationship with collision risk. Above a certain threshold, i.e. above a certain speed level, drivers appear to use feelings of task difficulty and risk as an input of speed choice. The TCI model is therefore a combination of the risk compensation part of Wilde's (1982) RHT, and the zero-risk part of the zero-risk model by Summala and Näätänen (1988).

2.3 Traffic safety measures

For a discussion of risky situations or of traffic safety in general, it is important to understand how the level of traffic safety can be determined. Measuring the level of safety of a certain situation or system is of major importance for this topic, and when thinking about safety analysis, accident statistics are the first type of measure that come to mind. However, accident records are not the best measure to support this type of conclusions.

Firstly, accidents are not always reported, leaving analysts with an incomplete set of data. Secondly, the registered information on the causes of accidents in these data is minimal, with practically no information on external causes or preceding driver actions. And thirdly, unlike conflict situations, accidents are relatively rare. However, the processes that result in accidents are similar to the processes that lead to less severe conflict situations (near accidents, serious traffic conflicts, etc), with the major difference being the outcome of the situation (Van der Horst, 1990).

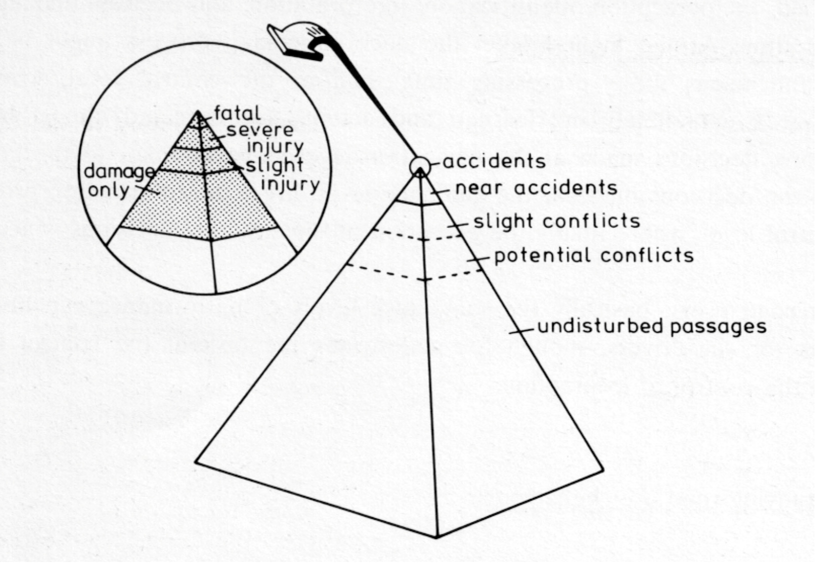

Figure 2.7 Incident pyramid (Hydén, 1987; reprinted with permission)

Figure 2.7 depicts the incident pyramid (Hydén, 1987), relating accidents at different severity levels to conflict situations and undisturbed passages. It shows that the number of occurred accidents is only a very small portion of the actual number of conflicts and near-accidents, and is built up from the same population of potential or actual conflicts.

With the relatively high number of conflict situations as compared to actual accidents, it seems more useful to look at alternative measures for traffic safety. A large number of surrogate safety measures have been defined over the past years. Some describe the safety of certain behaviours and can be obtained from a single car, such as Time to Line Crossing (TLC), Deceleration Rate (DR), and the standard deviation of the Lateral Position (SDLP). The TLC denotes the number of seconds until the vehicle will cross a lane boundary with its current position, heading, and (lateral and longitudinal) speed (e.g., Godthelp, Milgram & Blaauw, 1984). The severity of a line crossing depends on the traffic situation and is therefore not included in this measure. However, the (minimum) time left to cross a boundary in a specific situation can give insight into (un)safe driving behaviour, especially in combination with other measures (De Waard, 1996). The maximum Deceleration Rate may give an indication of the severity of the deceleration situation, as it denotes the maximum speed slope during deceleration. Finally, the SDLP gives an indication of vehicle control and is a measure of tracking capability. SDLP can not be used as a point measurement since it has to be computed over a number of samples, but it can give a clear representation of changes in level of control over time. The SDLP has also been used as a measure of performance, specifically in mental workload research (e.g., Blaauw, 1982; Green, Lin & Bagian, 1994; Hicks & Wierwille, 1979).

Other surrogate safety measures define the severity of conflicts between two road users. These surrogate safety measures include Time-To-Collision (TTC), time/ distance headway, and Post-Encroachment-Time (PET). The TTC was defined by Hayward (1971) as "*The time required for two vehicles to collide if they continue at their present speed and on the same path*" and is only valid in an approach situation. The smaller this value becomes, the closer the two vehicles approach each other, and thus the more severe the conflict situation is (with a TTC of zero meaning a collision of the two vehicles). The TTC value for two moving vehicles may change continuously, as they move closer or brake to avoid a collision. Distance headway and time headway represent the distance between two vehicles, and the difference between the time when the front of a vehicle arrives at a certain point and the time the front of the next vehicle arrives at the same point, respectively. Finally, Post-Encroachment-Time (PET), focussed specifically at crossing situations, is defined as the time between the moment that the first vehicle leaves the area of intersection (possible conflict location) and the moment the second vehicles reaches this area. Figure 2.8 gives a graphical representation of the calculation of the PET (after Van der Horst, 1990).

Together these measures can provide a relative comprehensive picture of the safety of a certain situation, without necessarily needing accident statistics as a safety measure. They produce valid and highly accurate estimates of average accident rates (Miglez, Glanz & Bauer, 1985 in Van der Horst, 1990). A number of these surrogate safety measures will be used in the present experiments to understand how the level of traffic safety or objective risk influences drivers' behavioural compensation to unexpected situations.

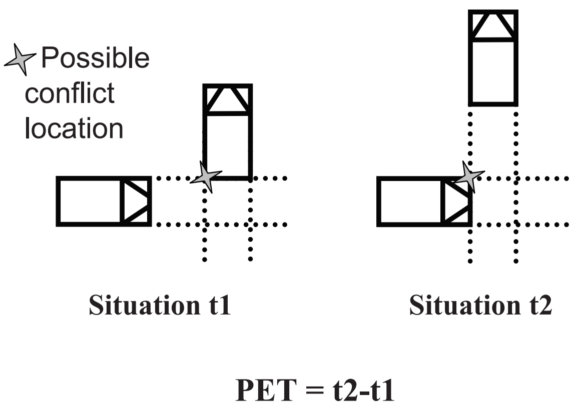

Figure 2.8 Calculating Post-Encroachment Time

2.4 Multi-tasking, distraction and mental workload while driving

Car driving is not just the consecutive execution of a number of subtasks, but also requires complex cognitive abilities on the part of the driver. This section focuses on multi-tasking and elaborates on a number of aspects which are connected with the notion of multi-tasking in general, as well as during driving. As was mentioned before, the text will refer to the human information processor as the *operator* in the first case, whereas the text will read *driver* where it concerns driving specifically.

2.4.1 Multi-tasking

Driving is a task which by nature requires switching between varying task goals, dividing attention and time-sharing between multiple tasks. Besides perceiving and interpreting the situation surrounding them, drivers are required to handle the steering wheel, the gas pedal and other car controls, while also keeping track of their route and other goals. In most cases this does not pose a problem, but sometimes drivers are at risk to be overloaded by the task demands or secondary activities. Multi-tasking is a skill that human operators possess naturally; think of the ease with which people can talk while walking, or listen to music while working in the garden. But although some tasks are seemingly executed simultaneously without diminishing overall performance, this is not possible indefinitely. Furthermore, not all tasks can be combined easily and without consequences. This is especially true for tasks which require conscious thought and decision making, i.e. tasks which are executed at the knowledge-based level. So there are limits to the possibilities humans have in multi-tasking, and some tasks are combined easier than others. Wickens' (1984) human information processing model describes how humans' limited information processing capacity and attention resources can result in a bottle-neck when executing tasks with high attentional demands. In the case of single-task performance, task performance is limited by the operator's capacity for that single task, and therefore depends on the ratio between task demand and resource capacity. When performing multiple tasks, however, performance on either of the tasks was found not to depend only on the demands placed on the operator or on the operator's task prioritization (favouring one task over the other, or neglecting some of the tasks). The level of task performance also depends on qualitative differences between the two tasks, specifically at the level of the demands placed on information processing. These differences, or dimensions, are the processing stages, perceptual modalities, types of responses required, and processing codes. Tasks that share the same modality often lead to a lower level of performance than tasks that use different modalities (Wickens, Sandry & Vidulick, 1983). For example, drivers are better at listening to route instructions while driving than at reading these instructions simultaneously, since driving and reading share the same visual modality.

Overall performance for multiple (simultaneous) tasks is determined by three factors related to the task characteristics: the level of confusion of task elements, competition for resources, and cooperation between processes (Wickens, 1991). When two or more tasks have very similar aspects, humans might become confused in the task execution. This may lead to poorer performance. However, cooperation between two tasks might also occur. This is the case when the execution of one task could help the execution of another task, due to high similarity in the processing routines. Finally, competition occurs when two different tasks compete for the same resources (Wickens, 1991).

Performing multiple complex tasks simultaneously is generally seen as challenging for human operators. Delbridge (2000) stated that when trying to do two tasks simultaneously, performance on one task is generally detrimental to performance on a second, simultaneous task. She therefore distinguished between simultaneous and sequential processing. Waller (1997) also stated that humans switch between multiple tasks rather than perform them at exactly the same time, either as individuals or in groups. Due to this sequential processing, there is the risk of diminished attention for the primary task if this primary task and a distracting task both demand (and thus compete for) conscious attention from operators. In a traffic situation, this diminished level of attention can have severe consequences for task performance; the following section elaborates this concept of driver distraction.

As was stated before, driving is a multi-tasking activity by nature. This means that competition for conscious attention does not only occur with external tasks, but also between driving tasks. At urban intersections, the three levels of the driving task (Michon, 1971, 1985) are relevant simultaneously, and thus need conscious attention from the driver. This might pose challenges on drivers, since drivers need to sequentially divide their attention to the route, their surroundings, and vehicle controls. However, the level of interference depends both on the modality of the tasks and on their level of execution (Rasmussen, 1987). Since decisions in driving are often based on visual information, the visual aspects of multiple concurrent driving tasks can easily interfere. Tasks which are performed at a knowledge-based level require conscious attention and using knowledge, and therefore pose a larger challenge than tasks at the rule-based or even skill-based levels. For tasks at the rule-based level, conscious attention is only needed for selecting the proper rule or programme, and this is a brief process. Tasks at the skill-based level hardly require any cognitive attention (Van der Horst, 2007).

Concluding, the driving task requires sequential attention allocation, switching between different subtasks and adaptation to dynamically changing situations. The concepts of driver distraction and mental workload are closely related to these aspects of driving. The definition and operationalization of these terms, and how they are related, is the focus of the following paragraphs.

2.4.2 Driver distraction

Driver distraction is a research topic that has been in the spotlight for many years, mostly because of its large impact on traffic safety conflicts. The American National Highway Traffic Safety Administration (NHTSA) has estimated that in approximately 25-30% of traffic accidents, driver distraction is a contributing factor (Wang, Knipling & Goodman, 1996). Driver distraction manifests itself in many ways, such as eating and drinking, tuning the radio, engaging in a conversation with a passenger or through a mobile phone, entering a destination in a navigation system or dialling a telephone number (Brookhuis, De Vries & De Waard, 1991).

The strong increase in mobile phone use while driving has served as a catalyst to driver distraction research. Epidemiological studies showed that the likelihood of being involved in a conflict or accident while using a mobile telephone was four times as high compared to not using a mobile telephone (Redelmeier & Tibshirani, 1997, McEvoy et al., 2005). The Dutch Institute for Road Safety Research SWOV calculated that in 2004 nearly 600 victims of traffic accidents could have been saved in the Netherlands alone if mobile phone use while driving were banned, i.e. approximately 8% of all registered hospitalized and fatally injured in the Netherlands (Dragutinovic & Twisk, 2005). Furthermore, some studies show that mobile phone users wear their seat belts significantly less than other drivers, leading to an increase in the seriousness of injuries as a consequence of traffic accidents (e.g., Eby & Vivoda, 2003). In other words, phoning while driving poses a serious traffic safety risk.

Whereas the aforementioned numbers focus merely on the risks of mobile phone use, driver distraction in the broader sense presents a general risk for traffic safety. The driving task is complex and demanding in terms of visual and cognitive attention. Without focused attention on the primary task, drivers are at risk of responding more slowly or less appropriately to complex or changing situations that require their full attention (e.g., Anttila & Luoma, 2005; Hancock, Lesch & Simmons, 2003; Lamble, Kauranen, Laakso & Summala, 1999; Patten, Kircher, Ostlund & Nilsson, 2004). Furthermore, drivers have difficulty assessing their own driving performance, especially while performing highly engaging distracting tasks (Horrey, Lesch & Garabet, 2008). As a result, they might not be inclined to change their risky behaviour while being distracted, as they are not fully aware of the risk involved with their actions. Finally, even though many distracting tasks within the vehicle, such as dialling a phone number or eating, are initiated by drivers themselves, drivers do not strategically postpone these distractions (Horrey & Lesch, 2009).

When studying a complex concept such as driver distraction, stemming from many sources and manifesting itself in many forms, uniformity in definitions is an important constraint for clear and unambiguous research results. Driver distraction is a subset of driver inattention, a situation in which the primary driving task is performed without complete, focused attention on that driving task. Whereas inattention can also occur without a specific distractor, just by no longer paying attention, distraction is related to something (a task, object or person) that draws away the attention that is needed to perform the driving task adequately.

Unfortunately, the research community has not until this point shown consensus on the precise definition of driver distraction. The definitions used so far vary from "*Diversion of attention from the driving task that is compelled by an activity or event inside the vehicle*" (Treat, 1980), which is completely confined to the cause of the distraction inside the vehicle, to "*A disturbance imposed within a lateral or longitudinal control vehicle loop*" (Sheridan, 2004), focusing solely on the possible effects on vehicle control. An extensive overview of definitions of driver distraction used in human factors research is given by Lee, Young and Regan (2008). This overview clearly shows the large variation between definitions, and gives some insight into how long the research community has already been searching for a uniform definition of the construct. This variation in theoretical definitions inevitably leads to difficulties in the uniform operationalization of the construct of distraction. Is distraction determined by the sole presence of a distracting task, object or event that does not directly contribute to adequate driving, by the decrease in attention to the driving task, or by reduced performance on the primary driving task? Or is driver distraction the result of the combination of these three questions? The answer to such questions is needed to operationalize the concept of distraction, which in turn is the key to comparing the different studies and their results on this subject.

Defining distraction in a broad way creates a complete definition, but also one that is difficult to operationalize. But a definition which incorporates strictly defined behavioural effects is on the one hand very clear for all and easy to measure, but may on the other hand fail to capture important aspects of distraction (Lee, Young & Regan, 2008). The definition that is proposed by Lee et al. (2008), based on their overview of definitions is the following: *"Driver distraction is a diversion of attention away from activities critical for safe driving toward a competing activity."* This definition makes clear that safe driving performance deteriorates when the driver is distracted. Attention that is crucial for driving safely is diverted away by a distracting task, leaving too few resources available for adequate performance in the primary driving task.

The measurable effect of driver distraction, based on the definition in Lee et al. (2008), is a decrease in driving performance, since attention is diverted away from activities which are vital for safe driving. The most commonly used measures for driver distraction are longitudinal control (speed and headway measures), lateral control (TLC and SDLP), event detection and gap acceptance performance (Young, Regan & Hammer, 2003). Particularly if a negative effect is seen on more than one of these measures during the performance of a secondary task, it can be concluded that driving performance deteriorates and that this performance deterioration might be attributable to distraction by the secondary task.

However, safe driving can not always be determined solely on the basis of directly observable measures. Driving safely also requires that the driver is ready to respond adequately to possible upcoming safety-critical situations, and distraction can affect this readiness. If this is the case, and a driver is in such a (distracted) state that his readiness to respond to an upcoming hazard is negatively affected, this form of decreased performance does not show in measures of operational driving behaviour when the complexity of the driving environment is low. However, it can be argued that the driver is no longer driving optimally. In this way, the presence of a secondary task can lead to three possible situations, each with a different effect on driving performance. These situations will be briefly described below and it will be determined whether and how distraction can be measured.

i. No distraction

The presence of a secondary task does not distract the driver from driving safely per se. The driver can choose to give first priority to the primary driving task without letting the secondary task affect the level of driver performance. Although this may lead to poor performance on the secondary task, distraction from the primary driving task does not occur. Even in safety-critical situations, the secondary task will not withhold the driver from responding appropriately and in a safe manner. It is important to note, however, that this does not mean that 'undistracted' drivers always drive safely; with an estimated 25-30% of crashes being related to distraction (Wang, Knipling & Goodman, 1996), the majority is not related to distracted driving. Task demands can outweigh drivers' capabilities in certain situations, and drivers can also make errors while fully focusing on the driving task. According to several studies, drivers can typically show three types of risky or aberrant driving behaviour: lapses (absent-minded actions), errors (mistakes in perception and decision making), and violations (deliberate actions which are not according to traffic rules, or which are not constructive for traffic safety) (Parker, Reason, Manstead & Stradling, 1995; Reason, Manstead, Stradling, Baxter & Campbell, 1990). All of these actions can pose a risk for the driver and the surrounding road users, although their impact may vary largely according to the characteristics and severity of the resulting situation.

So although the single fact that a driver can choose to focus on driving does not necessarily mean that there will be no conflicts or risky situations, drivers do have a choice to 'ignore' possible distracters in favour of safe(r) or more attentive driving.

ii. Manifest distraction

In the second situation the presence of a secondary task leads to such a distraction that a measurable decrease in driver performance can be observed directly. The driver makes sub-optimal decisions and the number of conflicts increases. In this situation, distraction can be assessed directly through measuring its impact on driving behaviour in terms of operational driving tasks and conflict measures. Furthermore, by looking at conflict situations, described in the previous section on safety measures, a statement can be made about the likelihood of an accident.

iii. Latent distraction

In the third situation, directly observable measures of driving performance such as operational driving measures or conflict measures seem to indicate safe driving in the presence of a secondary task. However, this does not definitely establish that the driver is not distracted. After all, driving safely does not simply mean that the driver is not in an unsafe situation, but also that s/he can adequately respond to upcoming safety-critical situations in his current state. In a situation with latent distraction, a driver can manage the current situation, but at the limit of his/ her capacity, and would therefore struggle to respond to a suddenly upcoming safety-critical situation. Consider for example a driver on the highway, maintaining the appropriate speed and headway, and keeping the correct lane. This driver seems to drive completely focussed, based on current distraction measures. However, this specific driver might actually be busy with a secondary task, which absorbs at least part of the necessary attention, such as programming a navigation device. Now consider the case where this driver’s lead vehicle suddenly brakes. Our driver might not respond quickly enough to avoid the impeding hazard, due to the distracting secondary task. Although the original distraction measurements based on the low-demanding driving situation would have resulted in the conclusion that the driver was completely focussed, this was not actually the case. Summarizing, while distraction can indeed be present, the current assessment methods are unable to establish or measure it. It would be useful to identify a way of predicting whether a driver is affected by this form of distraction. A tool that detects reaction times to cues in the environment, such as the Peripheral Detection Task (PDT), could be useful for assessing the readiness to respond. We propose to use the PDT as a tool in assessing latent driver distraction (also refer to Schaap, Van der Horst, Van Arem and Brookhuis, 2012). For more information on the PDT, please refer to Chapter 3 (Research tools).

2.4.3 Mental workload

A concept closely related to distraction is mental workload. De Waard (1996) conducted extensive research regarding the concept of mental workload and the measures that can be used for its assessment. He distinguishes between task demands, task complexity, task difficulty, and mental workload. Task demands are determined by the end goal of the task. Task complexity is related to a number of stages that have to be completed in order to successfully attain the end goal. Finally, task difficulty deals with the ability of the operator to execute the task, depending on the state of the operator. While in normal circumstances it might be easy for a driver to cover a certain stretch of road, it may be more difficult to accomplish the same level of performance on the same route after a late night party. He defines mental workload as follows: *“Mental workload is the specification of the amount of information processing capacity that is used for task performance”* (De Waard, 1996).

De Waard shows that mental workload depends on a number of circumstances and can vary between individuals and over time (De Waard, 1996). Mental workload can be affected by individual and temporal characteristics of operators, such as personality traits and emotional state (for a summary of studies concerned with these aspects, please refer to Ganey, Koltko-Rivera, Murphy, Hancock & Dalton, 2004, and Szalma & Hancock, 2005). Other studies show that mental workload can be affected by the experience of failure in task performance, especially in women (Hancock, 1989), by previous mental workload circumstances (Hancock, Williams, Manning & Miyake, 1995), and by the effective time available to reach the goal set for the task at hand (Hancock & Caird, 1993).

De Waard (1996) describes the effects of task demands on mental workload in a model. Figure 2.9 depicts the model of the overall relationship between workload, task demand, and performance, as presented in De Waard (1996). The model describes the relation between performance, task demands and mental workload in situations where the aim of the operator is to keep performance high over a longer period of time. The workload-performance relation has been separated into six regions, each with its own characteristics. In the three A-regions (A1, A2 and A3), the demands of the task are at a level that allows the operator to achieve a high level of performance. In the A2-region, demand and workload are optimal, and performance can easily reach the desired level. In A1, performance remains adequate, but the operator has to exert state-related effort (i.e., computational effort through controlled information processing) to keep performance high; in A3, the invested effort invested is task-related (i.e., compensatory effort). In the regions B, C and D, the operator is affected by the level of demand, leading to suboptimal performance. In region B, demand and workload are at a level that task-related effort no longer increases performance, and performance declines. Region C depicts overload of the operator, leading to a low performance level. In region D (D for de-activation), the lack of task demand coincides with a high workload level that the operator cannot cope with, so that performance deteriorates (De Waard, 1996). This concept of high workload in situations with very low task demands is supported by other authors (e.g., Nachreiner, 1995); recent work by Warm, Parasuraman and Matthews (2008) also underlines the same concept. The authors describe how vigilance tasks, which were traditionally seen as undemanding and unstimulating, are actually related to high levels of distress and mental workload (Warm, Parasuraman & Matthews, 2008).

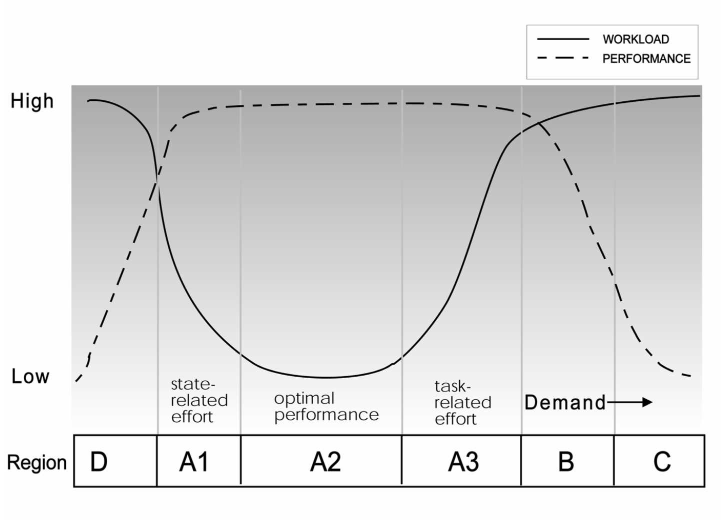

Figure 2.9 Workload and performance in 6 regions
(De Waard, 1996, Figure 2, pp. 24; reprinted with permission)

There are a number of ways in which mental workload can be measured, and some of these measures might be useful for an indication of distraction effects. The effects of increased mental workload can differ from one situation to another and from one individual to another. These differences depend largely on individual strategies and the region of performance involved, and measurements of the effects are best combined for a valid assessment of mental workload (De Waard, 1996). Due to either increased task demands or changes in driver state, drivers can feel a subjective increase in mental workload, can show physiological signs that stem from increased mental workload, and their task performance can be affected. Additionally, a decrease in performance of secondary tasks can occur. By combining the assessment results an overall indication of mental workload and driver state can be determined. Chapter 3 (Research tools) elaborates upon these mental workload measurements.

Mental workload can affect execution of different kinds of subtasks, from strategic tasks to operational tasks. It can therefore affect all three levels of the driving task. Figure 2.10 depicts this relationship between mental workload and the different levels of the driving task, including the interaction between task levels.

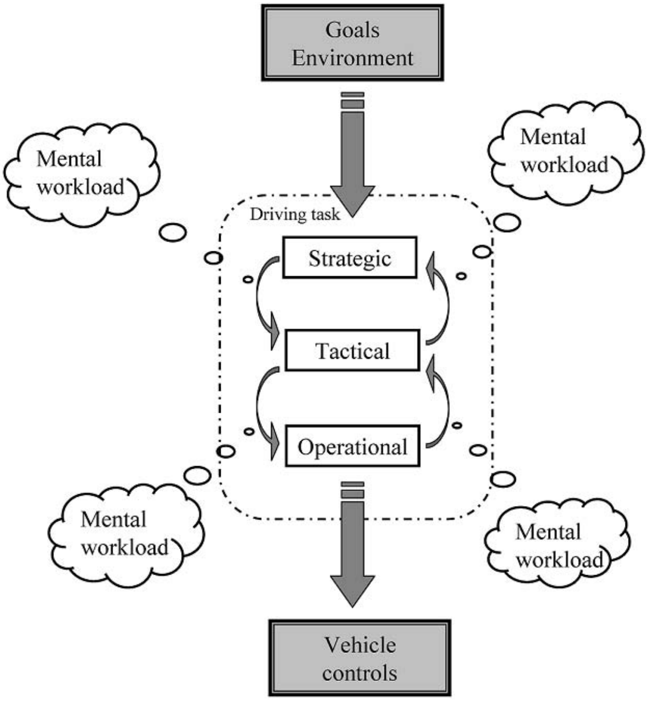

Figure 2.10 Mental workload can affect driving at different subtasks and at different levels of the driving task

2.4.4 Distraction and mental workload: bearing resemblance but not the same

Looking at the similarity between the assessment methods of driver distraction and mental workload one would be inclined to conclude that they are highly similar. Several studies actually equate an increase in mental workload to distraction, or impaired driving to an increase in mental workload. Some reservations about this are in order.

Presence of secondary task

The fact that distraction, by definition, can only exist in the presence of a competing activity, is not true for a change in mental workload. Hoedemaeker and her colleagues conducted a driving simulator study in which lane width and maximum speed were varied (Hoedemaeker, Janssen & Brouwer, 2002). Since no additional task was introduced, any effect seen could only be a result of the primary driving task and not of any competing activity. They showed that the percentage of highly frequent steering movements, a measure of effort exerted and therefore a measure for adequate performance of the primary task was significantly higher in the narrowest lane. Furthermore, subjective ratings (RSME, Rating Scale for Mental Effort, Zijlstra, 1993) confirm that driving was experienced to be more strenuous on narrow lanes and with increasing speed (Hoedemaeker et al., 2002). This is an example of a study in which mental workload was manipulated and measured, rather than distraction. This shows that mental workload is not necessarily accompanied by a secondary task, and that distraction does not need to occur when mental workload increases.

Motivation, effort and engagement

Although the sole presence of the secondary task may increase task demands in itself, as the demands of the secondary task supplement the task demands of the primary task, this does not necessarily mean that drivers will always become negatively affected by this additional task. Drivers' motivation to perform well in a certain task (either the primary or the secondary task) can have great influence on the degree to which drivers 'allow' themselves to be distracted, by directing the focus of attention to that specific task. As De Waard (1996) asserts, the instructions that are given to the driver are of great influence on the execution of the secondary task. Task instructions, or the resulting motivation to perform well on a specific task, can therefore influence safe driving performance greatly. This is also supported by other studies. For instance, Redenbo and Lee (2009) studied driving behaviour in combination with secondary (arithmetic) tasks, and varied the instructions to include task prioritization. Primary task performance was measured by reaction times and accuracy. The authors found that a high prioritization of (aspects of) the main driving task led to similar task performance in dual-task conditions as in single-task conditions. In other words, a possible distracter, an arithmetic task, did not actually distract drivers from their task in situations where they were motivated to not become distracted from their primary task, regardless of task demands. Because motivation and prioritization play a role in addition to task demands, it can therefore not be stated that an increase in mental workload directly translates into driver distraction. After all, distraction leads to decreased driving performance, and that is not necessarily the case in any situation where a secondary task is performed.

As it turns out, drivers distinguish between different types of secondary tasks, even without instructions, and safe driving is a key factor in making this distinction. Cnossen, Meijman and Rothengatter (2004) hypothesized that the nature of the secondary task may be important, and that secondary tasks serving the driving task (e.g., map reading) could receive higher priority than other secondary tasks (e.g., tuning the radio). Participants in a driving simulator study were asked to perform a working memory task (irrelevant for driving) and a map reading task (relevant for driving). In high demand conditions, the irrelevant task was indeed neglected, but the highly relevant map reading task resulted in more swerving, indicating that the subjects looked at the map despite the high task demands. Apparently, drivers protect high-priority task goals (safe driving) at the cost of lower-priority tasks, even if this results in becoming equally distracted (Cnossen et al., 2004).

A recent meta-analysis of effects of mobile telephone use on driving performance (Horrey & Wickens, 2006) showed that relatively demanding conversation tasks showed greater costs in driving performance than did relatively easy information processing tasks. This may be due to the greater 'engagement' associated with actual conversations (Horrey & Wickens, 2006). Furthermore, McKnight and McKnight (1993) compared concurrent driving and conversing at two complexity levels. They found that intense conversations were significantly more distracting than casual conversations. The level of distraction was measured by the proportion of appropriate responses to situations that required a speed or direction alteration, such as decelerating lead vehicle. The authors suggest that this significant difference between the two types of conversations is due to stronger engagement of the drivers in this complex conversation task (McKnight & McKnight, 1993).

One could think that task-related effort (the compensatory effort invested in the A3 region of the mental workload scheme, presented in Figure 2.9) is similar to engagement; they both represent focusing on task performance and investing energy in optimal performance on the primary task. However, the related effects are not the same for mental workload and driver distraction; in fact, they have opposite impacts on mental workload and distraction. When investing task-related effort, meaning that the driver focuses on increasing the performance of the main task at the cost of invested energy, mental workload increases. With distraction, the effects are opposite: as a stronger engagement leads to increased performance, the distraction from the secondary task decreases. So while for both concepts the performance increases as a result of the invested energy, mental workload increases and distraction decreases as a result of this task-related effort or task-engagement. It can be concluded that a driver's motivation to perform well in a certain task and the related engagement in the primary and secondary tasks influences whether or not the driver 'allows' him- or herself to be distracted. The primary task of safe driving can be protected by the driver, and this does not necessarily have to be connected to a certain level of mental workload.

It should therefore be noted that mental workload and distraction are not the same, and that manipulating mental workload does not necessarily lead to driver distraction. Therefore it is very important that the distinction between the two concepts is upheld, both in research question formulation, in experimental designs, and in measurement tools.

It is clear that both (in)attention and mental workload play an important role in the way the driving task is executed and the level of alertness that drivers demonstrate. However, having focussed attention on vital aspects of the driving task is not the sole determinant of the performance of the driver. Another vital aspect of good performance in complex traffic situations is the driver's ability to assess and predict the situation, and determine the action which is the most appropriate for the situation at hand. Section 2.5 will reflect on this aspect of driving.

2.5 Situation awareness

In dynamic, complex and safety-critical systems such as traffic, it is of vital importance for operators to have a good perception and comprehension of the current situation and possible situational developments. In 1995, Endsley presented a theory on this concept of understanding and foreseeing dynamic situation developments. She labelled this concept 'Situation Awareness' (SA), and defined it as "*the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (Endsley, p. 36). The theory behind this definition is that SA consists of three levels or hierarchical phases. At the first level, Level 1 SA, operators collect information about the current situation. This phase is also called 'Perception of the elements in the environment' (Endsley, 1995). The second level, Level 2 SA, is where operators interpret the information perceived and form an image of the current situation in the light of their goals, hereby using their knowledge and experience. This level of SA is therefore also called 'Comprehension of the current situation'. The third level (Level 3 SA), finally, consists of the prediction of future developments of the situation. To reach this level, a proper level of understanding of the current situation is required. This phase is what Endsley calls 'Projection of future status'.

Several factors can have an influence on situation assessment, the process of acquiring SA: the operator's abilities to acquire SA (experience, training and inabilities); system design (the way in which information is provided and presented); and features of the environment, such as task complexity, workload, and stress. Evidence also exists for the assumption that the way a problem is framed (goals) influences the way in which SA is reached and the level of SA acquired (e.g., Gollwitzer & Moskowitz, 1996; Vicente & Wang, 1998). As task complexity increases, SA becomes more important, since the prediction of future events can have a larger role in deciding which action to take next. Finally, multiple studies have linked the levels of the driving task (Michon, 1971) to the levels of SA (e.g., Ma & Kaber, 2005; Matthews et al., 2001; Ward, 2000). They suggest that drivers are engaged in actions on vehicle controls for stable vehicle control, which is a semi-automatic process requiring Level 1 SA to ensure that the operations have an appropriate outcome. At the tactical level, both Level 1 SA and Level 2 SA are required for ensuring that manoeuvring through the traffic are the environment are done appropriately (including a short span projection of future situations). Level 3 SA, finally, is related to longer term planning subtasks at the strategic level, which require the formulation of navigational plans and thus more extensive projection. The other two levels, Level 1 SA and Level 2 SA, are used in task execution when task comprehension and perceptual integration are involved (Matthews et al., 2001).

SA is highly temporal, meaning that information has a short tenability and needs to be updated frequently. Van der Hulst (1999) stated that reaching a high level of SA not only involves continuous updating of information and knowledge, but also confidence in the correctness of both the content and the timeliness of this knowledge. Driving SA has certain characteristics which are relevant for the driving task. First of all, recognizing and anticipating possibly hazardous situations are important subtasks of driving (e.g., Vlakveld, 2011), which can be interpreted as the projection of the future status of the traffic environment. Pradhan, Pollatschek, Knodler and Fischer (2009) showed that training can positively influence novice drivers' hazard perception skills, even in situations which were not part of the training. Furthermore, Jackson, Chapman and Crundall (2009) showed that processing time is an important factor in SA, especially for novice drivers. Novice drivers take longer to process information in the first two levels of SA, but can reach the same level of SA when given enough time for these first two stages (perception and comprehension). Since driving is partly a self-paced task, novice drivers might benefit from adopting a lower speed, since this allows for a longer processing time of possibly hazardous situations and therefore creates the circumstances for a higher level of SA.

SA was linked with expectations by Chauvin and Saad (2004). They stated that drivers (and especially experienced drivers) compare the acquired information to reference situations they have encountered before, and form expectations about the behaviour of other road users based on these typical situations. Whenever a roads user behaves differently from what was predicted, drivers increase their level of "monitoring" or take an anticipatory regulating action, such as speed reduction or lane change (Chauvin & Saad, 2004). Unexpected events might lead to a (feeling of) decreased SA which drivers try to neutralize by compensatory behaviour. Concluding, SA plays an important role in driving, both in normal driving and when encountering unexpected, safety-critical situations on the road.

2.6 Advanced Driver Assistance Systems and behavioural adaptation

As the matrix in Figure 2.4 showed, there are many levels at which drivers need to take decisions, take actions, or perceive their surroundings. For each of these levels, there are ways of supporting drivers in having a more comfortable, safe or time-efficient experience by means of intelligent in-vehicle systems. At the strategic level, a navigation system can help in making route choices by selecting the fastest, shortest, or perhaps the most scenic route possible, depending on the driver's wishes. Technologies for the support of tactical or operational level driving tasks are also being developed. Drivers may for instance be supported in maintaining a constant speed or distance from a predecessor (ACC, Advanced Cruise Control), in the forming of platoons with other vehicles on the road for safe and fuel-efficient driving, or in braking in unexpected situations, such as when a pedestrian suddenly crosses the street (Lindner et al., 2009). These systems are called Intelligent Transport Systems (ITS). The group of ITS aimed at supporting the driving task at the tactical and operational level and that is located inside the vehicle is often called Advance Driver Assistance (ADA) Systems.

2.6.1 Different types of ADA Systems

ADA Systems come in many varieties, but their common denominator is that they support the driving task at either the tactical or the operational level, and that they are vehicle-based. ADA Systems can be categorized by means of many aspects, of which we will discuss three here.

i. Level of support

ADA Systems can differ in the level of support they give the driver. They can assist drivers at three levels: by informing, by supporting part of the driving task (for instance by giving counter-pressure on the gas pedal), or by taking over (part of) the driving task. In-vehicle information systems (IVIS) can provide the driver with information about a certain aspect of the driving task, the driving situation, or the driver's current state. For instance, drowsiness detection systems (e.g., Daimler's [2010] Attention Assist) warn the driver if they detect that the driver is showing signs of drowsiness or sleepiness and inform them to take a break. Systems can also warn drivers in the case of speeding (current navigation systems often include this feature), or in other risky situations. An example which can be useful in urban settings is curve speed warning. These ADA Systems warn drivers when their speed is too high for an upcoming curve. The system can be based either on a digital map containing road geometry information to enable a safe speed estimate, or on particular curves that are known to be hazardous for speeding (Bishop, 2005, p. 106). Supporting systems help the driver by assisting in part of the driving task, for instance by starting a certain task or preparing the car for faster execution of a task. An active gas pedal, for example, can give counter pressure indicating that drivers should release the gas pedal slightly (refer to Van Driel, Hoedemaeker & Van Arem [2007] for more information on the congestion assistant, an integrated application of an active gas pedal). Another application is a lane keeping assistant, which can assist the driver in staying in the correct driving lane. One of the ways in which this system can assist the driver is by giving a short torque to the 'wrong' direction when drivers tend to cross their lane boundary (Kullack & Eggert, 2010). This system relies on drivers' reflexes to react and execute the desired steering action in the correct direction, and can effectively prevent the crossing of lane boundaries (Kullack & Eggert, 2010). In urban situations, this support can take the form of parking assistance, such as the Intelligent Parking Assist, first introduced by Toyota (Bishop, 2005, p. 112). This system can be used to assist the driver in difficult parking situations, although the driver always remains in charge and responsible for supervising. Finally, ADA Systems can also take over the driving task, whether partially or completely. A well-known application taking over part of the driving task is Cruise Control, which has in the last decade been adapted to include (time) headway (Advanced Cruise Control, ACC). It does not only maintain the driver's own desired speed but also adapts the vehicle's speed to the car in front, thus always maintaining a minimum distance or time headway between the two vehicles. ACC has been shown to have positive effects on traffic safety when used on highways in non-congested situations, in which cases it also reduces fuel consumption (SWOV, 2008). An application specifically designed for urban situations is a pedestrian detection and avoidance system, which brakes when pedestrians are close to the vehicle. Autonomous driving systems may also be feasible in the future, as the technology to accomplish autonomous driving already exists (e.g., Urmson et al., 2008).

ii. Driving task

ADA Systems can provide assistance for tasks at both the tactical and the operational level. Operational level tasks which can be supported by ADA Systems include collision avoidance, braking, or controlling the steering wheel. ADA Systems for operational tasks help drivers to maintain control over their vehicles. For example, by activating the brake pedal shortly before an impeding collision, Brake Assistance can assist in immediately applying the maximum level of pressure to the brake, due to which a full stop can be reached faster than without this brake activation. Support for tactical tasks, on the other hand, can include assistance for choosing the appropriate lane and maintaining an appropriate distance to surrounding vehicles. Figure 2.11 depicts the relationship between ADA Systems and the tactical and operational levels of the driving task.

iii. Level of cooperation

Third, the level of cooperation with other vehicles is part of the classification we use for ADA Systems. The information ADA Systems use is gathered by on-board sensors. ADA Systems can support the driver using information from their own sensors (autonomous systems; Bishop, 2005), or can communicate with other vehicles or beacons in the infrastructure to gather information, in addition to using their own on-board sensors (cooperative systems; Bishop, 2005). The biggest advantage to communicating with other vehicles or the infrastructure lies in extending the vehicle's 'information horizon', enabling ADA Systems to have information about locations beyond the vehicle's own sensors. This gives opportunities for proactive support, such as initiating a slower speed when an obstacle is detected behind an upcoming curve, or adopting larger safety margins when information about upcoming bad weather is transferred from vehicles downstream.

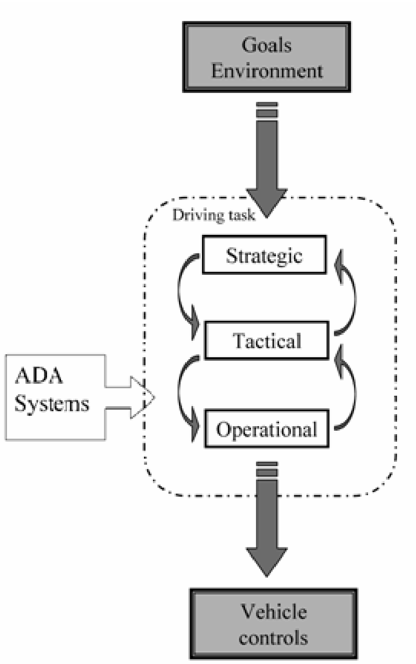

Figure 2.11 The relationship between ADA Systems and (the operational and tactical levels of) the driving task

2.6.2 Behavioural adaptation

One difficulty with ADA Systems as the solutions to traffic problems is that the actual effects of these systems may remain unknown until they have been implemented at a large scale. It is estimated by some that the number of collisions will decrease by as much as 69% when using an intersection collision warning system (Liu, Özgüner & Ekicim, 2005). But some researchers dispute the extent of such positive effects of ADA Systems, especially at first introduction. For example, Janssen, Wierda and Van der Horst (1995) predict that the introduction of automated support systems will lead to counterproductive adaptations to the support system, such as more risk-taking behaviour and decreased alertness in drivers, and to increased accident severity, before it could lead to the positive effects predicted by others. At least some of these predictions are supported by results from a driving simulator study with Intelligent Speed Adaptation (ISA), conducted by Comte (2000). She found that drivers showed riskier behaviour when the ISA system was operational. Another study into multi-tasking and partial automation (Harris et al., 2002) concludes that automating one task in a multi-task situation (such as driving) may decrease task demands and mental workload, but this does not necessarily lead to an increase in performance for the remaining subtasks. Furthermore, the authors suggest that, although operators may report that they experience lower mental workload when a task is partially automated, it cannot be concluded that task related fatigue is also decreased (Harris et al., 2002).

The following definition of behavioural adaptation was given by the Organisation for Economic Cooperation and Development (OECD, 1990): "*Behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change*." (OECD, 1990; p.23). These adaptations may be either positive or negative. Generally, behavioural adaptation occurs at the (sub)task which is being supported by the assistance system. For instance, Adaptive Cruise Control (ACC), an extension of a normal Cruise Control system that also helps the driver keep a fixed headway distance to the car in front, triggers a change in speed control. In the case of an intervening ACC, this leads to a shorter headway, higher speeds and lower driver workload assessment (for an overview of studies and a meta-analysis of behavioural adaptation to ACC, see Dragutinovic, Brookhuis, Hagenzieker & Marchau, 2005). Furthermore, in a study into the acceptance of a Lane Departure Warning Assistance (LDWA) system, about half of the drivers indicated doing other, non-driving activities while driving with the LDWA system, because of lower levels of effort needed (Katteler, 2003). A cause for this may be that drivers continuously monitor their own driving performance, and compare the outcome of their actions to the expected results. If this leads to a positive evaluation of the drivers' results, the control loop tends to get biased, leading to a persistently more positive view of their own performance (Kovordányi, 2005). Many ADA Systems have some type of effect on mental workload. In cases where mental workload is lowered from an unsafe high level to a normal level, this effect is positive. However, as was described earlier in this chapter, mental workload can also reach a threshold level below which it becomes too low to keep up high performance levels. In these cases, decreasing mental workload by taking over subtasks from the driver might result in attention diversion or decreased vigilance. Kulmala et al. (2008) identified nine mechanisms through which ITS can impact traffic safety, such as modification of the behaviour of both users and non-users, modification of exposure and modification of accident consequence. It is of the utmost importance to keep in mind that behavioural adaptation can occur when developing new ITS. Behavioural adaptation can also be defined as too high acceptance of the system - and thus, over-relying on it when this is not safe (Katteler, 2003). Katteler distinguishes three indicators for too high acceptance of a support system: relaxation, compensation, and substitution. These are indicators that should be kept in mind when evaluating the usability acceptance of an advanced driver assistance system.

The level at which the change of behaviour occurs, is important for safety evaluation. A study conducted by Summala (2002) revealed that behavioural adaptation can occur both at a lower, perceptual-motor level and at a higher, cognitive level. Change at the first level is suggested to be more dangerous, because of the subconscious change and the lack of feedback mechanisms for this level of adaptation (Kovordányi, 2005).

2.6.3 Human-centred design and development of ADA Systems

Concluding, ADA Systems should be developed with drivers in mind, and even more preferably based on their needs. Different ways exist to study drivers' preferences, for example using questionnaires (Van Driel, 2007). This research tool can adequately give insight into drivers' opinions and attitudes, and this plays a major role in the understanding of acceptance and market deployment. Another approach to incorporate driver's preferences into a human-centred design of ADA Systems was developed by Tideman, Van der Voort and Van Arem (2010). They used virtual reality simulation and gaming principles in a design process that gave users an active role in selecting their preferred options for a lane-keeping system.

Both approaches give a lot of information on drivers' preferences. However, drivers are not always fully capable of formulating their own safety needs. This is related to a number of aspects of the driving task and the range of situations in which this task is executed. Only a very select number of errors, lapses and mistakes lead to safety conflicts, and in turn a very small portion of conflicts is so severe that it leads to an actual accident. Although conflicts and accidents originate from similar situations, there are only a few moments that startle drivers and make them conscious of their (possibly risky) driving style. After all, if everything seems to go right, there might not be a reason to start doubting ones own functioning. Furthermore, studies of drivers' assessments of their own driving performance show that most drivers believe they drive better than their peers (e.g., Goszczynska & Roslan, 1989; Lajunen, Corry, Summala & Hartley, 1998). Moreover, we described earlier how the different levels of task execution (Rasmussen, 1987) relate to levels of more or less automatic task execution. Experienced drivers are no longer consciously thinking about every move to make and every action to execute, but rather execute many tasks at the skill-based or rule-based level. This is very positive in the light of efficient use of attentional resources. However, it leads to situations in which drivers are no longer conscious of operational actions. Concluding, although drivers might be able to formulate their attitudes and desires, they are not always capable of identifying their (safety) needs.

This thesis describes a series of experiments with the aim of identifying these needs, by means of determining actual driving behaviour in safety-critical situations. With this information, the development of ADA Systems can be based on driving behaviour safety needs, rather than on engineers' interpretations of drivers' needs.

2.7 Framework

This thesis focuses on driving behaviour at urban intersections, and specifically the bottom-up interaction between operational and tactical driving task at this location. Bottom-up interaction between driving tasks occurs when expectations are not met and a safe or efficient outcome of the situation requires compensation behaviour. Mental workload and the severity of these situations can have an effect on this bottom-up interaction. This interaction is depicted graphically in Figure 2.12. The solid, red line in Figure 2.12 encloses the focus of the experimental parts of this thesis.

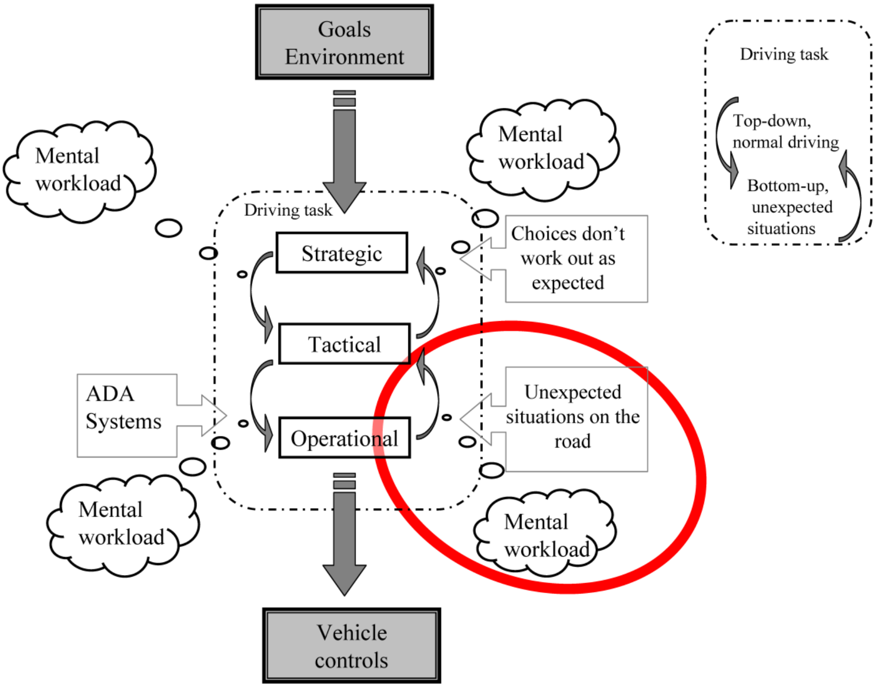

Figure 2.12 Theoretical Framework. The main focus of this thesis is on the bottom-up interaction between the operational and tactical level, and on the influence of mental workload and the severity of unexpected situations on this interaction (solid red line)

Chapter 3

Research tools

This thesis is concerned with compensation behaviour during and after safety-critical and unexpected events, and with the influence of mental workload, event urgency and driver characteristics on these compensatory actions. In order to determine this complex interaction between the driving task, driver characteristics, expectancies, mental workload, and the situations encountered, a large number of measures need to be taken during controlled experiments. All aspects of this complex interaction have one or more indicators which can be measured by different research tools. In this chapter we describe tools that can be used to record these indicators, and give an overview of the research tools that we used for our experiments.

3.1 Measuring driving behaviour

Driving behaviour can be measured by using a number of different tools. Four of the most used research methods for driving behaviour research are Field Operational Tests (FOT's), experiments with instrumented vehicles on test tracks, driving simulator experiments, and self report measures. They are different in external validity and controllability of the situations studied, and in the aggregation level of investigated driving behaviour for which their use is appropriate. In fact, there often is a trade-off between validity of the situations studied and controllability of these situations, which is graphically depicted in Figure 3.1. Self-report measures are not depicted in this figure, since they measure attitudes, experience and/ or preferences rather than behaviour and actions related to certain traffic situations.

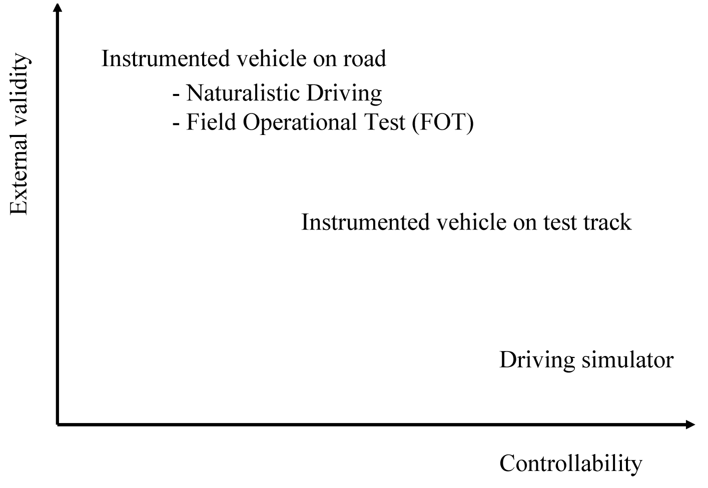

Figure 3.1 External validity and controllability of situations studied in driving behaviour research (adapted from Anund & Kircher, 2009)

External validity refers to level at which the methods and tools of a study approximate the real life situation that is being studied (Brewer, 2000); in other words, it describes the extent to which the 'looks' of a research tool represent reality. External validity is a specifically important constraint in the case of simulator studies, and will therefore be discussed more deeply in the following paragraph (3.1.3) on driving simulators. Controllability of a study refers to the degree of control that the researcher exerts or can exert over the study. This is not only related to the driving scenario but also to the selection of participants and their information and preparation.

In this section, all three types of research tools will be described, as well as their advantages and drawbacks for different types of behavioural research.

3.1.1 Instrumented vehicles: road and test tracks

In an instrumented vehicle, sensors record the actions undertaken by one driver. These records can also include characteristics of the driving situation, so that location on the road, steering wheel angle, speed, (time and distance) headway, performance on secondary tasks, video recordings of participants' expressions, eye movement data, vehicle environment and many other variables can be recorded simultaneously. Due to the fact that these variables can be combined in analyses, it is possible to determine which factors lead to certain situations, for instance driver distraction or traffic conflicts.

Instrumented vehicles can be used in two different settings: on real roads and on test tracks. The controllability and validity of the studies differ between test tracks and real-world situations. The level of control that can be exerted over scenarios, events, driving circumstances and participant safety is higher on a test track, but this goes at the cost of external validity. External validity is higher when driving on real roads, especially if the test track has an unrealistic shape (for instance, oval tracks). In both naturalistic driving studies and FOTs, drivers have free choice of routes and other aspects of driving behaviour, so researchers exert no control over the driving scenarios, so controllability is lower than in strictly experimental settings.

Two types of studies can be performed with instrumented vehicles on the road: naturalistic driving studies or Field Operational Tests (FOTs). Naturalistic driving studies focus on normal driving behaviour in everyday (current) circumstances. These studies are large-scale tests in which participants use equipped vehicles for their daily lives and data from their driving behaviour are collected. The first large-scale naturalistic driving study was the 100-car study (e.g., Klauer, Dingus, Neale, Sudweeks & Ramsey, 2006; Neale, Klauer, Knipling, Dingus, Holbrook & Petersen, 2002). In this study, 109 primary drivers (241 drivers in total) drove 100 cars over a period of roughly one year in the DC/ Northern Virginia area. Data were recorded over approximately 3.5 million vehicle kilometres (2 million miles) with 761 near-crashes and 8,295 incidents, and included inter alia digital video, GPS, front and rear sensors and lane tracking data (VTTI, 2010).

Field Operational Tests focus on the effects of equipping vehicles with ADA Systems or other Intelligent Transport Systems (ITS). Examples of recent FOT's are euroFOT (2010) and Volvo's Truck Field Operational Test (Volvo Trucks, 2005). The ITS tested in FOT's range from safety systems to systems for more efficient driving and comfort increasing systems. For instance, the trucks in the Volvo Trucks FOT were equipped with Advanced Cruise Control (ACC), a Rear-End Collision Warning System (CWS), an Electronically Controlled Brake System (ECBS) and new generation disk brakes; in euroFOT, 1,000 cars were equipped with eight different systems for safer and more efficient driving.

Both in FOT's and in naturalistic driving studies, subtasks at the tactical and operational task levels can be studied in a naturalistic environment. Strategic choices such as route planning can be inferred indirectly from the recorded data.

Instrumented vehicles can also be used for experiments on closed-circuit test tracks. In this situation, strategic choices are not part of the task, but tactical and operational tasks can be recorded both from inside and from outside the vehicle. Furthermore, the situations encountered by the driver can be controlled and monitored more closely than on real roads, since situations can be staged and repeated better than on real roads. However, this can go at the expense of external validity.

3.1.2 Driving simulator

The second tool described here is a driving simulator. A driving simulator is a mock-up of a vehicle, surrounded by screens on which a virtual environment is projected. By controlling the vehicle actuators (steering wheel, brake pedal, throttle, gears) drivers can control the vehicle and thus 'drive through' the simulated environment. A driving simulator can easily be used to measure all types of tactical and operational driving behaviour, such as speed, lateral position, pressure on the gas pedal et cetera. While it is also possible to measure strategic behaviour, in practice this is more difficult to realize. The strategic level describes higher level goals determined by the driver, and goals of this type are difficult to influence and can only be inferred indirectly from the registered driving behaviour. Moreover, making appropriate route choice decisions usually requires a certain level of familiarity with an environment, and in order to study this in an experimental setting all participants have to obtain the same level of familiarity before the study.

Driving in a driving simulator is always safe from a traffic safety view, because a manoeuvre that would be considered unsafe in real life will never result in a real accident in the simulated environment. Furthermore, the environment and the behaviour of the other road users can be fully controlled, so situations are highly reproducible and controllable. Simulated situations can be repeated many times to set expectations on the side of the participants, and all participants can encounter exactly the same situations. Also, anything can be simulated, as long as the software can calculate and visualize it. In other words, everything, including situations which are non-existing or dangerous in real life, can be studied.

On the other hand, this is also the main disadvantage of driving simulator experiments. Since safety is not a critical issue in driving simulator experiments, participants may behave in a different way in simulated situations than they would normally do in similar real-world situations. Moreover, most simulators, except for highly advanced driving simulators with moving bases, do not capture the movement of a driving vehicle correctly, and this might also influence the participants' behaviour. Therefore, the validity of driving simulator research is an issue that needs close attention when designing an experiment (Kaptein, Theeuwes & Van der Horst, 1996).

Kaptein et al. (1996) describe two types of driving simulator validity that can be distinguished. *External validity* refers to the looks of the simulator and relates to the simulator's fidelity. The simulator sound and level of detail in the virtual environment also contribute to the simulator's external validity. *Internal validity*, on the other hand, is the predictive value that the results from studies in the driving simulator have. This kind of validity can be either relative (the type of driving behaviour and the directions of behavioural changes are similar to those in real life), or absolute (the behaviour shown by participants in the driving simulator resembles the behaviour that people in real life would show in a similar situation). When designing and experiment, one has to determine which type of validity is needed to get generable results.

The aforementioned research tools differ in controllability and external validity, as well as in other characteristics, such as participant safety, deployment possibilities, time frames and other aspects of experimental setups. Table 3.1 gives an overview of the characteristics which are most relevant to our research for each research tool which was discussed.

3.1.3 Self-report measures

A third tool used for behavioural studies is a self-report measure, such as a questionnaire. Self-report measures can be used to study drivers' opinions or experiences as well as their (self-reported) driving styles, and reflections on aspects of the driving task. They record their measures on an aggregated level, meaning that the measurements are not sensitive to short-term changes but give insight into longer-term aspects of driving behaviour. Self-report measures are often used in conjunction with the previously mentioned tools, instrumented vehicles and driving simulators.

Self-report measures can consist of questionnaires and/ or rating scales. A commonly used questionnaire on driving style is the Driving Style Questionnaire (DSQ), developed by French, West, Elander and Wilding (1993). The type of driving style is determined by questions about 6 dimensions related to driving style: speed, calmness, social resistance, hesitancy, focus, planning and deviance. Answers to questions related to, for instance, choice of speed, headway, seat belt use and violations are related to these dimensions and give insight into the driving style adopted by the participant. Another well-known questionnaire is the Manchester Driving Behaviour Questionnaire (DBQ), developed by Reason, Manstead, Stradling, Baxter and Campbell (1990), and validated for international use by Åberg and Rimmo (1998), Blockey and Hartley (1995), Lajunen, Parker and Summala (1999), and Mesken, Lajunen and Summala (2002), among others. The DBQ measures the concepts of errors, lapses and violations in driving behaviour by asking drivers several questions about the frequency of certain types of behaviour, such as sounding a horn out of annoyance, overtaking on the inside or forgetting the location of their parked car. Other self-report measures exist, for instance on the subjective experience of mental workload (please refer to Section 3.2 for more information on these subjective measures for mental workload).

Questionnaires are highly controllable and reproducible, if the validity and applicability to a certain type of study and research question are guarded. However, a questionnaire can only reveal information about conscious decisions, actions and processes, since participants need to verbalize decisions that might be made while driving. Operational actions are mostly performed in a rule-based manner, which often does not require conscious decision making. Questionnaires are therefore very useful to study higher level variables such as personality, experiences, expectations or attitudes, but are less useful for determining the operational level behaviour that would be exhibited in a certain situation, such as the level at which the gas pedal is pressed or the direction and duration of glances. Furthermore, questionnaires or surveys can convey correlations but not causal relations.

Rating scales can have different dimensions. Some take the form of a single dimension along which the respondent is asked to indicate how they rate a particular aspect. Others include more dimensions. For instance, in the NASA Task Load Index (NASA-TLX) rating scale (Hart & Staveland, 1988), drivers give a subjective rating of experienced workload on six rating scales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration (Hart & Staveland, 1988). These multi-dimensional ratings can be combined to calculate an overall level of perceived mental workload. Oborne (1976) distinguishes analogue and category rating scales. With analogue scales, respondents mark their rating of the investigated aspect on a straight line with a fixed length. Analogue scales can provide information on an interval scale, but only if participants use both the scale extremes, and not just the centre of the scale. Category scales divide the one scale into several categories from which participants choose the one which best describes their rating. This scale provides information on an ordinal scale rather than an interval scale, which might complicate statistical comparison and interpretation.

3.2 Mental workload measurements

In Chapter 2, we defined mental workload as "*the specification of the amount of information processing capacity that is used for task performance"* (De Waard, 1996). Any task which requires a certain amount of attention or concentration puts a certain load on the available cognitive capacities of the driver; this is called mental workload. Driving in itself brings along with it a certain level of workload, comprised of physical, visual and cognitive load. Secondary tasks can possibly interfere with the main goal of driving safely, especially if the type of workload is similar to the type of workload placed on the driver by the driving task itself.

There are four main methods for mental workload assessment (Meshkati, Hancock, Rahimi & Dawes, 1995). All measures are related to the ways in which operators can react to increased mental workload. Operators can feel an increase in mental workload, show physiological signs that stem from increased mental workload, and/ or show decreased task performance. Also, performance on secondary tasks that do not interfere with the primary task of safe driving can decrease. Chapter 2 described how effects can differ from one situation to another and from one person to another. These differences depend largely on individual strategies and the region of performance involved, and measurements of the effects need to be combined to complement each other (De Waard, 1996).

3.2.1 Primary task performance

Increased mental workload can impair driving performance in certain situations. Measures sensitive to increases in mental workload are the Standard Deviation of Lateral Position (SDLP), the Standard Deviation of Steering Wheel movements (SDSTW) (De Waard, 1996), and the Steering Wheel Reversal Rate (SRR) (Macdonald & Hoffmann, 1980); these are all measures of tasks at the operational level. SDLP is a measure for the amount of serving a driver shows and it often used for mental workload measurements, although increasing mental workload was not always found to lead to increasing SDLP (De Waard, 1996). SRR is calculated by the number of times per minute that the direction of the steering wheel changes (Macdonald & Hoffman, 1980). Both SRR and SDSTW is always measured at straight road sections, and an increase in mental workload is usually found to lead to an increase in the SD of movements of the steering wheel (De Waard, 1996). The duration of glances to the mirror (mirror checking) is also sensitive to changes in mental workload (Fairclough, Ashby & Parkes, 1993).

Table 3.1 Advantages and disadvantages of different driving behaviour studies

Research characteristic	***Instrumented vehicle - real road***	***Instrumented vehicle - test track***	***Driving simulator***
External validity*	Very high	Moderate: participants know they are being observed; tracks not always realistic	Low-moderate: virtual environment, participants know they are being observed, no actual safety-critical situations, but simulation of these situations can have high validity
Control over driving scenario*	No control over driving scenario, route or any other driving circumstance	Moderate control over other road users and (staged) events due to safety restrictions	Very high control over scenario, e.g. route, weather, sight, timing and events
Repeatability of events	No control over events	Scenarios can not be repeated exactly but repetition can be approximated	Scenarios can be repeated
Task levels	Tactical and operational task levels; strategic choices can be inferred indirectly from recorded data	Tactical and operational task levels	Tactical and operational task levels
Use of mental workload measurements*	No measurements other than driving performance possible (they remind participants of being observed)	Obtrusive measurements possible but might influence validity	All measurements possible, will probably not influence validity
Participant safety*	Participants responsible for their own safety, no precautions necessary	Test track safety necessary	No safety-critical issues, other than possible simulator sickness
Average time duration of experiments	Several months	Several minutes to several hours	Several minutes to several hours

* Information in these cells was obtained from (Anund & Kircher, 2009)

Finally, Brookhuis, De Waard and Mulder (1994) developed a measurement of mental workload by means of a car following task. Participants were required to follow a leading vehicle at a safe and constant distance in real traffic. The leading vehicle's speed was preset by the researchers, and would fluctuate within a preset range of speeds. Reaction times and coherence and phase shift of the driver's response to the lead vehicle's changing speed were recorded and used as a measurement of impaired driving. Car-following is a tactical subtask in the hierarchical model of the driving task (Michon, 1971). It is included in a list of major mental workload measurement techniques by De Waard (1996), although one could argue that it is rather a measurement of driver distraction (through impaired driving) than of mental workload (for a discussion on the similarities and differences between mental workload and driver distraction, see Section 2.4).

Compensatory driving behaviour can also be found, and is often seen as a way to reduce the demands of the driving task. When task demands increase, a decrease in driving speed can be found (e.g., Alm & Nilsson, 1994; Lansdown, Brook-Carter & Kersloot, 2004). However, in a study described by Horrey and Simons (2007), no evidence was found that drivers adjust their safety margins during tactical driving. In fact, the authors suggest that during tactical driving, in which drivers accommodate multiple competing goals and monitor a dynamic driving situation, drivers expose themselves to greater risk in dual-task conditions than in single-task conditions. The difference with earlier studies lies in the fact that those studies often ask drivers to perform steady-state following tasks which are located at the operational level, rather than tactical driving tasks.

3.2.2 Secondary task performance

When mental workload increases, task performance may decrease. This does not only occur for the primary task of driving, but also for secondary tasks. Any trade-off between driving performance and secondary task performance depends highly on the instructions given to the driver and the level of obtrusiveness of the secondary task. Embedded tasks are considered to be the best secondary tasks for assessment of the mental workload stemming from a certain driving situation, due to their low primary task intrusion (De Waard, 1996). Two examples of such embedded tasks are car-following and mirror checking, and an increase in workload can be determined by a delay in these tasks.

There are however secondary tasks that are not obtrusive and are also not embedded in the driving task. A number of secondary tasks have been developed for mental workload assessment. We will describe four of them here: the Paced Auditory Serial Addition Task (PASAT), the Lane Change Task (LCT), the time perception task, and the Peripheral Detection Task (PDT).

First, the Paced Auditory Serial Addition Task (PASAT), developed by Gronwall (1977) is a secondary task assessing the speed of auditory information processing and working memory. Participants listen to an audio recording with single digit numbers, which are presented at fixed time intervals, and are asked to add the two most recently presented numbers. For instance, if the sequence is 3 - 5 - 1 - 2 - 8, the correct response would be 8 (3 + 5), 6 (5 + 1), 3 (1 + 2), and 10 (2 + 8). The PASAT requires use of working memory, attention and arithmetic capabilities. See Tombaugh (2006) for an overview of studies into the PASAT.

Second, the Lane Change Test (LCT) (Mattes, 2003) is a quick and easy methodology that has been standardized by ISO standards (ISO, 2008), and that is intended to assess task demand resulting from in-vehicle systems. Drivers repeatedly perform lane changes when prompted by signs at the side of the road. Participants' lane change performance is determined by comparing the driven path from the (predetermined) ideal lane change path. The extent to which the dual task condition results in increased mental workload or driver distraction is supposedly reflected in the mean deviation between the actual driven course and the ideal path (mean deviation in lane change path, MDEV).

Third, the time perception method was originally developed for mental workload assessment in aviation research (Hart, 1978), and its application to simulated car driving has recently been validated in an experiment (Baldauf, Burgard & Wittmann, 2009). Participants are asked during driving to estimate the duration of a time interval, and to respond to an acoustic signal after the number of seconds in this time interval has passed. By pressing a button mounted on the steering wheel, they can state when they think the time interval has passed since the acoustic signal. In the mean time, participants are asked distracting questions to prevent them from directly counting the seconds. Baldauf et al. (2009) chose a time interval of 17 seconds. They found that the length of intervals increase with higher mental workload. Furthermore, the authors found that the time-production task was sensitive to workload level changes and did not influence the driving task (i.e., the measure is unobtrusive).

Finally, the Peripheral Detection Task (PDT) is based on the fact that visual attention narrows as workload increases (Van Winsum, Martens & Herland, 1999). Originally, the PDT was applied in a driving simulator setting with the stimulus presented on the simulator screen (Van Winsum et al., 1999). In later studies, drivers wear a headband with a LED in their peripheral field, so that the LED moves with the drivers' head movements (Van der Horst & Martens, 2009). The left part of Figure 3.2 shows the headband with the LED. The LED lights up randomly every 3 to 5 seconds. Drivers also wear a small switch attached to their index finger, which they are instructed to press every time they notice the LED light. In general, the index finger of the dominant hand is chosen for this, unless the experimental setup does not allow for this (e.g., with manual transmission). However, in certain situations, such as in a simulator or vehicle with right-hand manual transmission, drivers cannot constantly have their right hand located on the steering wheel, due to which they cannot press their right index finger against the steering wheel whenever they notice the LED lighting up. In order to register all reactions correctly, the switch is therefore placed on the index finger of the left hand in these cases (right part of Figure 3.2).

Figure 3.2 Headband with LED in peripheral vision of participant (left); PDT switch on left index finger (right)

Mental workload can be determined with the PDT by analyzing reaction times and the number of missed signals.

The PDT has been shown to be reliable to the demands of the driving task (Van Winsum et al., 1999) and is also sensitive to peaks in workload (Jahn, Oehme, Krems & Gelau, 2005), which is important for driving safety research due to changes in task demands.

3.2.3 Subjective measures

Operators can experience their mental workload and give a subjective evaluation. These self-report measures are questionnaires that were developed to measure workload in human-computer interaction, but can be used for many interaction tasks as well, such as driving. One example, the NASA-Task Load Index (Hart & Staveland, 1988) was already discussed in Section 3.1. Another example of a self-report measure is the RSME, the Rating Scale Mental Effort (Zijlstra, 1993). It is a single-dimensional measurement of invested mental effort, on which participants are asked to mark their subjective mental effort invested. The marks on the scale take the form of “Absolutely no effort”, “Considerable effort”, to “Extreme effort”. The Activation scale (Bartenwerfer, 1969), originally in German, is also a single-dimensional scale; the marks on this scale are of a different type than the RSME’s, with statements such as “I am solving a crossword puzzle” and “I am trying to cross a busy street”.

The main disadvantage of self-report measures of mental workload is that they are no objective measurements (Van Winsum & Hoedemaeker, 2000), although their face validity is high (De Waard, 1996). Also, only an overall rating of workload over a whole ride can be given without disturbing drivers in their primary task, so a focus on specific situations is not possible. However, self-report measures give a clear indication of the level of workload perceived by drivers, and are cheap and easy to apply. They can therefore be useful to include in almost any workload-related research.

3.2.4 Physiological measures

When an operator experiences an increase in mental workload, the response is also reflected in physiological measures. For example, operators with high workload can have more dilated pupils, start sweating, and show increased blood pressure and decreased heart rate variability. An important advantage of determining the physiological effects of increased mental workload is the unobtrusiveness of most of the measurements involved (De Waard, 1996). However, physiological measurements require complex interpretation of results, and may also reflect emotional strain and physical activity in addition to mental workload (Jahn et al., 2005). An increase in heart rate (HR) gives an indication of an increase in overall workload, whereas decreasing heart rate variability is more useful for determining an increase in cognitive, mental workload (Eggemeier & Wilson, 1991). Three frequency bands were identified in heart rate measurements, of which the middle frequency band (0.10 Hz) has been found to be specifically related to blood-pressure regulation and mental workload (De Waard, 1996).

3.2.5 Combining measures of mental workload

In order to get a reliable assessment of mental workload, it is important to combine different workload measures, since not all workload measures are sensitive to workload levels in the same regions (De Waard, 1996). Increased task demands and an increase in complexity of the environment both have an effect on the self-report scale RSME, and on the physiological measure ECG. Secondary-task performance, in particular the embedded task of car-following, is also sensitive to both sources of increased workload. For primary-task measures, this effect is not the same. While additional tasks lead to a decrease in SDLP and SDSTW, an increase in complexity of the environment increases both measures. Finally, heart rate variability is mostly sensitive to an increase in complexity (De Waard, 1996).

As was discussed in Chapter 2, not every increase in mental workload leads to the same effects for the same task in the same person, since motivation and the difficulty of the task as perceived by the operator play an important role in the resources invested. Also not every measure of mental workload is sensitive in the same performance area (De Waard, 1996). Figure 3.3 shows the measures and the performance areas in which they are sensitive.

3.3 Driver characteristics

Drivers' personal traits, experiences and other characteristics may influence their driving style and types of (re)actions shown during driving. For instance, the level of risk drivers are willing to take, their reaction speed, and the experiences they have had can be important factors in the way drivers interact with other vehicles around them. There are four general types of driver characteristics: demographic characteristics, such as gender, age, and country of residence; personality traits, such as sensation seeking and cognitive abilities; attitudes and intentions; and driving experience.

Different types of driver characteristics can be recorded in different ways. Whereas drivers can be asked directly about their driving experience and demographic characteristics, personality traits and attitudes require different approaches. The above mentioned Driving Style Questionnaire (DSQ) (French et al., 1993), for instance, gives insight into drivers' subjective descriptions of their own driving style.

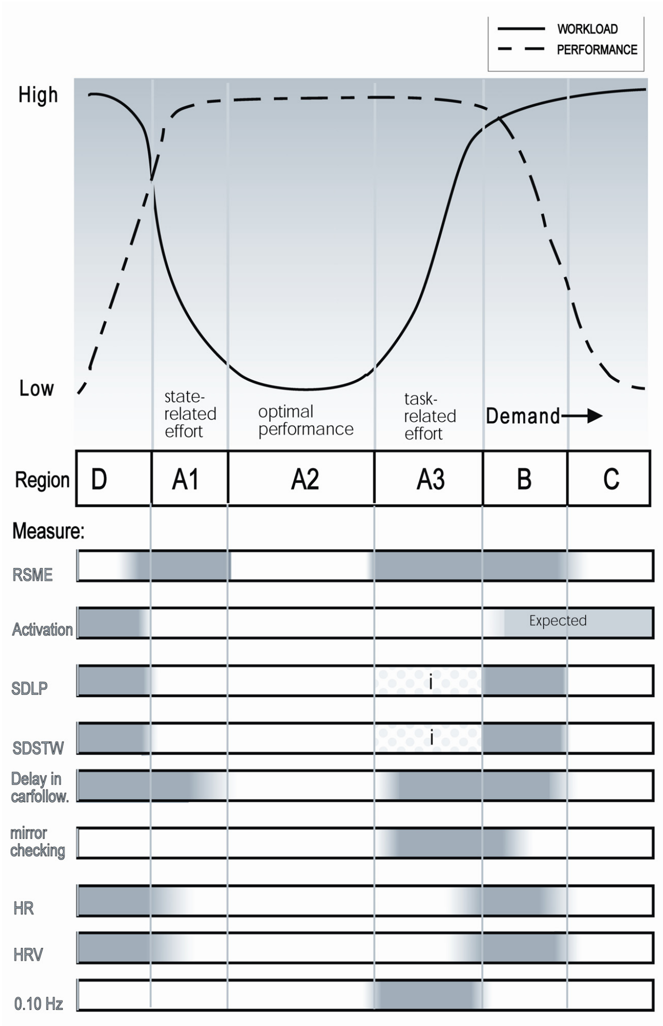

Figure 3.3 Sensitivity of workload measures for different performance areas (De Waard, 1996, reprinted with permission)

3.4 Research tools used in this thesis

In summary, the research described in this thesis is concerned with the following concepts:

- Operational and tactical driving behaviour
- a number of unexpected, safety-critical events with varying event urgency
- varying levels of mental workload
- basic driver characteristics

This section describes the research methods used in the experiments.

3.4.1 Experimental tools

We chose to perform a number of controlled experiments in a driving simulator. Drivers encountered several unexpected and safety-critical events during our experiments, and we determined it both unsafe and unethical to expose drivers to a possible risk of a conflict or collision in a real traffic system. Moreover, repeating the same conditions over and over in similar environments, and controlling the conflicts that were studied, is not possible in a real world situation. Therefore, we would also not be able to set the participants' expectations in the controlled manner in a real-world environment. The unexpected, safety critical events can will be programmed in a driving simulator, and their severity can be determined based on surrogate safety measures.

The driving simulators used for the experiments described in this thesis were programmed with the use of ST Software (ST Software, 2010). ST Software was developed by experts in the field of driving simulator technology and driving behaviour research. It consists of a number of modules in which researchers can build, run and analyse driving simulator studies. StRoadDesign is a module which can be used to develop a virtual road environment in a 2D grid, which then can be converted into a full 3D environment. In StScenario, the road users' actions and other aspects of the research scenarios can be built, leading to a complete experimental setup. Finally, StDataProc can be used for the real-time and accurate recording and basic analysis of a large range of different tactical and operational level tasks, as well as surrogate safety measures, information about all other road users, and time markers. The main advantages of ST are the natural driving behaviour of other road users, and the realistic traffic environment. Both the external validity and the relative internal validity of the experiments are therefore secured. ST Software can be applied in simulators for driver training, behavioural research, driver assessment and other fields of application (ST Software, 2010).

For the measurements of the (relative) level of mental workload, we decided to use the head-mounted Peripheral Detection Task (Van der Horst & Martens, 2009) and record drivers' reaction times and response rates to this secondary task. Furthermore, we recorded the participants' Heart Rate (HR) and Heart Rate Variability (HRV) in the second experiment as a supplement to these PDT measures. Task performance of an additional (arithmetic) task, where applicable, was also recorded in the second experiment as an indication for mental workload level.

Primary driving performance was measured during all experiments, but was not used to determine a state of increased mental workload. According to Horrey and Simons (2007), drivers adopt their safety margins in a different way when they are asked to perform tactical tasks (such as in the experiments described in this thesis), than when they are performing a steady-state task such as car-following. In our study, changing safety margins are therefore a result of the level of mental workload at hand, and will not be used the other way around, as evidence for a certain level of mental workload. Finally, participants' basic demographic characteristics (gender and age) were recorded before the experiment, as well as their driving experience (in years) and annual mileage. Participants' (changing) expectations about the driving scenarios and experiences during the trials were tested in a questionnaire.

The experiments described in this thesis were both conducted using driving simulators. Certain characteristics of the two simulators used in the experiments varied; they will therefore be described in each corresponding chapter. Table 3.2 shows the parameters which were recorded in each experiment.

Table 3.2 Experimental variables and methods of recording

Type of data recorded	**Specification**	**Recorded parameter**	**Method**	**Number of experiment in which parameter was recorded**
Driving	Longitudinal	Driving speed	Driving simulator[2]	1 & 2
		Acceleration	Driving simulator	1 & 2
		Distance Headway	Driving simulator	1
		Time Headway	Driving simulator	2
	Lateral	Lateral position	Driving simulator	1 & 2
		Lateral speed	Driving simulator	1 & 2
		Lateral acceleration	Driving simulator	1
Workload	Driving behaviour	Primary task performance	Driving simulator	1 & 2
	Physiological measure	Heart Rate	Polar watch	2
		Heart Rate Variability	Polar watch	2
	Peripheral Detection Task (PDT)	Reaction Time	PDT	1 & 2
		Percentage of missed signals	PDT	1 & 2
	Secondary task performance	Number of correct answers	Recorded by experimenter	2
		Percentage of false answers	Recorded by experimenter	2
Other vehicles		Location of lead car	Driving simulator	1 & 2
		Speed of lead car	Driving simulator	1 & 2
		Location of most recent car from right	Driving simulator	2

[2] In Experiment 1, variables were recorded at a sampling rate of 256 Hz; the sampling rate used in Experiment 2 was 100 Hz.

Table 3.2 Experimental variables and methods of recording (continued)

Type of data recorded	Specification	Recorded parameter	Method	Number of experiment in which parameter was recorded
Other	Controls	Gas: percentage of maximum position	Driving simulator	1 & 2
		Steer: percentage of maximum angle	Driving simulator	1 & 2
		Brake: percentage of maximum position	Driving simulator	1 & 2
	Time	Time since start of experiment	Driving simulator	1 & 2
	Location	Location of participant's vehicle (both road section and distance to intersection)	Driving simulator	1 & 2

The recorded variables, all related to tactical level or control level driving tasks, were used to answer the question whether, and in what way, drivers change their driving behaviour after an unexpected event requiring control level compensation.

3.4.2 Calculation of variables from raw data

As Table 3.2 showed, a large number of parameters were recorded at relatively high sampling rates in both experiments (256 Hz and 100 Hz, respectively). The average variable values were calculated from this raw data as follows. The average speed was calculated by dividing the distance driven (either 100 metres for intersections, or 10 metres for 10-metre cells) by the time it took to drive this distance. All other variables were calculated by adding all recorded values over a specific stretch of road (e.g., the last 150 metres of each intersection), and dividing them by the number of values in this calculation. This latter method might have resulted in an over- or underestimation of certain effects, since lower speeds have a more prominent input in this calculation, and certain behavioural aspects can fluctuate with changing speeds. This might lead to an overrepresentation of certain values at low speeds: since distances travelled in a certain amount of time are smaller at low speeds than is the case at high speeds, more values are recorded for stretches with low speeds than with high speeds. The variables at which this prominent presence of values at lower speed will probably have the largest effect, are the lateral position (and related to this, lateral speed and acceleration) and the distance headway. To start with the first, large lateral position effects are likely to be underestimated due to this calculation, since lower speeds are often related to smaller lateral position deviations. The distance headway is also generally smaller at lower speeds, which might lead to an underestimation of distance headway effects. Since it is difficult to calculate average values of distance headway and lateral position other than by averaging the recorded values, this is an aspect of data recording and analysis that needs to be considered when interpreting the results. We will discuss whether this may have lead to an under- or overestimation of the effects in the corresponding chapters.

3.4.3 Statistical analysis for both experiments

Experiment 1 had a repeated measures design with two within-subjects variables: Trial (4 conditions) and Intersection (20 conditions). Mental workload (3 conditions) and severity of the unexpected, safety-critical events (2 conditions) were both between-subjects variables. The variables were analyzed with a Repeated Measures ANOVA using SPSS. Correlations between variables were also computed. Tukey's Honestly Significant Difference (HSD) test was performed as a post-hoc test to determine which means were significantly different from one another when an interaction effect was found. Since multiple hypotheses were tested on the same dataset, the Bonferroni confidence interval adjustment method was used to prevent a distortion of the family-wise error rate of multiple comparisons.

Experiment 2 also had a repeated measures design. The design contained two trials which consisted of three sections each, in which the mental workload was varied for participants. These sections in turn each contained 20 intersections. Both mental workload condition and severity of the unexpected, safety-critical situation (2 conditions) were between-subjects variables. In order to study the differences between conditions, we compared a number of variables in the different conditions by means of Paired Samples t-tests. To assess the behavioural effects of the braking event, we studied the main effects and two-way interactions by means of Analysis of Variance (ANOVA) method for Repeated Measures. The statistical significance level was set at .05 for all statistical tests. Whenever a significant violation of the sphericity assumption was detected in the repeated measures ANOVA, the Huynh-Feldt procedure (Huynh & Feldt, 1976) was applied to correct the degrees of freedom. The corrected degrees of freedom are reported in the text. Tukey's HSD test was performed to check for significant differences between means.

η_p^2 (Partial Eta Squared) was determined as effect size for the ANOVA. This effect size describes the proportion of variance accounted for by the factor when excluding other variables. The benchmarks were based on Cohen (1992) and Keppel and Wickens (2002). For the t-tests, the effect size was calculated using Pearson's correlation coefficient *r* (Cohen, 1988; Cohen, 1992). Table 3.3 shows these two effect size measures and their interpretation.

Table 3.3 Effect size measures and interpretation

Effect size	**η_p^2 (Partial Eta Squared)**	**Pearson's *r***
Small effect	0.20	0.10
Medium effect	0.50	0.30
Large effect	0.80	0.50

Chapter 4

Experiment 1: Drivers' reactions to unexpected events

The first experiment was a large driving simulator experiment with the aim to explore driving behaviour during and after unexpected situations. The notion of behavioural adaptation as a result of compensatory actions related to unexpected situations is related to the hierarchical model of the driving task, developed by Michon (1971, 1985). According to Michon (1985), driving behaviour can change from top-down interaction in normal driving, to bottom-up interaction when a driver encounters an unexpected situation to which compensation is required. We are interested in determining how this directional change in task level interaction manifests itself in driving behaviour. Do drivers consistently change their driving behaviour after an unexpected event requiring control level compensation, and if so, in what way and at which task levels? Do all unexpected events trigger a change in direction of interaction between task levels, regardless of the type of compensation required? And what is the role of mental workload and event urgency on this? The current experiment was aimed at testing two hypotheses about these sub-questions and developing additional hypotheses.

4.1 Research tools

As was described in Chapter 2, the hierarchical task model by Michon (1971, 1985) gives an overview of the levels that constitute the driving task and their interactions. In normal driving behaviour, the influence between the task levels is top-down, from strategic level choices to tactical level action patterns and on to operational level actions. During certain specific situations, however, this task level interaction can be turned around to bottom-up influence. This is expected to occur as a result of compensation to unexpected situations (Michon, 1985).

In order to get more insight into the interactions between task levels, and specifically the behavioural adaptations resulting from directional changes in these interactions between normal driving behaviour and driving in unexpected situations, a driving behaviour study was set up. It was decided to use a driving simulator, since both the exact repetition of conditions and the continuous safety of participants could only be fully guaranteed when using a driving simulator. The aim was to test two hypotheses about behavioural adaptations resulting from changes in task level interactions and expand these hypotheses, developing additional hypotheses relating to the influence of mental workload and event urgency. The two initial hypotheses that the experiment was based upon were:

- The type of compensation behaviour (longitudinal, lateral, or a combination) required to safely handle an unexpected, safety-critical event determines the type of any (temporary) behavioural effect. Therefore, longitudinal compensation behaviour leads to changes in longitudinal driving behaviour only, and lateral compensation behaviour leads to changes in lateral driving behaviour only.
- After an unexpected event for which drivers need to perform compensatory actions, they adapt their driving behaviour. This is the result of a directional switch in task level interaction.

Recorded data therefore included driving behaviour measurements, mental workload measurements, measurements of the events and circumstances, and information on drivers' perceptions and expectations. Table 3.2 lists all recorded variables.

The fixed-base driving simulator available at TNO Human Factors in Soesterberg, the Netherlands, was used for the experiment. This simulator consists of the following sub systems:

- A left-seated Volkswagen Golf 4 mock-up, with passenger seat and manual transmission
- The vehicle model computer, which calculates the simultaneous position and heading of the simulated vehicle
- Projection on three screens in front and to the side of the simulator, with a total horizontal field of view of 180° and the total vertical field of view of 45°
- Stereo sound system

The simulator's rear view mirror was projected on the main projection screen, at the location where one would normally look into the rear view mirror. Figure 4.1 shows this fixed-base driving simulator.

This simulator's relative internal validity is high due to the realistic behaviour models included in StSoftware (StSoftware, 2010). The head-mounted Peripheral Detection Task

(PDT) was used for the participants' mental workload measurement. The LED lighted up randomly every three to five seconds, and stayed on for one second or until the participant pressed the finger switch. Reaction time was recorded, and reaction times of over two seconds were seen as missed signals. Refer to Section 3.2 on mental workload assessment for more information on the PDT. Furthermore, we used StRoadDesign for the design of the simulated urban environment, StScenario for development of the experiments, and StDataProc for data recording (StSoftware, 2010; also refer to Section 3.5). Questionnaires were designed to study participants' experiences within the experiment, and the level to which participants' expectations were set and/ or met.

4.2 Participants

Eighty-seven subjects participated in the experiment. The selection criteria for participants were:

- in possession of a driver's license for five or more years
- age between 20 and 60 years old
- at least 7,000 kilometres driven annually
- no indication of motion sickness (e.g., no negative experience with car sickness, positive experience with driving simulator experiments)

We aimed at getting a cross-section of the complete group of 'experienced, regular drivers' in our studies; however, due to possible respondent-bias, it might be that our selection of participants was not representative of all drivers.

Due to simulator sickness, 11 participants (13%) did not complete the experiment. An error in the data storage led to an incomplete dataset for 37 participants. Thirty-nine complete datasets were used for analysis. The average age of the 39 participants was 41 years (SD 13, minimum 23, maximum 60); 26 participants were male, 13 female. All participants were paid € 18,– for their participation.

Seventeen of the 39 participants participated only in this experiment, while 22 also participated in another driving simulator experiment on the same day. This second experiment focused on in-car information systems for speed advice (Duivenvoorden, 2007). There was no relation between its content and the content of this experiment. Furthermore, all participants were given at least fifteen-minute breaks between the different experimental sessions, so no effect of this extra experiment on alertness or fatigue was anticipated.

4.3 Experimental design

The experiment consisted of four rides in an urban environment. Participants were divided into two groups, with one group driving all four rides without an additional task and one group driving while performing an additional task. All participants encountered a set of two unexpected events during their four rides, the order of which was balanced among the participants. These two unexpected events could occur at three levels of event urgency. The two levels of mental workload (driving without and with a secondary task) and the three levels of event urgency (low, medium and high; labels will be explained later in this section) led to six event conditions in a complete between-subjects set-up so as to avoid carry-over effects.

An urban layout was simulated as one long road divided by 20 four-way intersections, resulting in 21 individual road sections. Subjects were instructed to drive straight on each intersection with a maximum speed of 50 km/h and give priority to traffic coming from the right according to Dutch traffic regulations. Each of the 21 road sections was at least 250 metres long, and one complete ride took on average 9½ minutes. The infrastructure was similar at each intersection. A lead car drove in front of the subject during the whole ride, slowing down when the subject fell too far behind (more than 48 metres away) and speeding up when the subject came too close (within 18 metres). At 50 km/h, a distance headway of 48 metres is equivalent to a time headway of 3.5 seconds, and a distance headway of 18 metres to 1.3 seconds.

When the participant was approaching an intersection, a car coming from the right always crossed the intersection first. The participant and a lead car then reached the intersection, and a car coming from the left approached the intersection, yielded to the participant and the lead car, and crossed behind them. These actions of the other road users were similar at each intersection. The intersection layout and the positioning of other road users when the participant was about to cross an intersection are depicted in Figure 4.2.

Figure 4.1 TNO's fixed based driving simulator

Figure 4.2 Standard intersection layout with lead car and vehicles from left and right

Figure 4.3 Braking lead car after intersection 5 (road section 6) in one of the event trials

The experiment consisted of four such experimental trials, and one introduction ride preceding the actual experiment to give all participants the opportunity to gain some experience with the driving simulator and the simulated environment. In the reference trials (first and third trials), participants drove only on standard road sections, setting their expectations about the situations to come. The second and fourth trials were event trials, in both of which one of two unexpected events occurred. The order of these events was balanced among participants to avoid contaminating the results with any learning effects. Based on the model developed by Michon (1971, 1985), we expect that the direction of influence between driving task levels changes as a result from unexpected events. According to the model, compensatory actions on a lower level serve as input for choices and actions made at the nearest higher level. We expect that there is a difference between longitudinal compensation and lateral compensation and their effects on driving behaviour. Therefore, two different types of events were staged, requiring two different types of compensatory actions: longitudinal (braking) and lateral (moving away).

The first of the unexpected events was the sudden braking of the lead car, which occurred shortly after the participant had passed the fifth intersection of the trial (at the sixth road section), see Figure 4.3. The lead vehicle braked unexpectedly and then accelerated again to its initial speed after the participant had driven 5, 10 or 20 metres, i.e. three levels of urgency, labelled low, medium and high. This gave a good indication of event urgency if participants were at the same distance before the event. However, participants were free (within limits) to choose their own headway at all times and this original indicator of urgency did not take into account how close to the lead car the participant was driving. A low urgency event could therefore potentially be a situation in which the lead car would brake relatively close to the participant, whereas a highly urgent event could also be a braking lead car far away from the participant. Therefore, a second measure of criticality was determined, namely the participant's distance headway after braking had stopped. This measure is more directly related to the possibility of a conflict, and parts of the data were therefore also analysed with this criticality variable. The three criticality levels were set at high criticality (a distance headway of less than 18 metres), medium (distance headway between 18 and 30 metres), and low criticality (distance headway over 30 metres). These criticality levels are explained more thoroughly in Section 4.6.4.2. The order of the trials with the unexpected event and the other (reference) trials was balanced among participants. The braking event occurred only once for each participant to ensure it was unexpected. Appendix A.1 gives the annotated code for the two unexpected events, as well as the regular driving behaviour for the lead vehicle.

The second unexpected event was an event that required a different type of compensation behaviour from the participant. The car from the left, which had until that moment always yielded according to the rules, abruptly accelerated before it stopped to avoid colliding with the participants. This happened at the eighth intersection of the trial. The car would start to approach when the participant was at either 10 metres from the intersection, 6 metres from the intersection, or at start of the intersection, and these levels of urgency were also labelled low, medium and high due to their relationship with the level of conflict raised by the approaching car.

Half of the participants were given an additional cognitive task to perform while driving, in order to determine the effects of mental workload the driving task level interactions. They were instructed to iteratively subtract a number between four and nine from a three-digit figure during each of the four complete trials. Table 4.1 lists these four serial subtraction tasks. Participants were encouraged to continuously perform this additional task and were reminded of their task after a number of seconds without an answer, but they were allowed to give their final answers at their own pace.

Table 4.1 Serial subtraction task in each of the four experimental trials for participants with elevated mental workload

Trial	Starting number	Number to subtract	Solution
1	851	4	847, 843, 839, etc
2	735	6	729, 723, 717, etc
3	800	7	793, 786, 779, etc
4	900	8	892, 884, 876, etc

Participants were asked to complete a questionnaire following each trial, with 20 questions about simulator sickness, the predictability of the driving task and whether performing the PDT had interfered with their driving. For the participants with the arithmetic task, two additional questions were asked about the level of difficulty of this task, and whether it had influenced the participant's driving style. Participants had to rate their answers to the questions on a 5-point Likert scale. The questions were phrased as follows:

What did you think of the behaviour of other road users? Please rate your answer on the scale below.

Predictable X X X X X Unpredictable

What did you think of the predictability of the driving task?

Predictable X X X X X Unpredictable

Participants had the opportunity to write additional remarks at the end of the questionnaire. The complete questionnaire is given in Appendix C.1 (in Dutch).

4.4 Procedure

Participants were welcomed at TNO and were taken to a waiting room. They received instructions about the aim and content of the experiment, and general information about the project and the driving simulator. Participants were then given the opportunity to ask general questions about the project and the experiment. After signing an informed consent form, all participants drove one introduction ride preceding the actual experiment to gain some experience with the driving simulator and the simulated environment.

Next, participants were given more information about the specific arithmetic and driving tasks in the experiment. They were instructed to give the highest priority to driving safely. The serial subtraction task, when applicable, should be given second priority, and the PDT should receive lowest priority, but should still be completed as fast as possible. The instructions for this experiment can be found in Appendix B.1 (in Dutch).

After a short break in which they could ask the last procedural questions, participants drove the four experimental trials. The 22 participants who also participated in the study on green wave speed advice (Duivenvoorden, 2007) alternated these four trials with three trials from that study.

After each trial, participants were given a questionnaire with questions regarding their health, the predictability of the task and other road users' behaviour, and the influence of the secondary tasks on their driving style. After the final ride and questionnaire, participants were paid for their participation. Participants who still had questions regarding the aim of the experiment were given a detailed explanation after completion of the experiment.

4.5 Data registration and analysis

Since our research focused on both anticipation to the intersection and intersection driving, all results were based on the values calculated from the last 100 metres before the next intersection centre. This stretch of road will be called 'intersection' in this chapter, describing both anticipation behaviour to the intersection and actual intersection driving behaviour. Furthermore, we looked at speed patterns by determining the minimum speed within this section of 100 metres, as well as the location at which this minimum speed was reached. Finally, speed was also calculated for parts of road sections with a length of 10 metres, from hereon labelled 10-metre cells, between 100 metres before the intersection and the intersection centre (this leads to 11 cells with values averaged over the stretch of road from 100 to 90 metres from the next intersection, 90 to 80 metres from the next intersection, 80 to 70 metres, et cetera).

We studied the main effects and two-way interactions by means of a Repeated Measures Analysis of Variance (Repeated Measures ANOVA) method. The statistical significance level was set at α=0.05. Correlations between variables were calculated as well. Vertical bars in each figure denote 95% confidence intervals. Where figures display results that are not statistically significant at the 0.05 level, the effects are denoted by (ns) for 'not significant'.

The analyses of the predictability of the rides were based on

- Question in questionnaire: predictability of driving task, predictability of behaviour of other road users
- Trial (4)

The following between-subjects variables were furthermore studied:

- Mental workload condition (2): driving only or driving with an additional arithmetic task
- Urgency (3): high, medium or low
- Criticality due to distance headway after the braking event (3): close/ high criticality, medium criticality or far/ low criticality

4.6 Results

This section contains the results of the first driving simulator experiment. In the first part of this section, we determine whether our research constructs were implemented correctly. Were the events really unexpected to the participants? Did participants have an increased cognitive workload due to the additional mathematical task? We also study the learning effect to driving in the driving simulator and to the experimental setup, and the data from the trials are therefore organized chronologically in this first part. The second part shows the overall driving behaviour in the different trials and between-subject conditions, including one reference trial and two trials with unexpected events. In order to ensure effect comparison for similar events, we rearranged the data for the second and fourth trials to ensure that similar conditions could be compared directly. Throughout this chapter, we will therefore refer to these three trials after rearrangement as 2-BLC (the trial with the Braking Lead Car), 3-Reg (the Regular reference trial) and 4-Acc (the trial with the Acceleration event). The third part zooms in on the effects of these unexpected events, focusing specifically on speed, speed approach patterns, distance headway and lateral position and acceleration.

4.6.1 Validation of research construct and setup

As was described earlier in this chapter, we implemented a number of variables to determine how drivers adapt their behaviour as a result of unexpected situations on the road. In order to establish what these effects were, it was first necessary to determine whether the experimental constructs were implemented correctly. We also checked any possible effects of other factors that might have contaminated our results, such as the characteristics of the participants and the layout of our intersections. The effects of the varied event level will be discussed in Section 4.6.4, after rearranging the data according to the order of the conditions.

4.6.1.1 Expectations about regular intersections and unexpectedness of safety-critical events

The expectations of the participants were tested by studying the learning effects in their driving behaviour (i.e. habituation during the four trials). The average driving speed increased during the first trial, $F(2.612,86.198)=12.080$, $p<.001$, while the standard deviation of the driving speed decreased after the initial trial, $F(3,99)=24.724$, $p<.001$ (see Table 4.2). This supports the expectation that participants got used to the standard intersections during the first experimental trial.

Table 4.2 Average speed and standard deviation of speed per trial

Trial	**Average speed (km/h)**	**Standard deviation of speed (km/h)**
Trial 1 (regular)	40.74	6.92
Trial 2 (event)	42.68	4.61
Trial 3 (regular)	44.64	4.57
Trial 4 (event)	44.18	4.54

These results showed that the learning effects had a measurable effect on driving behaviour. Because these learning effects can influence the comparison between trials, it was decided to exclude the data from the first trial from the analyses. Furthermore, learning effects were not only seen in a difference in speed and standard deviation of speed after the first trial, but also in the speed development at the first intersections of each trial. At the first four intersections of each trial, participants increased their average speed from 37.14 km/h at the first intersection to 40.69 km/h, 43.28 km/h and 43.58 km/h on average at the second, third and fourth intersection of each ride respectively. This was a significant increase, $F(3,99)=33.001$, $p<.001$. Tukey's HSD post-hoc test showed that all but the third and fourth of these intersections differed significantly from each other. In order to eliminate these learning effects from the analyses, the first four intersections of the remaining three trials were also not included in any of the final analyses. An explanation for these recurring learning effects at each trial may be the relatively long breaks between each experimental ride (approximately 15 minutes), after which participants had to get used to driving in the simulator again.

Additionally, participants' answers to two questions concerning the predictability of the driving task and the behaviour of other road users were examined. The answers to the two different questions did not differ significantly, $F(1,31)<1$ (Crohnbachs $\alpha=0.72$), and the answers were therefore combined in the analyses. The combined answers (two per trial per participant) revealed that the reference conditions were seen as significantly more predictable than the trials with the unexpected events. Table 4.3 shows the combined results of the analyses determining learning effects and expectations of the participants.

Table 4.3 Learning effects and expectations of participants as a function of Condition

Variable	F-value	p-value
Average speed	Totaal: F(3,99)=12.08	p <.001
Standard deviation of speed	Totaal: F(3,99)=30.241	p <.001
Answers to questionnaire	Totaal: F(3,99)=4.14	p <.010

4.6.1.2 Mental workload

The effects of the additional cognitive task on workload were established by analyzing the data from the PDT (reaction times to PDT stimuli and percentage of missed PDT stimuli, with reaction times over two seconds). The additional task significantly increased both the reaction times to the PDT and the number of missed signals (Table 4.4), confirming the hypothesis that the additional task increased the cognitive workload of the drivers. Figure 4.4 shows these results graphically. Answers to the questionnaire revealed that the PDT was generally not seen as difficult or interfering with driving; 90% of the participants responded after each trial that the PDT was easy to perform, and 97% answered that the PDT had no influence on their driving behaviour.

Table 4.4 Main effect of additional arithmetic task on mental workload

Variable	Driving only	Driving with additional task	F-value	p-value
Average reaction time to PDT	M= 571.19 SD=40.30	M= 798.59 SD= 49.92	F(1,29)= 54.725	p <.001
Percentage of missed PDT signals	M= 9.67 SD= 10.34	M= 24.18 SD= 16.28	F(1,33)= 34.873	p <.001

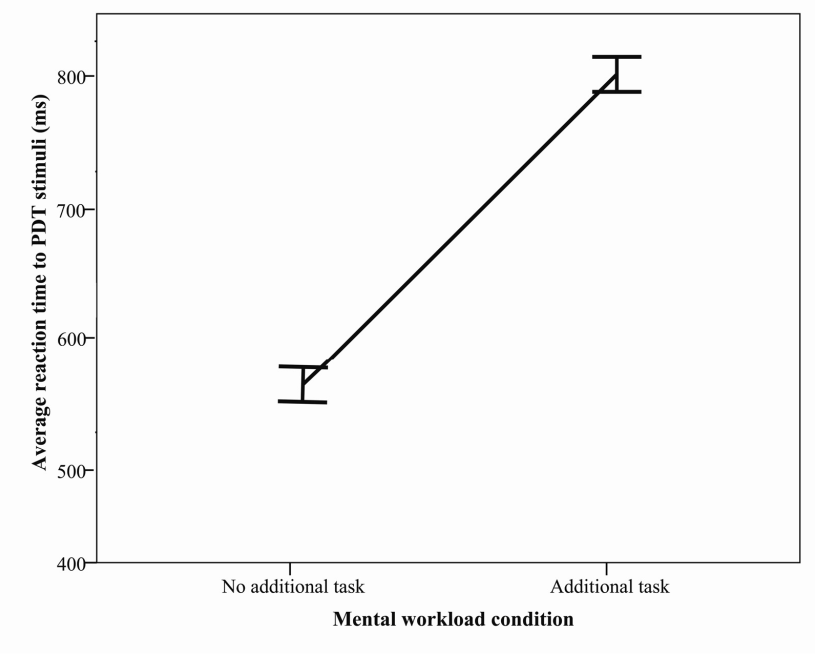

Figure 4.4a Effects of mental workload conditions on average PDT reaction time (ms)

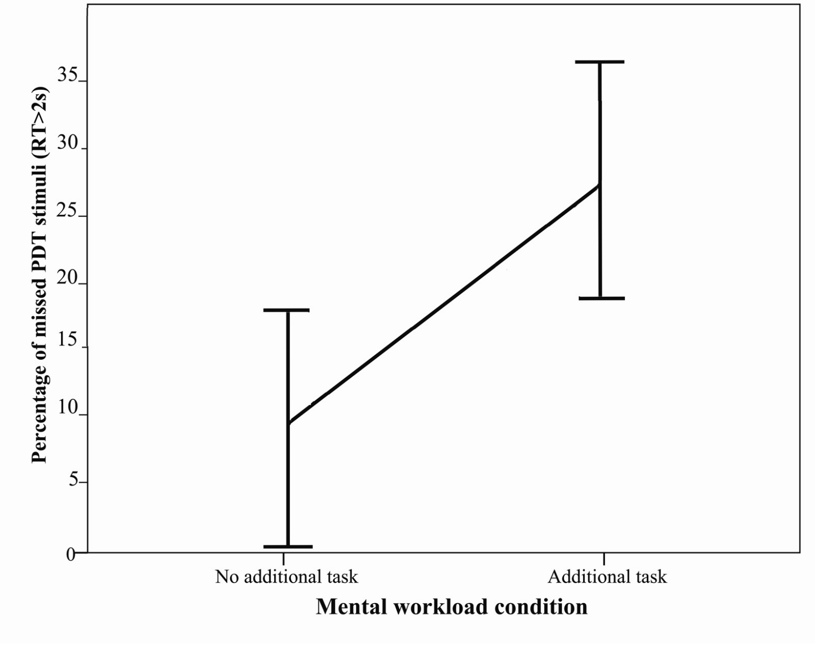

Figure 4.4b Effects of mental workload conditions on percentage of missed PDT stimuli

4.6.1.3 Duration of the experiment: alertness and fatigue

On average, each trial took 9 ½ minutes, and participants were given a 15-minute break after each trial. The reaction times to the PDT did not increase with time; in fact, the reaction time to the PDT decreased significantly after the first ride, $F(2.972,86.184)=8.229$, $p<.001$, and did not change significantly after this. There was no statistically significant difference between trials for the percentage of missed PDT stimuli, $F(1.286,42.443)=0.617$, $p=.475$. Although learning and fatigue can in theory have opposite effects, it has been found that the effects of fatigue usually only become relevant after more than 10 minutes of continuous driving (Steyvers, 1991). With the current experimental setup in which enough breaks were given to the participants and the drive times were not too long to affect the alertness of the drivers, fatigue was not an issue in this experiment. This was reconfirmed by the fact that the drivers' reaction times did not increase during driving.

4.6.1.4 Layout of individual intersections

The experimental intersections were designed to be similar in layout and approaching traffic, but simultaneously look slightly different with respect to decoration (houses, pedestrians, etc) and direction (some of the intersections were for instance followed by a turn to make completing the four trials less tedious). To check whether these small differences had an effect on driving behaviour, we performed an Analysis of Variance (ANOVA) for Repeated Measures on the twenty intersections for each of the three trials used for comparison, trials 2-BLC, 3-Reg and 4-Acc.

Driving behaviour at a number of other intersections throughout the experiment also deviated, which led to a more thorough investigation of the layout of these intersections. Analyses showed that the driving speed deviated at five specific intersections, $F(8.161,269.319)=7.957$, $p<.001$. Pairwise comparisons showed that the driving speed at these intersections was either significantly lower (numbers 6, 9, and 13) or higher (numbers 5 and 10) than at other intersections (see Figure 4.5).

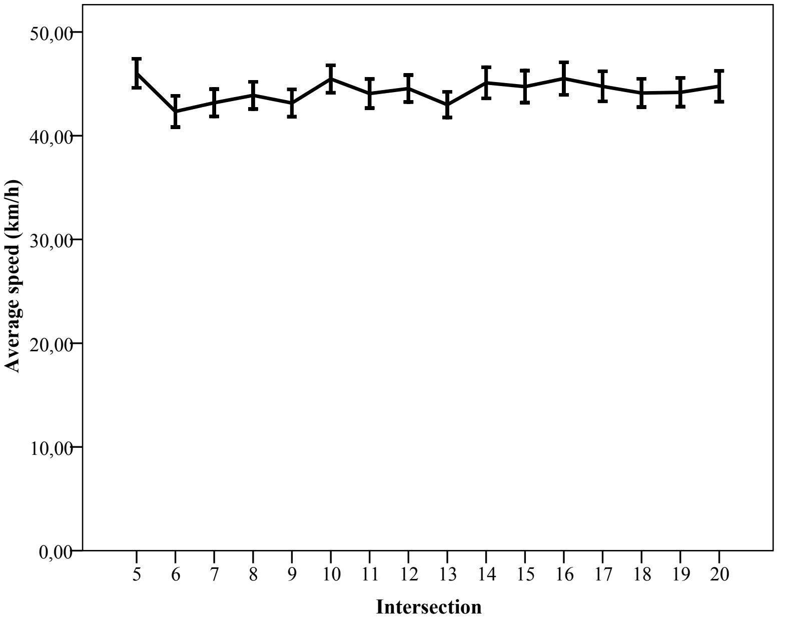

Figure 4.5 Average speed at 16 intersections for the three trials combined

There was also a large variation between individual intersections in the location relative to the next intersection (DTI, distance to intersection) at which drivers reached their minimum speed, $F(10.108,333.566)=3.277$, $p<.001$, see Figure 4.6.

The largest deviation was found at intersection number 13, where the minimum speed was reached significantly farther away from the intersection than at other intersections. The layout of these five intersections which seemed to induce deviating driving behaviour was different in certain respects from the layout of the other intersections; specific differences will be discussed in Section 4.8.1[3].

A location farther away from the intersection (larger DTI) for the minimum speed means that the driver decelerates earlier in the intersection area. Combined with a lower speed this can be classified as driving more cautiously. As average speed was also significantly lower at intersection 13, drivers were apparently driving more cautiously here than at other road sections.

[3] Most of the intersections that evoked deviating driving behaviour turned out in later inspection to have less view from the start of the intersection than the other intersections. Furthermore, intersection 10 was preceded by a bend. The behavioural effects of the deviating characteristics of these intersections will be thoroughly discussed in Section 4.8.1.

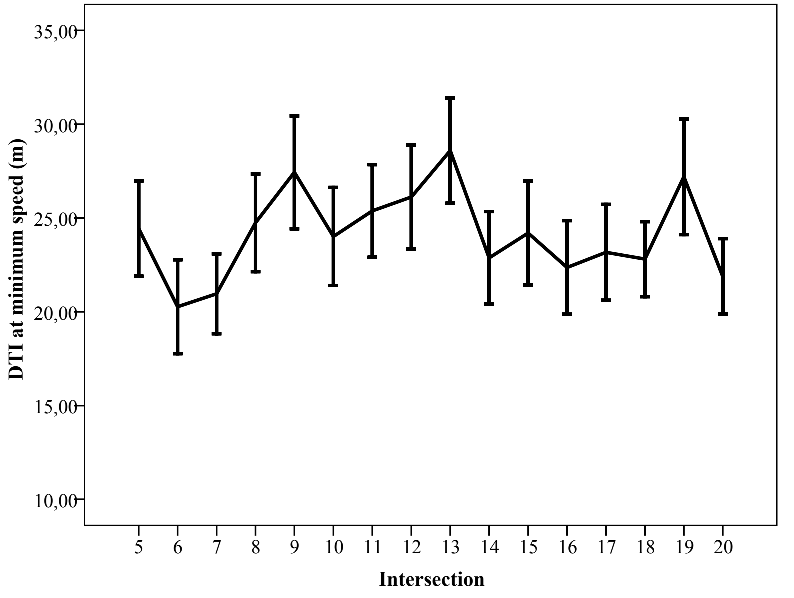

Figure 4.6 DTI of minimum speed at 16 intersections for the three trials combined

Distance headway also differed significantly over the sixteen intersections, F(4.062,101.545)=5.347, p=.002, see Figure 4.7. The most prominent differences were again found at intersections 5 and 9 and additionally at intersection 17, with intersections 5 and 17 showing a smaller headway and intersection 9 a larger headway. This could partly be related to the higher (more aggressive) driving speed at intersection 5 and the more defensive, lower speed at intersection 9. The deviating distance headway could not be related to a difference in speed at intersection 17.

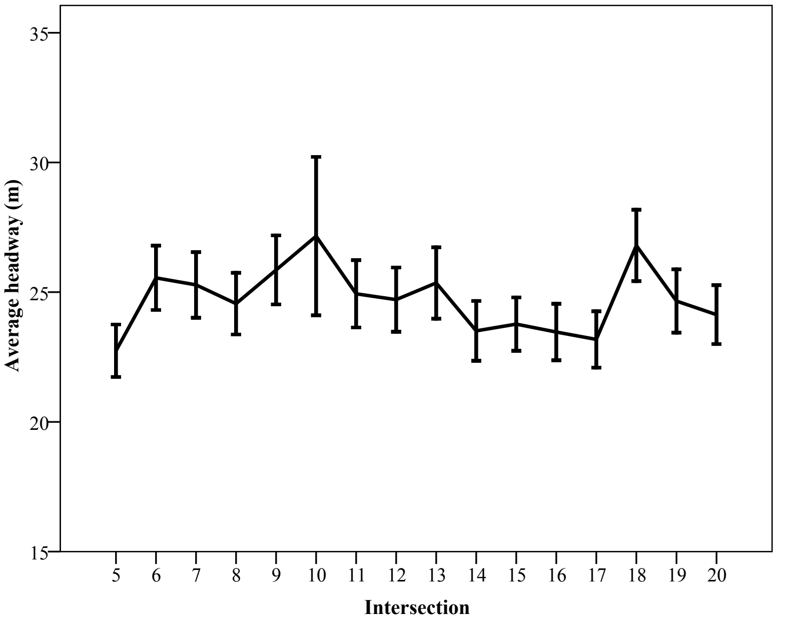

Figure 4.7 Average distance headway at 16 intersections for the three trials combined

Outliers were filtered from the lateral position dataset. Based on visual inspection of the data, lateral position data with an absolute value of 2 metres and 50 centimetres or over were determined outliers.

The lateral position and lateral acceleration showed a number of significant changes over the sixteen intersections, $F(6.480,110.156)=27.417$, $p<.001$ for lateral position and $F(3.878,127.961)=129.777$, $p<.001$ for lateral acceleration. Lateral position oscillated around zero, with the exception of intersection 10, where participants were situated in general more to the outside of the road (negative value), see Figure 4.8a. Lateral acceleration at that same intersection was directed to the left (positive lateral acceleration value), as well as on the fifth intersection; it was directed to the right at intersections 12 and 14, see Figure 4.8b. Remember that intersection 10 followed a bend in the road, which could explain this deviation from the rest of the intersections.

Concluding, the layout of certain individual intersections had a significant effect on a number of variables, related to either longitudinal or lateral driving behaviour. This will be elaborated in the next chapter.

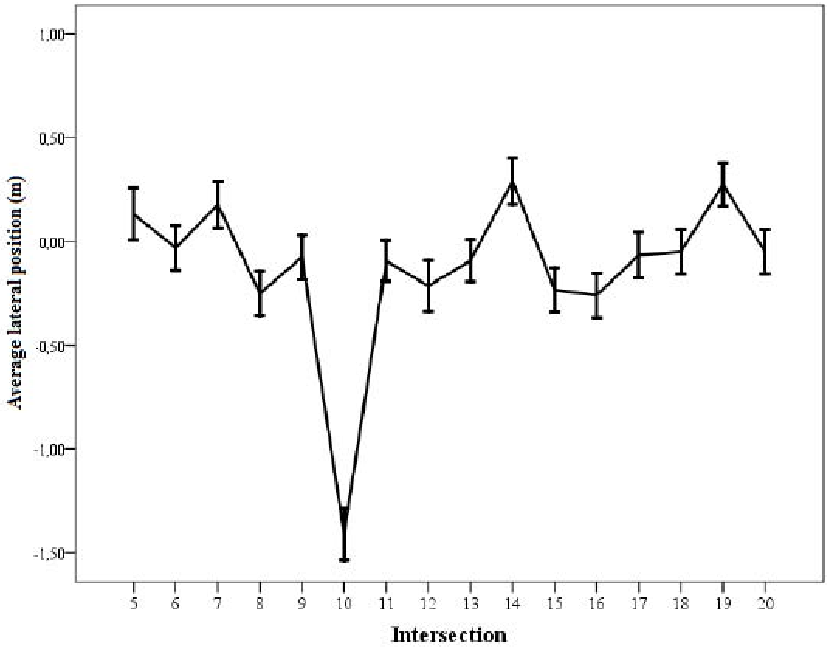

Figure 4.8a Lateral position at the sixteen intersections

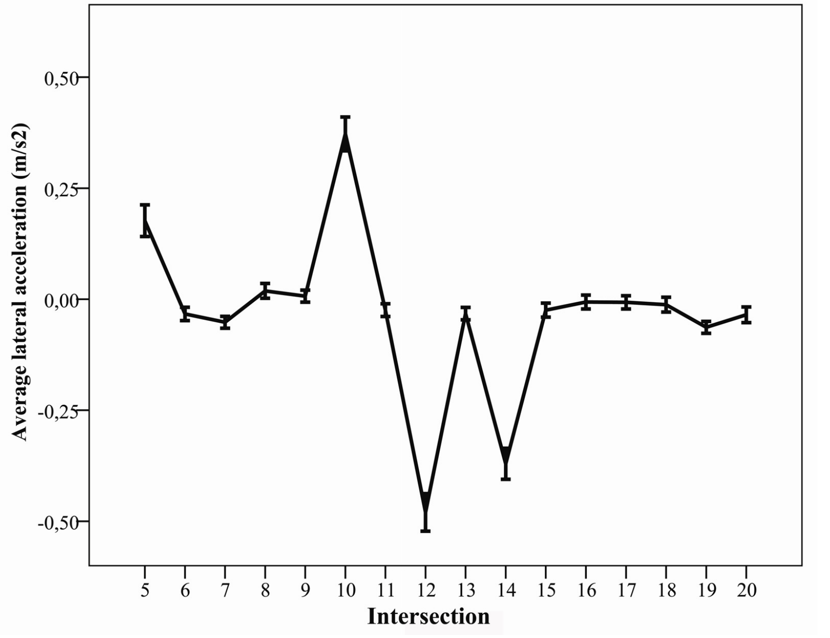

Figure 4.8b Lateral acceleration at the sixteen intersections

4.6.2 Differences between trials: within-subject effects on driving behaviour

All participants drove one trial in which the lead car suddenly braked (trial 2–BLC), one reference trial (trial 3–Reg), and one trial in which a car from the left accelerated instead of giving priority to the participant (trial 4–Acc). Note that the order of trials 2-BLC and 4-Acc was balanced among participants, so any effect seen in the results was not as a result of a learning effect, but rather due to one or both of the unexpected events. This section gives an overview of the observed driving behaviour in each of the full trials. The first four road sections of each trial and the last road section (where the participants stopped to park the car) are not included in any of the analyses, due to the strong learning effect that was found in these parts of the trials. All other road sections are included in the analyses, which lead to averaging over 16 road sections and three trials in total.

4.6.2.1 Differences between trials: longitudinal driving behaviour

Speed, distance headway and time headway constitute the most important attributes of longitudinal driving behaviour. As was described in an earlier chapter, an error in the data recordings at the transition from one road section to another at an intersection led to missing recording of the exact distance headway values at these locations. These values were reconstructed by adding the driver's distance to the centre of the next intersection and the lead car's distance from the centre of that same intersection. We chose to use distance headway and speed as the main variables describing following behaviour in this experiment.

With respect to the average speed, there was no statistically significant difference between the trial with the accelerating event (4-Acc) and the reference trial 3-Reg, but speed was significantly lower in trial 2-BLC, see Figure 4.9. The same was true for minimum speed, which was lower in the braking event trial than in the reference trial and the trial with the accelerating event. However, the location at which this minimum speed was reached (distance to the next intersection) and the average headway did not differ between the three trials. Table 4.5 gives an overview of these effects.

Table 4.5 Effects of trial on average speed, minimum speed, location of minimum speed and average distance headway

Variable	**3-Reg (reference)**	**2-BLC**	**4-Acc**	**F, p**
Average speed	M=44.88, SD=2.35	M=42.91, SD=1.99	M=45.57, SD=2.40	$F(1.866,55.994)=5.217$, $p=.010$
Minimum speed	M=38.04, SD=2.87	M=35.83, SD=2.66	M=38.63, SD=2.79	$F(1.690,64.235)=4.146$, $p=.026$
DTI at minimum speed	M=24.84, SD=3.20	M=25.39, SD=3.06	M=24.77, SD=3.24	$F(2,67)=0.044$, $p=.957$
Average distance headway	M=24.73, SD=6.03	M=25.66, SD=7.42	M=25.00, SD=7.17	$F(2,50)=1.648$, $p=.203$

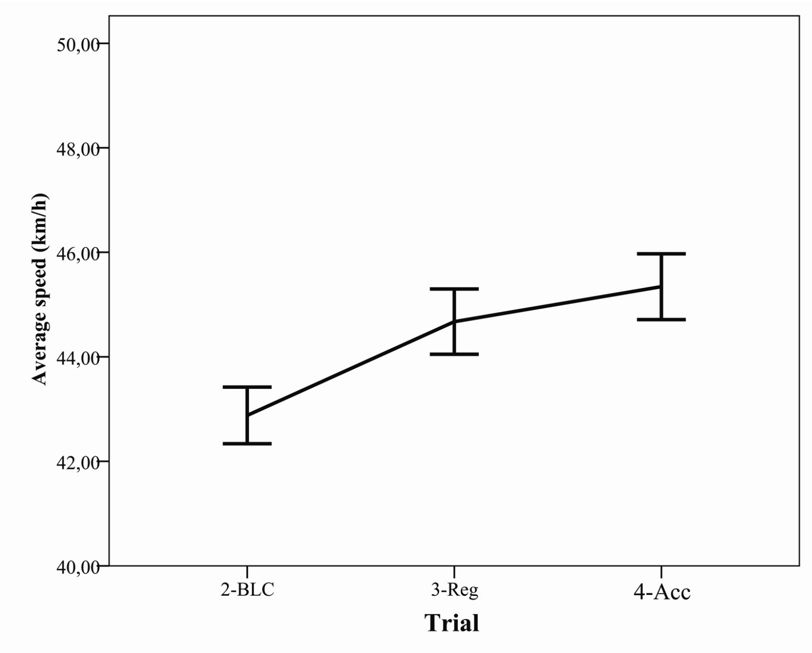

Figure 4.9 Average speed in trials 2–BLC, 3–Reg and 4–Acc

4.6.2.2 Differences between trials: Lateral driving behaviour

The lateral position and speed define at which position on the road relative to the road marking drivers are positioned and in which direction they move. Negative lateral speed values denote a movement to the right relative to the middle of the lane (outside of the road), whereas positive lateral speed values denote movement towards the centre line of the road.

The type of trial (event trial or reference trial) did not affect drivers' lateral position, $F(1,17)=0.130$, $p=.723$, nor did it affect drivers' lateral acceleration, $F(2,66)=1.453$, $p=.241$. However, lower speeds were more prominent in the values used for averaging and ceteris paribus, lower speeds can be related to smaller deviations in the lateral position (e.g., Green, Lin and Bagian, 1994; also refer to Section 3.4.1). Possible side-effects of this correlation will be elaborated in Section 4.8 (Discussion of results).

4.6.2.3 Differences between trials: operational compensation behaviour

As was described before, the event with the suddenly braking lead car required actions of compensation in the longitudinal direction, such as braking and lowering driving speed. The accelerating car from the left required a combination of steering away and braking. With respect to the longitudinal behaviour, participants had both a lower average speed and a lower minimum speed in trial 2-BLC than in reference trial 3-Reg, but their speed was not affected in the trial with the accelerating car from left. However, the location at which this minimum speed was reached did not vary between the trials. With respect to lateral driving behaviour, lateral position was not affected in any of the trials, nor was lateral acceleration. It appears that the type of compensation required partially determines how driving behaviour after the events changed.

4.6.3 Effects of between-subjects factor: mental workload conditions

As described in the previous chapter, half of the participants drove while performing an additional arithmetic task. The effect of this serial subtraction task was that mental workload increased (see Section 4.6.1.2). When looking at the complete trials, mental workload led to a change in driving behaviour, both longitudinally and laterally.

The speed pattern in the approach of the intersection differed significantly between the two mental workload conditions over the three trials (interaction effect 10-metre Cell x Mental workload condition), F(11,363)=2.194, p=.014 (see Figure 4.10). Participants driving with an additional task drove faster over the whole last 100 metres before the intersection and hence showed a smaller range of values in the speed patterns than regular drivers. This difference became especially clear in the locations closer to the intersection.

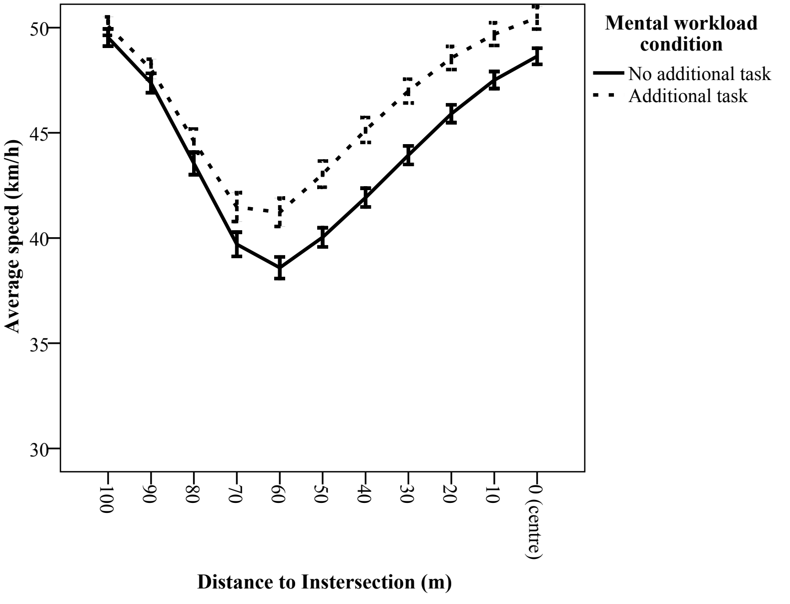

Figure 4.10 Average speed per 10-metre cell in both Mental workload conditions

Furthermore, an interaction effect of workload and trial on average speed per intersection was found. Participants with higher workload drove slower in trial 2-BLC than in the reference trial and trial 4-Acc, F(2,28)=6.606, p=.004, whereas regular drivers did not show a significant difference in average driving speeds between the three trials, F(1.681,31.931)=0.850, p=.419. Table 4.6 and Figure 4.11 show how drivers with increased workload drive faster than regular drivers in both the reference trial and the trial with the accelerating car from the left (4-Acc), but not in trial 2-BLC, in which a braking event took place. We will elaborate further on these interaction effects in Section 4.5.4, when we zoom in to the direct effects of the events.

Table 4.6 Average and standard deviation of speed for each mental workload condition

Condition	**Trial 2-BLC**	**Trial 3-Reg**	**Trial 4-Acc**
Without additional task	M=42.66, SD=2.94	M=43.28, SD=3.11	M=43.78, SD=3.21
With additional task	M=43.27, SD=2.75	M=46.67, SD=3.81	M=47.51, SD=3.58

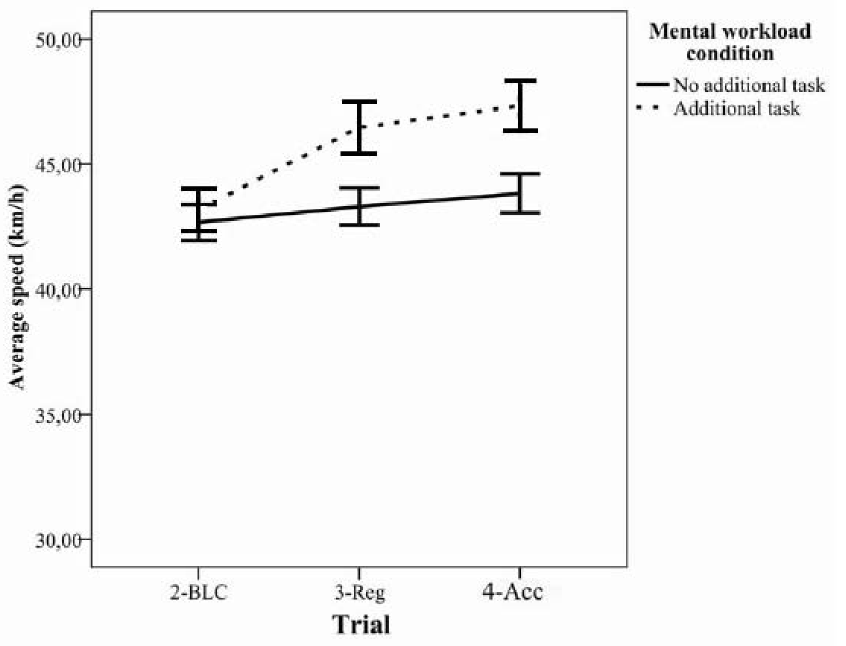

Figure 4.11 Average speed, interaction effect of mental workload condition and trial

There was a significant effect of the level of mental workload on the positioning of drivers relative to the road markings, F(1,17)=7.753, p=.013. Regular drivers (driving without an additional task) stayed more to the outside right of their lane (M=-0.17, SD=0.31) than their counterparts driving with an additional task, who tended to drive slightly more to the left of the centre of their lane with positive lateral position values (M=0.20, SD=0.31). Driving more to the outside of the lane could indicate more defensive driving, although one might also argue that this is not the case in situations in which one needs to look further upstream in oncoming traffic. However, since overtaking was not an option in this experiment, this argument will not be taken into account for this situation, and driving more to the outside of the lane will be considered as more defensive driving. Figure 4.12 shows this effect of workload on lateral position. No other effects of mental workload condition on any of the variables measured were found.

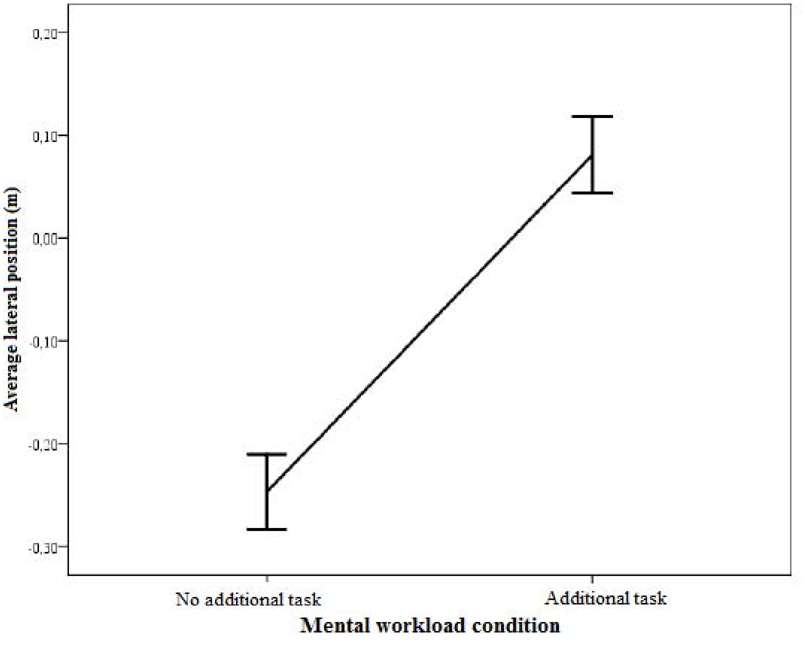

Figure 4.12 Effect of workload on lateral position (negative lateral position = right of lane centre)

In the previous paragraphs, we described the mean effects of large sets of intersections over a complete trial. The following sections will zoom in to the locations where the events actually occurred. It is expected that effects of aspects directly related to the specific events, such as event urgency, will only surface when they are viewed in relation to the actual events. This is less the case for aspects which influence driving throughout the complete trial, such as mental workload.

4.6.4 Effects of the unexpected events: a closer look

In the next sections, we focus on the effects of the two unexpected events. These results will be used to test the initial two hypotheses and, where applicable, develop additional hypotheses concerning behavioural reactions to unexpected, safety-critical events and directional changes in task level interaction.

The effects of the unexpected events were only clear over a certain stretch of route; after this, the effect decayed until it was no longer possible to distinguish between effects of the event and normal driving behaviour. In order to determine the magnitude and length of the effects we analyzed behavioural adaptations to the unexpected events over a limited number of intersections.

4.6.4.1 Behavioural compensation during and after the braking lead vehicle event

The braking event occurred directly after intersection 5 in trial 2–BLC. The urgency of the event was defined by the duration and length of the braking event (event levels low, medium or high). A number of behavioural changes occurred after the braking event. Eight intersections including the ones directly before and after the braking event were used for all Analyses of Variance (ANOVA) for Repeated Measures in this section.

Participants lowered their speeds for a number of intersections directly following the braking event, $F(6.482,213.902)=3.638$, $p=.005$. Figure 4.13 shows the speed development over the eight intersections following the braking event.

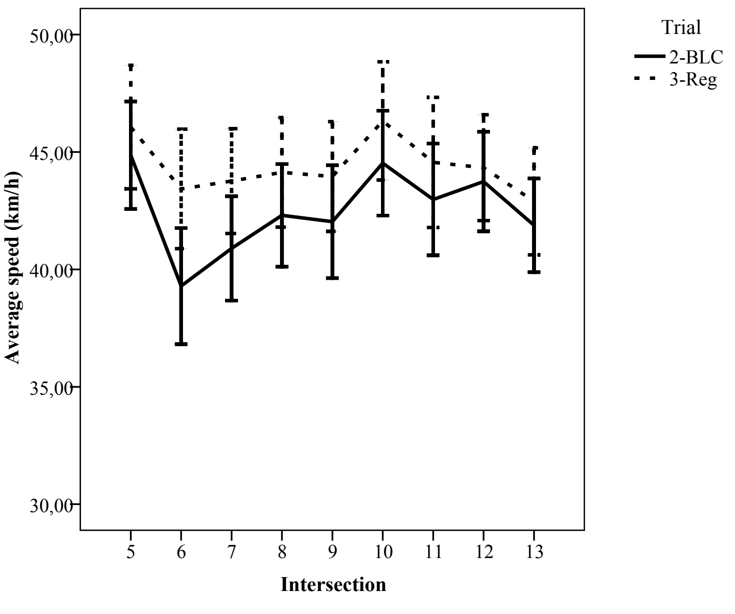

Figure 4.13 Average speed as a function of Trial and Intersection

The speed adjustment resulting from the braking event was different for groups with varying mental workload, $F(1,33)=4.167$, $p=.049$. While regular drivers did not drive at a different speed in the reference trial (M=42.90, SD=2.97) than in the trial with the braking lead vehicle (M=42.18, SD=2.76), those who experienced higher mental workload due to the additional task drove significantly faster in the reference trial (M=45.98, SD=3.36) than in the event trial (M=42.36, SD=3.12), see Figure 4.14.

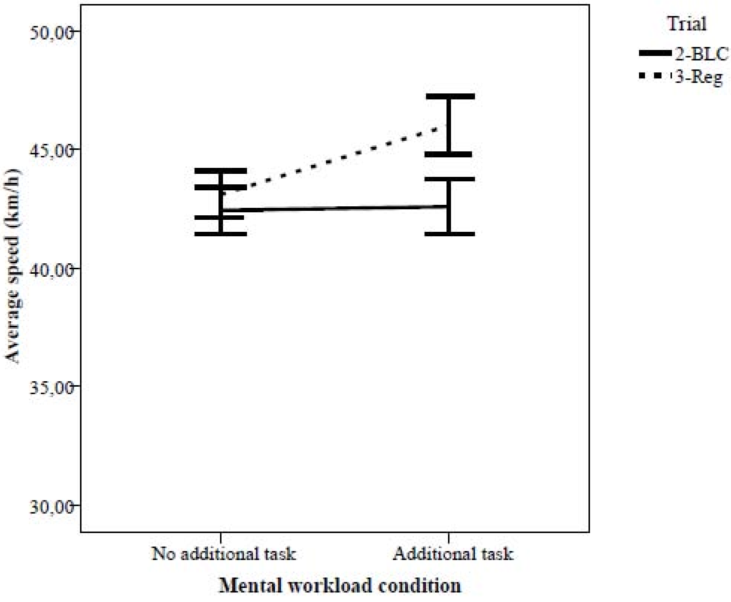

Figure 4.14 Average speed as a function of Trial and Mental workload condition

The average distance headway became larger with higher event levels, although this effect was not significant at the .05 level, F(2,25)=3.156, p=.060. The interaction effect of Trial x Intersection (indicating a change after a certain intersection in a certain trial) was not significant, F(2.126,53.162)=0.214, p=.821, nor were any other effects of the braking event.

The interaction effect of Trial x Intersection on lateral position, which would point to a direct effect of the braking event, was not significant, F(7,161)=1.469, p=.182. Since there were also no significant three-way interaction effects on lateral position, it can be concluded that lateral position was not affected by the braking event itself. This is according to our expectations based on the type of compensation behaviour required for the braking event.

4.6.4.2 Re-calculated criticality of the braking event

In the programming phase of the experiment, the urgency of the braking event was set as a combination of the time during which the lead car would brake and the maximum distance the participant would drive during this braking event (see Section 4.3). It was expected that there would be differences between groups in the level of conflict encountered as a result of varying headway after the braking event with this scenario (see Appendix A.1 for the annotated code for the lead vehicle). However, there turned out to be a large variation between distance headway values during driving for individual drivers, which in turn led to large differences in distance headway after the braking event within groups as well as between groups.

In order to get more clarity on the actual criticality of the events, a new indication of event urgency was determined. A number of options exist for the classification and categorization of event urgency. Some are related to driving behaviour shown by the participants (e.g., brake reaction times, jerk, or maximum deceleration); others show the severity of the process or outcome of the situation (e.g., distance headway after the event or minimum TTC). Since the new re-calculated event criticality is an independent variable intended to show how event urgency influenced driving behaviour, choosing an independent variable directly from participants' driving behaviour was not an option. Therefore, we looked at options from the second type of event urgency indicators, minimum TTC and distance headway after the event. As the data for the TTC included a large number of missing values (up to 60% in certain cases), it was decided that the distance headway after the event would serve as independent variable indicating event urgency.

The braking events were categorized according to the distance headway after the braking event, with three categories: more than 30 metres (low criticality, N=8), 18 metres to 30 metres (medium criticality, N=20), and less than 18 metres (high criticality, N=11). The correlation between this new variables and the original level of urgency was $r = 0.26$ (N= 39), which was too small to deduce a strong positive relation between the two variables. We therefore chose to do the analyses of the data once more with the new criticality variable. Since the new criticality variable was based on headway after the braking event, headway effects of the braking event were not determined in this section. Eight intersections including one directly before, one during and the rest after the braking event were again used for all Analyses of Variance (ANOVA) for Repeated Measures in this section, unless stated otherwise.

Both average speed and minimum speed decreased dramatically after the braking event (interaction effect of Trial and Intersection), $F(6,198)=2.186$, $p=.046$ for average speed and $F(7,231)=2.524$, $p=.016$ for minimum speed.

Participants encountering higher criticality events on average drove at lower minimum speeds over the two trials, $F(2,33)=7.144$, $p=.003$. It is not completely clear whether this is a causal relation, with higher criticality events leading to lower minimum speeds, or a result of a positive correlation between two types of cautious driving behaviour. However, minimum speed was also lowered for several intersections directly after the braking event (interaction effect of Trial and Intersection), $F(7.737,55.305)=2.293$, $p=.023$. Furthermore, the location at which this minimum speed was reached was significantly different for the three Criticality groups, with higher criticality levels leading to deceleration being finished closer to the intersection (lower DTI), $F(2,33)=3.859$, $p=.032$.

The speed per 10-metre cell was changed significantly as a result of varying Criticality, $F(2,33)=6.010$, $p=.006$; the interaction effect of Criticality and 10-metre Cell was also significant, pointing to a different speed patterns for the three Criticality groups: $F(5.040,90.715)=3.589$, $p=.005$. Furthermore, the speed pattern changed directly after the braking event in participants driving with an additional task. Figure 4.15 shows the different speed approach patterns at intersection 6, directly after the braking event, for the between-participant factors Mental workload condition and Criticality. Even though the 95% confidence intervals are quite large, it is visible that there is not a big difference between levels of event urgency for the regular drivers. In the group of participants driving with the additional task, however, the lowest event urgency decelerated substantially less and showed a smaller range of values in the speed approach pattern than all the other groups, whereas participants encountering the highest event level (High) had a much more profound deceleration curve, F(22,363)=2.143, p=.002 (three-way interaction effect of Cell, Criticality and Mental workload condition).

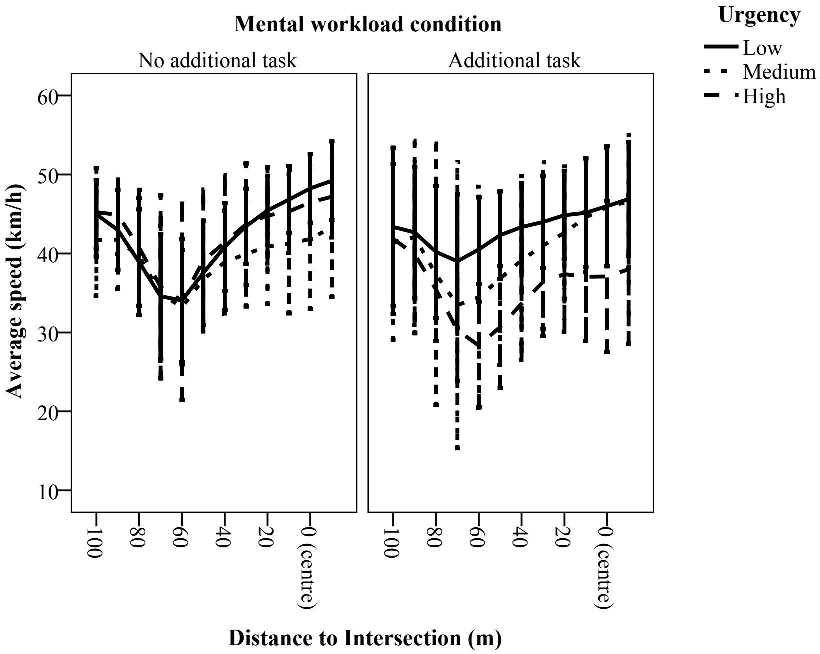

Figure 4.15 Average speed as a function of criticality and distance to intersection, without additional task (left) and with additional task (right)

When looking only at the braking event, participants in both mental workload conditions had similar initial reactions on distance headway to the braking lead car at intersection 6. However, participants driving with an additional task normalized their headway directly after this intersection, whereas regular drivers drove with an increased headway for a longer period of time, F(2,25)=3.402, p=.049 (Figure 4.16). Furthermore, using a Univariate Analysis of Variance (ANOVA) at only the path of the braking event, a significant interaction effect on headway was found between event criticality and drivers' mental workload conditions. Whereas regular drivers (no elevated mental workload) already showed a larger (distance) headway as a result of the medium critical event, this threshold was lifted for drivers with the serial subtraction task, who only showed a reaction after the most critical event, F(2,25)=6.097, p=.007. Figure 4.17 shows the interaction.

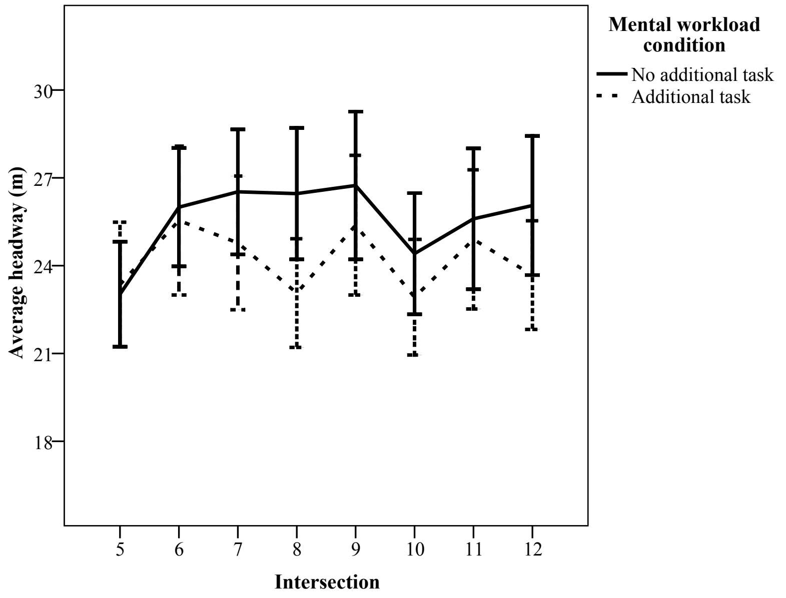

Figure 4.16 Distance headway during and after the braking event as a function of mental workload

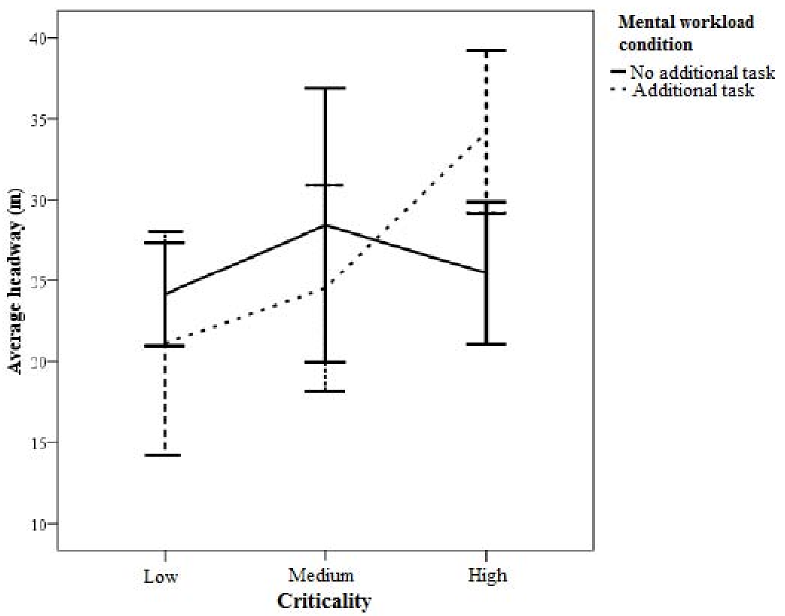

Figure 4.17 Distance headway as a function of mental workload condition and event criticality

Finally, we also found some interesting effects in the type of deceleration applied by the drivers as a result of event criticality. Participants encountering a lower criticality event released their gas pedal more often to decelerate, F(2,33)=6.847, p=.003, whereas participants in higher critical braking event would actively apply the brake pedal more often, F(2,33)=4.044, p=.027. Furthermore, participants on average braked more often after the braking event (interaction effect of Trial and Intersection) than in the reference condition, although this effect was not statistically significant at the .05 level, F(13.739,226.690)=2.010, p=.056.

Not surprisingly, again no effects of the braking event (interaction effect of Trial and Intersection) on lateral position were found with the new criticality categories, F(7,161)=1.049, p=.399, or lateral acceleration, F(4.333,142.987)=0.600, p=.676.

4.6.4.3 Accelerating car from left

The event with the suddenly accelerating car from the left occurred at the eighth road section in trial 4–Acc. In this section, driving tasks are compared between eight intersections in trials 3-Reg and 4–BLC (intersections 7-14) using the two between-subject variables Mental workload condition and Event urgency.

There was no effect on any of the analyzed variables that could be related directly to the accelerating event (which would be indicated by a significant interaction effect of Trial x Intersection), see Table 4.7. The urgency of the acceleration event did not have a substantial effect on average speed, F(2,33)=2.49, p=.099, minimum speed, F(2,33)=2.89, p=.070, or lateral position, F(7,126)=1.949, p=.067. However, although these effects are not statistically significant, they do represent a trend: the more serious the acceleration event, the lower average and minimum speed appear to be, and the more to the right of the road markings people tend to drive. The average headway, on the other hand, increased with acceleration urgency, although this change was again not significant at the .05 level, F(2,27)=3.25, p=.054. All of these effects point to slightly more cautious driving styles with increasing event urgency. Figures 4.18 a-c show these urgency effects on average speed, lateral position, and headway.

Table 4.7 Interaction effects of Trial and Intersection on a number of behavioural variables after the accelerating event

Variable	F-value	p-value
Average speed	F(6.650,219.461)=1.579	p=.147
Minimum speed	F(6,198)=1.265	p=.269
DTI at minimum speed	F(3.803,125.485)=1.964	p=.107
Distance headway	F(5.828,116.567)=1.400	p=.222
Lateral position	F(7,161)=1.949	p=.067
Lateral acceleration	F(5.658,186.726)=0.674	p=.662

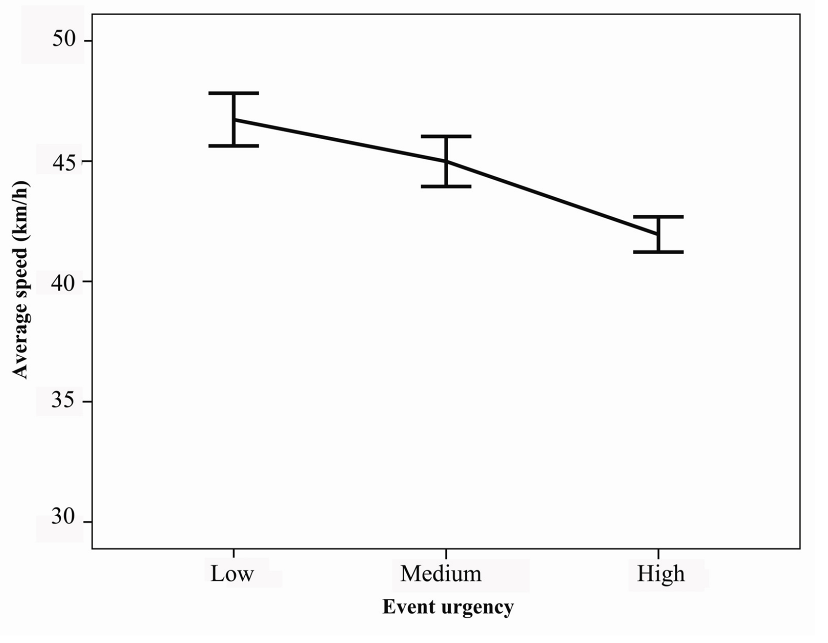

Figure 4.18a Effect of acceleration event urgency on average speed (ns)

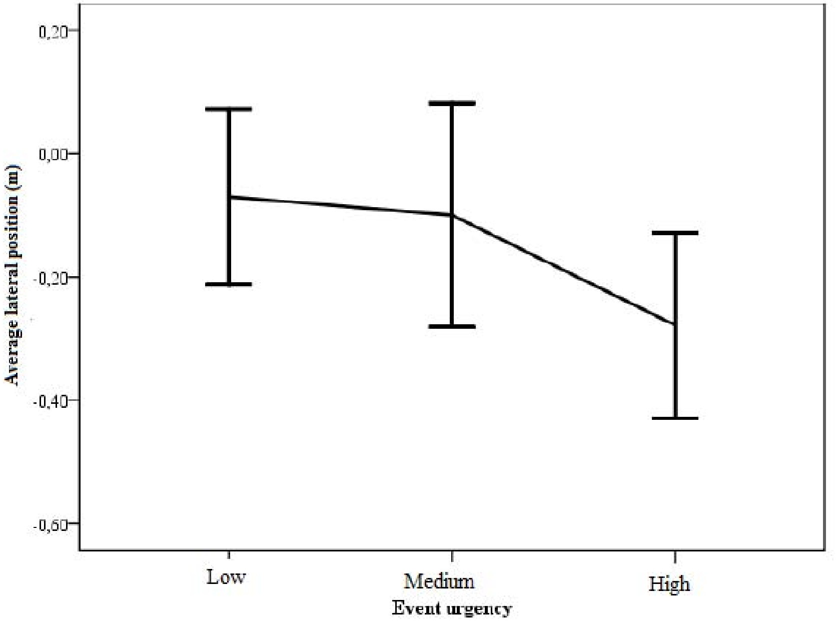

Figure 4.18b Effect of acceleration event urgency on lateral position (ns)

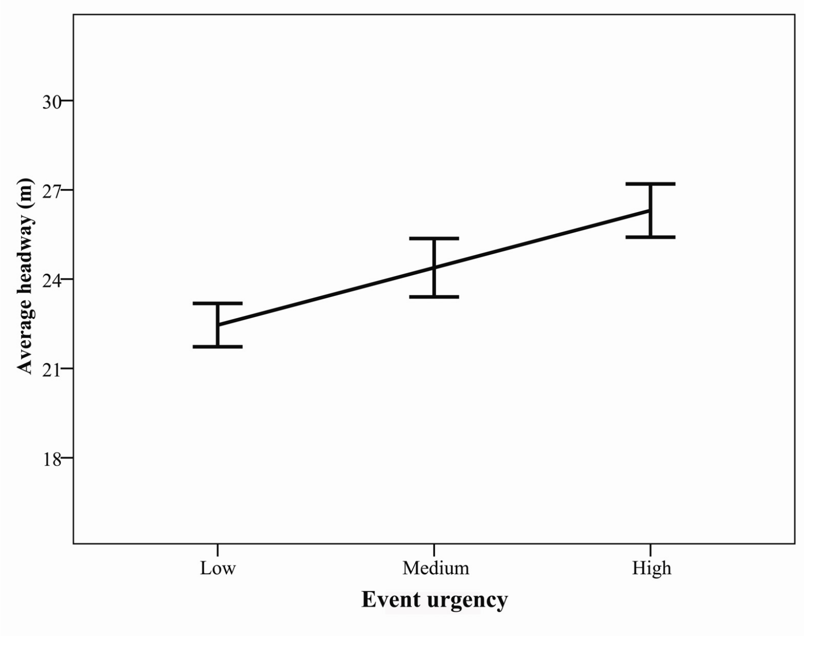

Figure 4.18c Effect of acceleration event urgency on average distance headway (ns)

The speed pattern as given by the speed values averaged per 10 meter did change significantly from one intersection to another, $F(77,2541)=4.33$, $p<.001$, and this change was influenced by Mental workload condition (Interaction effect Intersection x Cell x Mental workload condition), $F(77,2541)=1.456$, $p=.006$.

As described in Section 4.6.3 (Effects of mental workload conditions), an effect of mental workload condition on average speed in trial 4-Acc was found when comparing the three trials overall. However, this main effect of mental workload condition on average speed was not reproduced when taking only trial 4-Acc into consideration, $F(1,33)=3.432$, $p=.073$.

Finally, lateral position was significantly affected by the urgency of the acceleration event, $F(2,18)=3.947$, $p=.038$. None of the individual levels of urgency were shown to be significantly different from the other urgency levels in a post-hoc test.

Despite the fact that some of the changes in driving behaviour could not directly be related to the accelerating event by data analysis, a good share of the results that were found provide a solid starting point for further investigation. In the next section, these results will be discussed and additional hypotheses will be drafted based on this first driving simulator experiment.

4.7 Interpretation of results and additional hypotheses

The first driving simulator experiment revealed a number of results related to the initial two hypotheses, and led to results on which a number of additional hypotheses for the final experiment can be based. This section gives an overview of these results and provides an interpretation of their meaning and relevance. Finally, the hypotheses for the final driving simulator experiment will be given.

4.7.1 Overview and interpretation of results

The hypotheses for this initial experiment were as follows:

- The type of compensation behaviour (longitudinal, lateral, or a combination) required to safely handle an unexpected, safety-critical event determines the type of any (temporary) behavioural effect. Therefore, longitudinal compensation behaviour leads to changes in longitudinal driving behaviour only, and lateral compensation behaviour leads to changes in lateral driving behaviour only.
- After an unexpected event for which drivers need to perform compensatory actions, they adapt their driving behaviour. This is the result of a directional switch in task level interaction.

As was described in the introduction of this chapter, the aim of this experiment was to test these hypotheses about behavioural adaptations resulting from changes in task level interactions and expand these hypotheses, developing additional hypotheses relating to the influence of mental workload and event urgency.

The results presented in the previous section revealed a number of trends related to the behavioural changes after an unexpected event, and more specifically, to the influence of mental workload and event level. First of all, our expectation about different compensatory actions resulting in different types of behavioural changes was supported. The two different types of required compensation behaviour indeed led to different effects after the unexpected events. Initial compensation to the (longitudinal) braking event included lowering (longitudinal) speed, and this event later resulted in lower speeds but no change in lateral driving behaviour. The acceleration event required both deceleration and moving to a safer lateral position, but did not result in behavioural changes that could be directly linked to this event. In other words, the type of compensation required to safely handle a safety-critical event does temporarily influence the behaviour after this event. However, initial lateral compensatory actions were not shown to lead to behavioural adaptation regarding tasks in the lateral direction. The first hypothesis will therefore be slightly altered.

Both the average and minimum speed per intersection were lowered for a number of road sections as a result of a sudden braking event, while headway increased. This suggests that drivers temporarily drove more cautiously after encountering an unexpected braking event.

We studied event level in two ways: by using the original deceleration distance and duration, and as defined by the participant's headway directly after the braking event. The reason for choosing the second indication of event level was that the minimum distance between two vehicles is related to the level of conflict, and that this is not necessarily included in the first measure of event level. The latter event level indeed showed to be a better predictor of behavioural changes after the braking event, with significant effects on the average and minimum speed values after the braking event, and on the location at which drivers ended their deceleration and reached their minimum speed. A significant effect on the way in which participants decelerated was also found, with lower criticality leading to more passive deceleration (by means of releasing the gas pedal) and the highest criticality level leading to active braking. Summarizing, a braking event with a higher criticality led to a stronger change in driving style from normal to more cautious than a less critical braking event, and this change was furthermore reached by more active changes and ways of deceleration in the critical situation than in the less safety-critical situation. These results might partially be effects of the braking event, and could also be connected to a certain driving style. Participants who chose a larger headway might also be the participants who generally drive more slowly and change their speed on an intersection area less (smaller range of values in the speed pattern). This could account for the fact that this same group reached their minimum speed at a location closer to the intersection centre.

The most striking effects were seen in the interactions with the additional task. It was found that, when controlling for incident criticality, participants in both mental workload conditions had similar initial headway reactions to the braking lead car, but different reaction durations. After the first road section following the event, regular drivers continued to drive with an increased headway for some time, whereas participants with high workload directly normalized their headway. In other words, drivers with high mental workload initially reacted in the same cautious manner as did normal drivers, but fell back to their normal driving behaviour much faster than drivers who could completely focus on driving. Moreover, the threshold for increasing the headway after an unexpected braking event was higher when driving while performing an additional task than in normal workload circumstances. Whereas regular drivers reacted to both medium and high criticality events by increasing their headway, drivers with high workload only responded to the most serious event category. Apparently, only the most serious braking event triggered this latter group of drivers.

Furthermore, drivers with an additional task approached faster and with a less profound speed pattern (smaller range of values) when encountering low criticality events, whereas the highest event criticality was related to a more profound deceleration curve than for drivers without an additional task. A possible explanation could be that drivers with higher workload are more occupied with their additional task and therefore give less attention to the unexpected event. They might generally drive more habitually and give less conscious control to parts of their driving task, since they have less available attentional resources to react to cues in their environment. However, when the unexpected event reaches a certain threshold, its effect appears to come through more strongly, leading to a strong change in behaviour. This was also seen in distance headway effects: participants with an additional task react stronger but shorter to the braking event than participants without an additional task.

Finally, drivers with high workload drove more to the left side of their lane. One could argue that driving on the left side of the lane could give drivers the opportunity to see further upstream in the opposing direction when driving with a leading vehicle that might obscure the driver's line of sight. This would mostly be useful in situations where the driver is planning to overtake in the near future. However, it could also be seen as less cautious driving, since the lateral position of the vehicle is closer to opposing traffic, leading to a higher risk of head-on conflicts. This is especially the case for our experimental setup, in which the lateral position of opposing road users was fixed, overtaking was neither part of the task nor possible, and driving more to the left side of the lane therefore directly entailed driving closer to the opposing traffic without direct use. Moreover, the other actions also pointed to less cautious driving in high mental workload conditions. For instance, decelerating to obtain a good overview when approaching an intersection can generally also be labelled as driving cautiously, and drivers with increased workload showed this behaviour less than drivers with normal mental workload levels. We therefore conclude that increased mental workload seems to lead to a less cautious driving style. The additional task might take some of the attention required for safe and cautious driving away from the available resources, leading to performance reduction and possibly distraction.

Concluding, we can say that:

- Drivers who can focus most or all of their attention on the driving task temporarily drive at a defensive or cautious driving style as a result of a safety-critical braking event. They lower their speeds and keep larger headways.
- Drivers who have to divide their attention between driving and an additional task either do not show this defensive driving style, or quit this driving style sooner.
- Drivers spend less attention on certain aspects of the driving task, such as decelerating before an intersection, keeping right, and maintaining an appropriate speed, when driving with an additional task. This is also reflected in the fact that drivers under high mental workload only respond to highly critical events, whereas drivers under normal circumstances respond to all levels of events.
- The level of safety-criticality of a braking event does not influence the complete approach pattern of normal drivers, but it does influence the way in which drivers decelerate; higher criticality events evoke a more active way of deceleration (i.e., through braking) than less critical events, after which drivers more often release the gas pedal.
- Drivers with an additional task remain to drive faster and with a less profound speed pattern than normal drivers during the braking event (i.e., the range of speed values is smaller). This might be a result from the division of attention between the driving task and the additional task, leading to a lower level of awareness of the safety-criticality of the event. However, when the braking event reaches a certain threshold, drivers with high mental workload react stronger, as if they are startled more than regular drivers. The level of criticality does not influence the speed pattern of regular drivers.

This means that the first hypothesis on the type of compensatory actions leading to a specific type of behavioural adaptation, was only supported for longitudinal tasks, so this hypothesis will be optimized for the next experiment. Our second hypothesis, regarding the effect of an unexpected event on behavioural adaptation, was supported, but more information about this behavioural compensation and the effects of external factors such as mental workload and event urgency was found. This second hypothesis will therefore be expanded for testing in the next experiment.

4.7.2 Hypotheses for final experiment

Based on our results, we conclude that the type of compensation (longitudinal, lateral, or a combination) required to safely handle an unexpected, safety-critical event determines the type of any behavioural effect shown for some time after the event. As lateral compensation behaviour did not lead to any longer-term effects, the final simulator experiment will focus only on longitudinal compensation behaviour and the related (temporary) behavioural effects. The additional hypotheses for this final experiment are formulated as follows:

- Drivers driving with high mental workload pay less attention to the driving task, leading to a more inattentive style of driving; in other words, they are driving on in an automatic fashion.
- Drivers have a more defensive driving style after encountering a safety-critical situation when they can focus their full attention to the driving task. When this is not the case, for instance when driving with the pressure of high mental workload, this defensive driving behaviour diminishes quickly.
- Although drivers quit their defensive driving style when driving under pressure, the defensiveness re-emerges even stronger when the unexpected event reaches a certain threshold of safety-criticality. In other words, startled drivers can get pulled out of their inattentive/ habitual driving style if the level of event criticality is high enough.

4.8 Consequences of current experimental setup for results and lessons learned

The validity of the results was checked by scrutinizing the experimental setup and the aggregation method for calculating the variables. Four categories of aspects of the experimental setup were investigated:

- Layout of virtual environment
- Programming of unexpected events
- Programming of the lead car's speed choice
- Data recording

4.8.1 Layout of virtual environment

The layout of certain individual intersections had a significant effect on a number of variables. Intersections 5, 6, 9, 10, 13 and 17 showed to influence longitudinal driving behaviour whereas intersections 5, 10, 12 and 14 showed to be different from other intersections with respect to its effect on lateral driving behaviour, which might lead to an overestimation or underestimation of some of the results at this intersection. Intersection 10 was preceded by a bend, which probably led to the relatively large deviation in lateral position directed towards the outside (right side) of the lane. When combining both headway and speed, drivers drove more aggressive (driving faster with smaller headway) at intersection 5, but more defensive (larger headway and lower speed) at intersection 9 than at other intersections.

Although all intersections were designed to be similar in setup, the buildings framing the streets turned out to be placed a little closer to the street in a limited number of intersections. The fact that a full view of the side street was only possible at a farther location than at other side streets might have resulted in participants driving at lower speeds and maintaining a lower speed for a longer time, overall leading to a lower average speed at some intersections.

Furthermore, a rather large number of participants fell ill with driving simulator sickness during the experiment (11 participants had to stop because of serious dizziness or nausea, which is equivalent to 13% of the total group of participants). Most of them complained of objects in the virtual environment flashing past rather quickly as they drove through the road environment, which made the driving environment unpleasantly dense in their perception.

Studies into driving simulator sickness have revealed that it is related to a discrepancy between cues (both auditory and visual) and motion feedback. According to this sensory (or cue) conflict theory, this discrepancy induces discomfort and a number of different symptoms related to simulator sickness (Lin, Abi-Rached & Lahav, 2004). Other simulator aspects related to simulator sickness include the scene content, flicker, the duration of the experiment, the number of unusual movements, the angle and rate of movements made, and the screen refresh rate and resolution (Kolasinski, 1995). In order to optimally avoid simulator sickness, some aspects of the setup of the next experiment will be altered from the current setup. This includes placing objects in the virtual environment farther away from the road, creating more straight roads as opposed to bends, and using a simulator with optimal motion feedback and screen quality. Unfortunately, these alterations to the setup do not guarantee that simulator sickness is no longer a risk, but they do minimize the chance of simulator sickness.

4.8.2 Programming of unexpected events

The unexpected events could occur at three levels: low, medium and high urgency. Urgency of the braking event was programmed as the distance participants had travelled during the duration of the braking of the lead vehicle (so the closer participants came to the lead car relative to the start of the event, the higher the urgency level). This would give a good indication of event urgency if participants were at exactly the same time headway from the lead vehicle right before it would brake. However, participants were free (within limits) to choose their own headway at all times and this variable did not take into account the initial distance between the lead vehicle and the participant. The effects of the variable 'urgency' were only found to be significant for headway (larger headway after more serious events) and lateral position (drivers encountering the most serious events drove more to the outside of the road). When we looked at a different realization of event level, namely the headway to the lead vehicle at the moment directly after the event had finished, the effects of the variable increased dramatically. This event level indicator, 'criticality', was of significant influence on average speed, minimum speed and speed pattern (as measured by the location of the minimum speed and the speed values per 10 metres). Lateral position was not influenced by this measurement of urgency. It can be concluded that the urgency of the braking event was designed suboptimally. The duration of the braking event and the distance travelled during this time were not always directly related to the participants' experience of urgency. In further research, the urgency of unexpected events should be related to conflict measures, for instance by using time-to-collision or minimum time headway.

4.8.3 Programming of lead car's speed choice

As was described in the previous chapter, the lead car was programmed to choose a desired speed based on headway values between the participant and the lead vehicle. Effects of this interaction between speed and headway, caused by this way of basing a desired speed on the current headway, can therefore not be ruled out. Furthermore, an indirect interaction was discovered between the participant's speed choice and the behaviour of the vehicle approaching the intersection from the right side street at each intersection. If the participant decelerated early before the intersection and kept a large distance to the lead car, the vehicle from the right would also decelerate. This would cause the lead car and the car approaching from the right to come into conflict. The lead car would then decelerate in order to give way to the car coming from the right, resulting in a decreasing headway. Participants keeping a large headway and decelerating at large distances to intersections are probably more cautious drivers than others, and this cautiousness could be encouraged by the interaction with the car from the right leading to the lead car's behaviour at certain intersections. Future experiments should try to avoid these interactions between variables and between vehicles.

4.8.4 Data recording

The raw data in this experiment were sampled with 256 Hz, which is the default sampling rate of StSoftware (also see Table 3.2). This led to a situation in which more values were recorded for the stretch of road if participants drove this distance at a lower speed than if they would have driven the same distance at a higher speed. As was described in Section 3.4.2, the average speed was calculated by dividing the distance driven (either 100 metres for intersections, or 10 metres for 10-metre cells) by the time it took to drive this distance; all other variables were calculated by adding all recorded values over a specific stretch of road, and dividing them by the number of values in this calculation.

The headway was lowered for one intersection in all mental workload conditions, but directly normalized again in high mental workload conditions. This difference might be actually larger than we calculated with the current averaged values, since the driving speed remained lower for a number of intersections. With stretches of road driven at lower speeds being more prominent, increases in headway values might have been slightly averaged out by the aggregation method. Large lateral position effects are also likely to be underestimated due to this way of calculating the average value, since lower speeds are often related to smaller lateral position deviations.

Finally, the level of mental workload was measured using a secondary (or in some cases tertiary) task, the Peripheral Detection Task. Although this is a valid and highly sensitive measure of fluctuations in mental workload (Jahn et al., 2005), including additional measures sometimes leads to more optimal information about the causes of mental workload fluctuation. According to De Waard (1996), different measures are sensitive to different mental workload regions (please refer to Chapter 2 for more information on mental workload regions). Where possible, future experiments should not only include information about primary task performance and PDT performance, but should also include performance rates for the secondary tasks which were used to elevate mental workload, and preferably a physiological measure of mental workload.

4.8.5 Modifications on experimental setup for final experiment - lessons learned

Based on the discussion of validity, experimental setup and hypotheses, the following modifications will be made to the experimental setup as compared to the current experiment:

- Every road section will have a similar infrastructure and layout, including the level of sight at intersections.
- No bends or other road infrastructure shapes will be made in the blocks in which driving behaviour is measured.
- Any interaction between the different road users in programmed speed choice behaviour will be avoided as far as possible.

- The behaviour of the lead vehicle will be based on the time headway of the participant rather than on the headway, since this relates closer to realistic speed choice behaviour.
- It is difficult to generalize among different types of unexpected events. We will therefore focus on only one type, namely a safety-critical braking event. The level of conflict (e.g., time-to-collision, time headway) will be determined to assess the event criticality level.
- The focus will be on the interaction of mental workload level and event criticality. In order to get a complete view of the development of the mental workload during the experiment, PDT performance, secondary (arithmetic) task performance and a physiological measure will be recorded. Furthermore, mental workload level will be made a within-subjects factor, so that valid conclusions can be drawn based on smaller participant numbers.
- Buildings will be placed farther away from the road, since a relationship between closeness of large objects and simulator sickness is expected.
- The moving base simulator will be used, in order to increase internal simulator validity, increase screen resolution, provide motion feedback and thus reduce simulator sickness.

Chapter 5

Experiment 2: Effects of unexpected braking events under varying mental workload conditions

Based on the first driving simulator experiment, described in Chapter 4, we developed a number of hypotheses regarding behavioural change resulting from unexpected events and the effects of several other factors, such as mental workload and event urgency. The analyses of the first experiment revealed some limitations to the experimental setup with regard to differences in the layout of individual intersections, data recording, and the determination of the level of mental workload. The current experiment was designed to incorporate improvements on these aspects. After describing the method and setup of the experiment, an overview of the experimental results is given. The chapter concludes with a discussion of the generalizability of the results and a note on the experimental setup.

5.1 Hypotheses

The hypotheses for the current driving simulator experiment, based on the results from the first experiment, are as follows:

- Drivers driving with elevated mental workload pay less attention to the driving task, leading to a more inattentive style of driving; in other words, they are driving in an automatic fashion.
- Drivers have a more defensive driving style after encountering a safety-critical situation when they can focus their full attention to the driving task. When this is not the case, for instance when driving with the pressure of high mental workload, this defensive driving behaviour diminishes quickly.
- Although drivers quit their defensive driving style when driving under pressure, the defensiveness re-emerges even stronger when the unexpected event reaches a certain threshold of safety-criticality. In other words, startled drivers can get pulled out of their inattentive/ habitual driving style if the level of event criticality is high enough.

A fourth hypothesis, which was formed earlier based on the model by Michon (1971, 1985) and was studied in the first driving simulator experiment, concerns the type of compensation and the related changes in driving behaviour, resulting from bottom-up influence between the driving tasks.

- The type of compensation (longitudinal, lateral, or a combination) required to safely handle an unexpected, safety-critical event determines the type of any (temporary) behavioural effect. Therefore, longitudinal compensation behaviour leads to changes in longitudinal driving behaviour only.

5.2 Research tools

The final driving simulator study was performed in order to test the hypotheses about behavioural adaptations resulting from changes in task level interactions, about the influence of mental workload and event urgency. Our data therefore included driving behaviour measurements, mental workload measurements, and information on drivers' perceptions and expectations.

The experiment was performed in the TNO Human Factors moving-based driving simulator with automatic transmission. This moving-base driving simulator (Figure 5.1) consists of the following sub systems:

- The Mock-up, a BMW 318I with automatic transmission, left seated driver, and normal controls
- The vehicle model computer, which calculates the simultaneous position and heading of the simulated vehicle
- The Motion Base System, a 6 degrees of freedom MOOG 2000E hexapod motion platform with the associated control equipment

- The outside visual, a projected image on a radial screen in front of the mock-up, with a field of view of 120° horizontal and 35° vertical, and two large screens behind the mock-up, projecting the rear-view images reflected in the car's mirrors
- A 34" LCD display, mounted in the rear of the mock-up, for rear view display
- A supervisor computer for the communication with the experimenter and the other subsystems, the control and monitoring of the experiment, data storage, controlling the behaviour of other traffic, et cetera

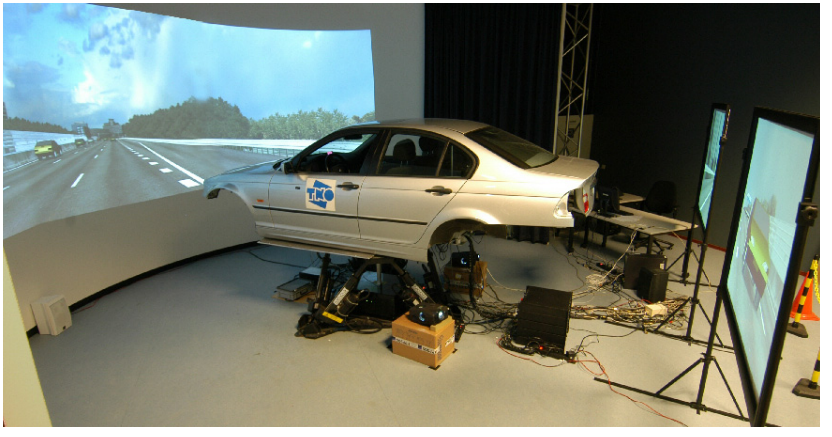

Figure 5.1 TNO's moving-base driving simulator

Furthermore, the video and sound are processed through separate PC systems. The Motion Base System increases external validity (Kaptein, Theeuwes & Van der Horst, 1996).
In order to assess participants' mental workload during driving, their heart rate and heart rate variability were measured using a Polar S810i training computer and transmitter during driving. Furthermore, participants were required to perform the Peripheral Detection Task (PDT) (Van Winsum, Martens & Herland, 1999) during driving. More on the PDT can be found in Chapter 3.2.2.

5.3 Participants

A total of 46 subjects participated in our experiment. The selection criteria for participants were:

- in possession of a driver's license for five or more years
- age between 24 and 60 years old
- at least 7,000 km driven annually
- no indication of motion sickness (e.g., no negative experience with car sickness, positive experience with driving simulator experiments)
- no indication or history of heart disease

Eight participants (17% of the total number of participants) were unable to finish the experiment due to simulator sickness. Furthermore, the datasets of two participants were excluded from analyses due to repeated non-compliance to the traffic regulations. The analyses are therefore based on complete data sets of 36 subjects who completed the experiment. They were between 23 and 60 years old, had their driver's license for at least five years and drove 7,000 kilometres or more annually. The average age of the 36 participants was 48.9 years (SD 11, minimum 23, maximum 60); 29 participants were male, 7 female. Participants drove 22,190 kilometres annually on average (SD 15,250, minimum 10,000, maximum 60,000). All participants were paid € 30,– for their participation. Most of the participants had prior experience in driving simulator studies.

5.4 Experimental design

An urban layout was simulated as a long road divided into three blocks with twenty (20) four-way intersections each, resulting in 60 road sections for a complete trial. Subjects were instructed to drive straight on each intersection with a maximum speed of 50 km/h and give priority to traffic coming from the right according to Dutch traffic regulations. Each of the 60 road sections was at least 175 metres long, and each block of 20 road sections was separated by curvy 70-km speed limit parts. One complete trial took an average of 18 minutes.

The infrastructure was comparable at each intersection. A lead car drove in front of the subject during the whole drive, slowing down when the subject fell too far behind (time headway larger than 2.5 seconds) and speeding up when the subject came too close (time headway smaller than 0.8 seconds). Furthermore, the lead car would decelerate at 45 metres before each intersection at a rate equivalent to releasing the gas pedal (maximum deceleration of 1.5 m/s^2), as to take enough time to get a good overview of the complete intersection situation. At 10 metres before the intersection, the lead car would accelerate again to normal speed with a maximum of 2.0 m/s^2. The lead car did not use its brake lights during this manoeuvre. At certain intersections, a car coming from the right or the left crossed the intersection before the participant and the lead car. Traffic from the opposite direction approached at random intervals within a range of 4.0 and 10.0 seconds.

The experiment consisted of two such experimental trials, which in turn consisted of three blocks of 20 road sections. The mental workload level was varied between the three different blocks of each trial, according to a pre-assigned order, and in three of the in total six blocks the lead car braked. In the first trial, this was in the second block; in the second trial, the braking happened in the first and third block. The lead car thus braked three times in total, once for each level of mental workload. Figure 5.2 shows the overview of the two experimental trials and the order in which reference blocks and event blocks were varied.

In the blocks in which the lead car braked, participants first drove six to nine standard road sections, setting their expectations about the situations to come. The exact number of road sections that the participants drove before the lead car braked depended on how quickly all constraints for the braking even were met. The constraints were set as follows:

- Time headway between 1.0 and 2.0 seconds
- Location between 100 and 45 metres from the next intersection

If the participant had passed the first three road sections selected for braking (the sixth, seventh and eighth road section of the current block) and not all constraints had been met, the braking event would take place at a largely fixed location at the fourth option, namely at the ninth road section of the block, between 80 and 90 metres from the next intersection.

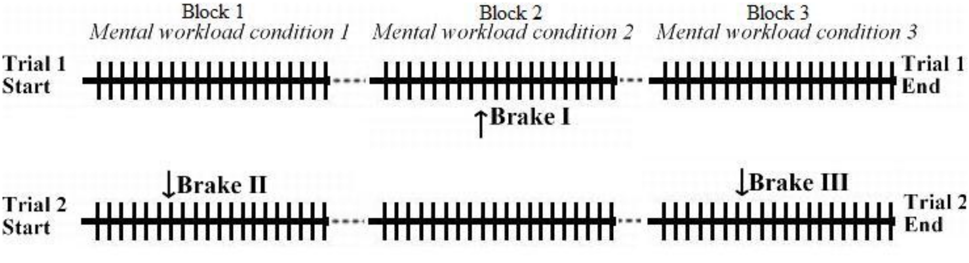

Figure 5.2 Overview of experimental trials with order of mental workload conditions and event versus reference sections

Either as soon as all constraints were met at one of the selected road sections, or at the designated fallback option (the ninth road section), the lead vehicle braked suddenly. After some time it accelerated again to its initial speed. Deceleration was set at 4.0 m/s^2 for a non-urgent braking event, and at 5.0 m/s^2 for an urgent braking event, and the headway after the event was varied for the two urgency levels. Appendix A.2 provides the annotated code for the lead vehicle's behaviour, including these braking events. Participants encountered either three urgent or three non-urgent braking events in their experimental drives; urgency of the braking event was therefore a between-subjects factor. Mental workload level, on the other hand, was a within-subjects factor. This variable had three levels: no additional task (only driving, baseline workload level), driving while performing an easy arithmetic task (slightly elevated workload level), and driving while performing a difficult arithmetic task (highly elevated workload level). Participants encountered all of the workload levels during their experimental drives. The three braking events took place at different mental workload levels, so in each level of mental workload exactly one block with and one block without a braking event was encountered. Figure 5.2 clarifies this setup.

Since one and the same arithmetic task can bring varying levels of elevated workload for different participants, we tested the arithmetic skills of all participants before the experiment and selected the participants with 'good arithmetic skills' from those with 'less arithmetic skills'. This was done by asking them to iteratively subtract the number four (4) from one-hundred (100). If they could do this quickly and without many errors, they were considered to be in the well-skilled group; if they made many errors or were struggling with the task, they were assigned to the less-skilled group. The easy and difficult arithmetic tasks were different for these two groups, but the structure remained the same for all tasks. Participants were instructed to iteratively subtract a one-digit number from a three-digit figure during the sections with the arithmetic task. Exact serial subtraction tasks for each condition and skill-group are given in Table 5.1. Participants were furthermore instructed to continuously perform the additional task and were reminded of their task after a number of seconds without an answer, but it remained a self-paced task.

Table 5.1: Additional tasks for each skill-group and each elevated workload condition

Skill-group	Simple arithmetic task (slightly elevated workload)	Difficult arithmetic task (highly elevated workload)
Good arithmetic skills	850-7	850-17
Bad arithmetic skills	450-4	850-13

The three levels of mental workload (driving only, driving with simple arithmetic task. and driving with difficult arithmetic task) and the two levels of urgency (braking close to participant and far away from participant) were combined to 12 combinations and counterbalanced among participants. As described before, all levels of workload were presented to all participants in a within-subjects setup; the order of the mental workload level and the level of urgency were in a between-subjects setup. Table 5.2 shows the 12 conditions, consisting of the combination of counterbalanced orders of workload level and the urgencies of the braking event.

Table 5.2 Twelve conditions of workload level and urgency of the braking event

Condition	Mental workload 1	Mental workload 2	Mental workload 3	Urgency
1	No additional task	Easy arithmetic task	Difficult arithmetic task	Non-urgent
2	No additional task	Easy arithmetic task	Difficult arithmetic task	Urgent
3	No additional task	Difficult arithmetic task	Easy arithmetic task	Non-urgent
4	No additional task	Difficult arithmetic task	Easy arithmetic task	Urgent
5	Easy arithmetic task	No additional task	Difficult arithmetic task	Non-urgent
6	Easy arithmetic task	No additional task	Difficult arithmetic task	Urgent
7	Easy arithmetic task	Difficult arithmetic task	No additional task	Non-urgent
8	Easy arithmetic task	Difficult arithmetic task	No additional task	Urgent
9	Difficult arithmetic task	No additional task	Easy arithmetic task	Non-urgent
10	Difficult arithmetic task	No additional task	Easy arithmetic task	Urgent
11	Difficult arithmetic task	Easy arithmetic task	No additional task	Non-urgent
12	Difficult arithmetic task	Easy arithmetic task	No additional task	Urgent

Heart rate and heart rate variability (inter-beat intervals) were recorded using a Polar watch which could be synchronised with the data recordings by means of digital markers in the data. The supervisor of the experiments pressed a button at the supervision panel of the driving simulator each time the participant started a new part of each experimental trial, so that the time in the driving simulator and the time on the Polar watch could be exactly matched and the heart rate fluctuations could be related to the events and changes in mental workload. Unfortunately, these markers were not recorded properly in many of the trials. The Polar watch started the data recordings as soon as the participants put the watch on their wrist, whereas the driving simulator started the recordings as soon as the experimenter started the scenarios. Because of this ‘mismatch’ between the starting times of the experimental trials and the starting time of the heart rate data recordings, the markers were necessary to relate the heart rate data to the experimental trials and the event times. Due to the loss of the markers, it was no longer possible to relate the data in the heart rate recordings to the actual data, and many of the heart rate datasets could not be used for data analysis. Therefore, we unfortunately could not include heart rate data in our final analyses.

After each of the two trials, participants were given a break and a questionnaire, with two questions about simulator sickness, three questions about the predictability of the driving task, the driving environment and the other road users, and one question asking whether performing the PDT had interfered with their driving. Furthermore, three additional questions were asked about the experienced difficulty of the arithmetic tasks and whether they had influenced the participant’s driving style. Participants had to rate their answers to the questions on a 5-point Likert scale. The questions were phrased as follows:

What did you think of the behaviour of other road users? Please rate your answer on the scale below.

Predictable X X X X X Unpredictable

What did you think of the predictability of the driving task? Please rate your answer on the scale below.

Predictable X X X X X Unpredictable

Participants had the opportunity to write additional remarks at the end of the questionnaire. Appendix C2 gives the full questionnaire (in Dutch).

5.5 Procedure

Participants were welcomed to TNO and were taken to a waiting room. They received general information about the project and the driving simulator. Participants were then given the opportunity to ask general questions about the project and the experiment. After signing an informed consent form, all participants drove one introduction drive preceding the actual experiment to give them the opportunity to gain some experience with the driving simulator and the simulated environment.

Next, participants were given more information about the specific arithmetic and driving tasks in the experiment. They were categorized according to their arithmetic skills based on a short arithmetic task (see Section 5.4). After this categorization participants received their instructions. Driving safely was to receive the highest priority. The arithmetic task, when applicable, should be given second priority, and the PDT should receive lowest priority, but should still be completed as fast as possible. The instructions can be found in Appendix B2.

After a short break in which they could ask the last procedural questions, participants drove the two experimental drives. Participants were randomly assigned to one of 12 conditions, and based on this assignment they were presented with a certain type of braking event (urgent or non-urgent) and the three mental workload levels in a certain order. The mental workload levels corresponded with the three parts per drive. At the start of each new part, the supervisor of the experiment told the participant which arithmetic task, if any, he or she had to perform in that part. The experiment supervisor recorded each participant’s correct and false answers to the arithmetic tasks on an answer sheet. Heart rate and heart rate variability were measured unobtrusively throughout the complete trials, and digital markers were placed at the start of each new part of a trial.

After each of the two trials, participants were given a questionnaire with questions regarding their health, the predictability of the task and other road users’ behaviour, and the influence of the secondary tasks on their driving style. After completion of the experiment, participants were paid € 30,-. Participants with questions regarding the goal of the experiment were given a detailed explanation of the setup and aim of the experiment.

The parameters recorded in this experiment were given in Table 3.2 (Section 3.4). Section 3.4 also describes the statistical tests used for the analysis of the dataset.

5.6 Results

This section describes the results of the final experiment. Firstly we will determine whether our research setup was valid, and inspect any possible confounding factors in the setup. Were the braking events implemented correctly? Did participants experience increased mental workload due to the additional mathematical task? Did the overall characteristics of the participants not influence their driving behaviour? Secondly, we determine what effects the braking events and their urgency have on driving behaviour. Do drivers indeed drive more carefully after the braking events? And does the urgency of the braking event have an effect on this behavioural reaction? And finally, we investigate the effects of mental workload on general driving behaviour and the reactions to the unexpected braking events.

Vertical bars in each figure denote 95% confidence intervals. Tables describing the comparison between braking conditions contain information about one road section before the braking event, the road section of the braking event itself, and a number of road sections following this event. The number of road sections included in the tables is dependent on the number of road sections with a statistically significant effect. We included two road sections after the final significant effect, to make sure no falsely undetected effect at a certain road section would be mistaken for the end of the behavioural change. In certain tables the significance values of many consecutive locations (distance to intersection, DTI) on a specific road section are given. In these tables, multiple consecutive non-significant results are combined for space efficiency reasons. Their significance values are denoted as (ns) for ‘not significant’.

5.6.1 Construct validity and setup

As was described in Chapter 4, we manipulated a number of variables to determine the effects of an unexpected braking event on driving behaviour in several conditions of mental workload elevation. In order to give a solid and valid answer to these questions, it is first necessary to determine whether the experimental constructs were implemented correctly. Besides checking whether the setup of the experiment was done correctly, it is also important to determine whether there were any possible other confounding factors that might have contaminated our results, such as the characteristics of our group of participants and the order in which mental workload was varied across conditions.

5.6.1.1 Mental workload

In order to check whether adding the additional task onto the driving task had had an effect on the mental workload, we analyzed the average reaction time to the PDT stimuli and the percentage of missed PDT stimuli in each of the mental workload conditions. The data show that adding an additional task to the driving task increased mental workload, and that an increase in difficulty of this secondary task led to a further increase in mental workload.
Swerving showed a slightly different pattern: the standard deviation of the lateral position (SDLP) was significantly lower in the easy arithmetic task condition than the normal driving condition. The other conditions did not differ significantly from each other. Swerving, in other studies often related to high mental workload, was therefore strongest in both the normal driving condition and the high mental workload condition, and decreased in the easy additional task condition. These findings coincide with results reported by Brookhuis, De Vries and de Waard (1991). The results of the three measurements of mental workload are displayed in Table 5.3; Figures 5.3a and 5.3b give a graphic display of the results on PDT stimuli (Reaction time and Percentage of missed signals).

Table 5.3 Effects of task difficulty on mental workload measurements (average and 95% confidence intervals)

Measure	Driving only	Driving with easy arithmetic task	Driving with difficult arithmetic task	Effect and effect size
Reaction Time to PDT (ms)	M= 495.75 (462.53, 528.97)	M= 697.75 (650.27, 745.23)	M= 747.73 (698.42, 797.04)	$F(2,66)= 116.122$, $p<.001$, $\eta_p^2=0.779$
Percentage of missed PDT stimuli (%)	M= 9.38 (5.89, 12.87)	M= 31.24 (24.36, 38.12)	M= 41.21 (34.09, 48.33)	$F(1.726,58.628) = 62.181$, $p<.001$, $\eta_p^2= 0.647$
Swerving (SDLP) (m)	M= 0.073 (0.066, 0.080)	M= 0.064 (0.059, 0.070)	M= 0.068 (0.061, 0.074)	$F(1.636,37.628)= 11.315$, $p<.001$, $\eta_p^2= 0.330$

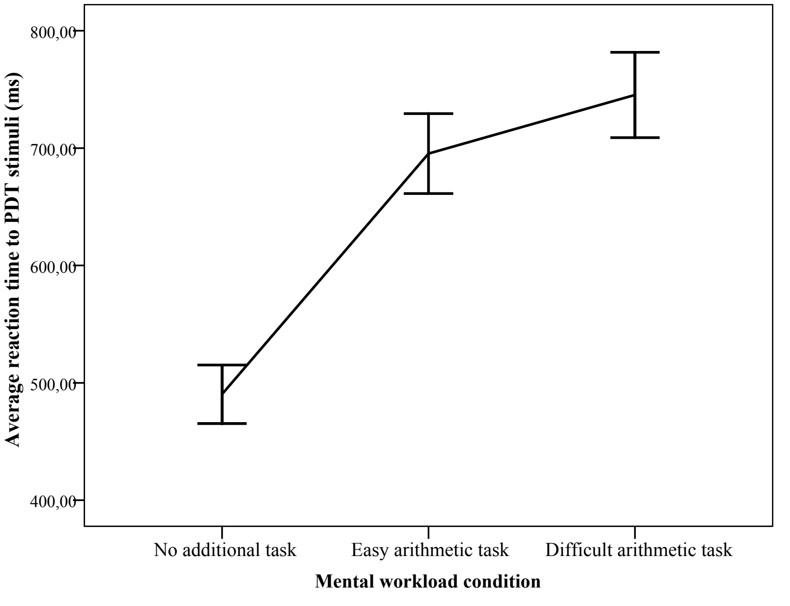

Figure 5.3a Reaction time to PDT (ms) as a function of mental workload condition

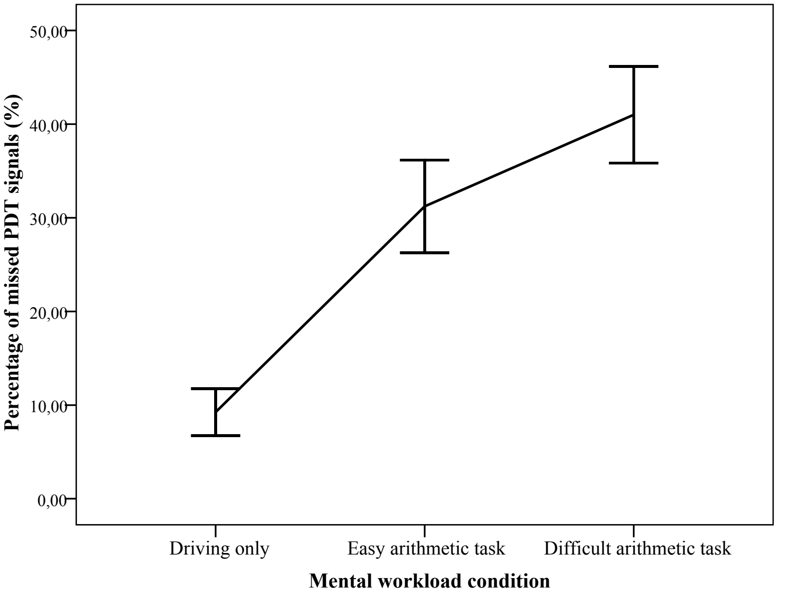

Figure 5.3b Percentage of missed PDT stimuli as a function of mental workload condition

We also determined participants' performance on the arithmetic tasks. Together with primary task and PDT performance, this measure can give a good indication of mental workload, especially when there are signs of giving up on either the primary or the secondary task. When driving while performing the easy arithmetic task, participants on average gave 102.5 answers in total, and made 2.6 mistakes (2.9%). In the difficult arithmetic task, 47.3 answers were given and 4.8 mistakes were made (12.5%). Therefore, participants on average performed much better on the easy task, with 2.4 times more answers and only one third of the proportion of wrong answers. This could suggest that participants gave up on the difficult arithmetic task in order to focus on the primary task of driving (please refer to Chapter 2 for more information on multi-tasking).

5.6.1.2 Location of the braking events

As Section 5.5 described, the braking event was programmed to occur at one out of four designated road sections per block of the experiment. The braking events occurred if a participant's time headway fell within certain limits between certain distances to the next intersection at the first three possible paths. If this situation did not occur within the first three road sections, there was a fallback option at a fourth road section, where the braking event would take place at a fixed distance from the next intersection. Of all braking events, 64.8% occurred at the very first possible road section, and 86.1% occurred within the first three possible road sections selected for braking. The other 13.9% of the braking events occurred at the fallback road section, all within 140 and 80 metres before the next intersection.

We compared time headway and speed at the start of the braking event for these two options: fallback option (N=15) or braking within constraints (N=93). Independent samples t-tests showed that time headway at the start of the braking event at the fallback road section was significantly shorter (M=0.77, SD=0.16) than time headway at the start of the braking event in the first three selected road sections (M=1.34, SD=0.31), t(32.487)=10.523, p=<.001, *r*=0.88. Speed was significantly higher in the fallback option (M=52.13, SD=3.71) than in the constraint-option (M=49.74, SD=3.48), t(106)=-2.439, p=.016, *r*=0.23.

These differences in starting conditions could have led to a possible overestimation of the results for 13.9% of the 108 braking events, since the higher speed and the shorter headway might together have led to a higher urgency of these events than the other 86.1% of the events. When driving with a shorter time headway as well as with a higher speed, a braking lead vehicle can startle a driver more than in other situations. However, we do not believe that this difference in urgency has led to a relevant or notable difference in the results for the conditions. First, the fallback options were not concentrated within one mental workload condition. A distortion of mental workload results is therefore not expected. And second, although a difference of 0.6 seconds is a rather large difference between two time headway values, the conditions were still programmed and executed in the same way as in the other situations. We therefore conclude that no effects of this fallback option on the results are to be expected, and the location of the braking situation will therefore not be taken into account for the current analyses.

5.6.1.3 Driver characteristics and order of mental workload condition

We determined the effects of age, gender, number of kilometres driven annually, and the order in which the mental workload variations were presented, on a number of driving tasks: maintaining average speed, standard deviation of speed, lateral speed, and headway. This was done by analyzing the results of 36 complete datasets using a Repeated Measures Analysis of Variance (ANOVA). Neither any of the driver characteristics, nor other unintended factors in the setup of the experiment, had a significant effect on any of the driving tasks (α= .050). It can therefore be concluded that any behavioural effects found can fully be attributed to the deliberate programming in the experiment.

5.6.2 Effects of the braking event on driving behaviour

In this section, the effects of the braking event on both longitudinal and lateral driving behaviour are described. We studied average effects and effects on approach pattern for the following five variables: speed, following distance (headway), time headway, lateral position and lateral speed.

Road sections are labelled ‘paths’ in the remainder of this chapter, referring to the recoding that was necessary for the comparison of different mental workload conditions. As was described before, there were four possible road sections at which the braking event could occur. We recoded their road section numbers in such a way that allowed comparison between and within conditions and participants. The road sections at which the braking events took place were recoded as path 0, and will be referred to as such throughout this chapter and the next. The sections leading up to the braking event were recoded with negative path numbers, with lower numbers referring to sections farther away and numbers closer to zero referring to sections closer to the braking event. The same was done for the paths after the braking event, but in this case positive numbers were used. The road directly before the braking event was therefore recoded as path -1, the road section of the braking event as path 0, and the road section after the event as path +1. In the trial without the braking event, these codes were copied, leading to the recoding of all road sections in the whole experiment. Figure 5.4 shows the resulting scheme of the experiment.

We determined the effect of braking on driving behaviour by comparing certain (recoded) road sections in a block with a braking event, to the same roads in the block without the braking event. This means that path 0 in the braking condition was compared to the same path in the reference condition, so the same path in the next trial (which was then recoded to path 0). The subsequent path in each condition was recoded as path +1 and compared to the other condition, and this was done for all the other paths within the comparison range as well. This way, the same paths and the same mental workload condition could be used as a factor in comparison; the only difference was the brake condition.

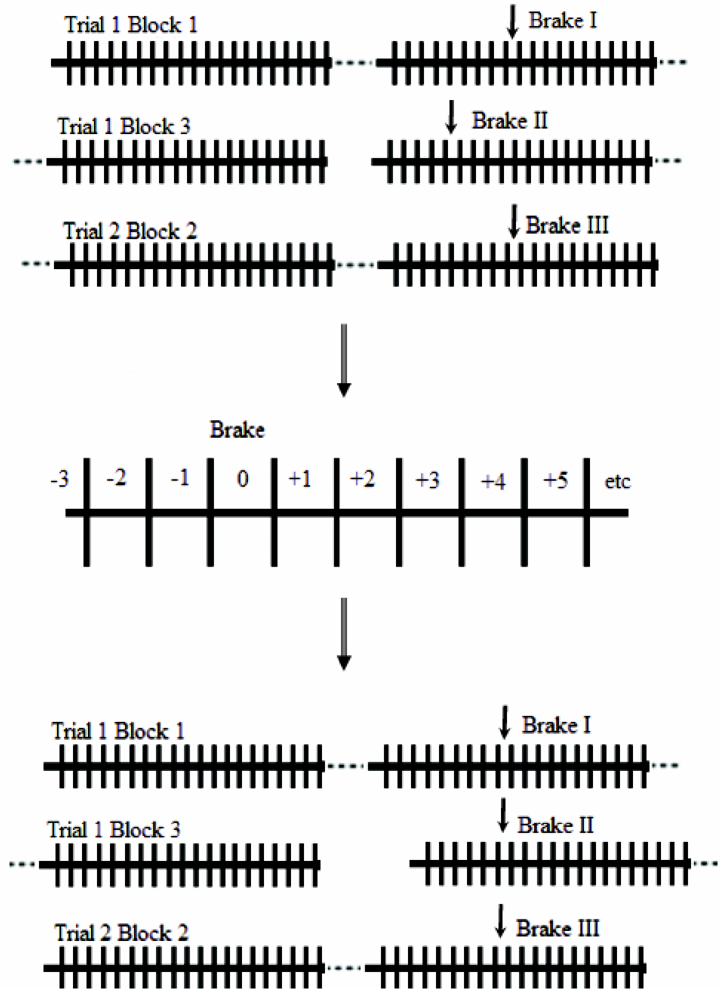

Figure 5.4 Scheme of experimental setup. Top: Brake events occur in Trial 1 Block 2, Trial 2 Block 1 and Trial 2 Block 3. Bottom: Locations of braking events are used as baseline for recoding of road sections

5.6.2.1 Speed

In this section we describe the effects of the braking event and its urgency on average driving speed. Average speed was calculated by dividing the distance travelled by the time it took a participant to drive this distance (km/h).

General effect of the braking event

We compared the difference between paths after the braking event to the same paths in the condition without the braking event.

The braking event had a large effect on the speed at path 0, as compared to the condition without a brake event, $F(1,34)=1292.097$, $p<.001$, $\eta_p^2=0.974$. The difference between the condition with the braking lead car and the reference condition was also statistically significant for path +1, $F(1,34)=14.935$, $p=<.001$, $\eta_p^2=0.305$, indicating a small-sized effect. At path +2, the difference between the reference condition and the condition with the braking event was no longer statistically significant. Table 5.4 and Figure 5.5 give an overview of the speed differences between the two brake conditions on paths -1 to +3. It can be concluded that the effect of the braking event on speed was real during one path after the braking event, but disappeared directly after this.

Table 5.4 Speed comparison between both braking conditions at paths -1 to +3

Path	**Mean and 95%- C.I. non-braking (km/h)**	**Mean and 95%- C.I. braking (km/h)**	**F(1,34)**	**p-value**	**Effect size (η_p^2)**	**Observed power**
-1	43.48 (42.53, 44.44)	43.95 (42.98-44.92)	1.566	.219	0.044	0.229
0	44.60 (43.99, 45.21)	30.06 (29.27, 30.86)	1292.09	<.001	0.974	1.000
+1	45.59 (45.00, 46.18)	43.28 (42.01, 44.56)	14.935	<.001	0.305	0.964
+2	43.57 (42.97, 44.17)	43.01 (42.26, 43.75)	1.730	.197	0.048	0.248
+3	43.25 (42.41, 44.09)	42.75 (41.73, 43.76)	0.060	.391	0.022	0.135

Effects on approach pattern

In the approach pattern, a similar effect was found: at path -1 the patterns were similar, no matter whether a braking event followed. Analyses for each location (10-metre cells) using ANOVA for Repeated Measures confirmed that the speeds did not differ at any location; this is according to the expectations.

At path 0 the patterns differed strongly between the two brake conditions. In the condition without the braking lead vehicle, the speed pattern was similar to that at path -1, which is again according to expectations. The speed values after the braking event were all lower than in the reference condition, and the effect of the braking event was profound. Next, at path +1, the speed in anticipation to the intersection (location 40 – 100 metres from the next intersection) was lower than in the reference condition, but the intersection speed itself was not. Similar comparisons were made for the next path ahead, path +2. Again, the speeds in the braking condition were lower at some locations than in the reference condition, but only between 80 and 110 metres to the intersection. Figure 5.6 (next page) gives a graphical overview of the speed patterns before, during and after the braking event. Table 5.5 (next page) shows the significant results of the ANOVA for Repeated Measures for paths 0 to +2.

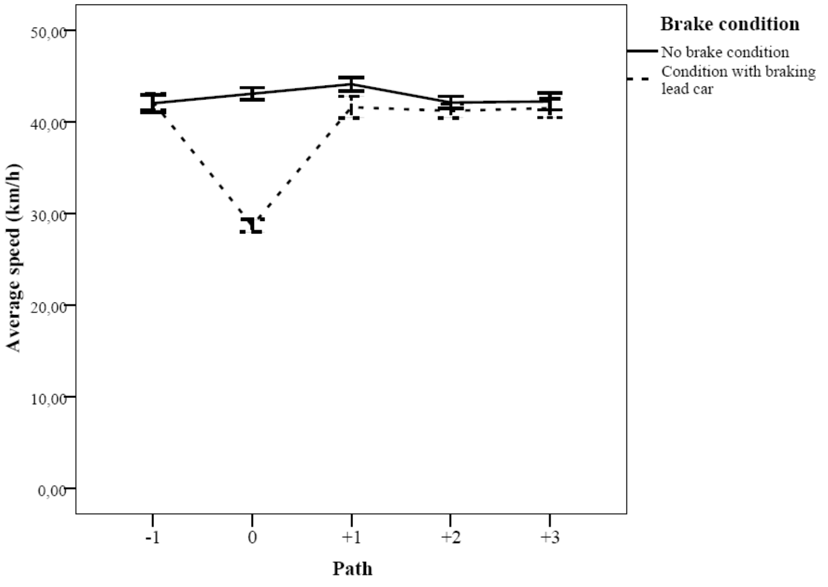

Figure 5.5 Average speed (km/h) at paths -1 to +3 in both braking conditions

Most differences between the braking condition and the reference condition disappeared at path +3. There were no statistically significant changes in speed at this path for any of the DTI's. One very small but statistically significant interaction effect between workload and brake condition was found at 50 metres before the intersection, $F(2,68)=4.704$, $p=.012$, $\eta_p^2=0.122$. However, due to its very small effect size, this result is not practically relevant. No significant effects were found at path +4.

Effects of urgency

There was a significant interaction effect of urgency and braking condition at path 0, $F(1,34)=30.416$, $p<.001$, $\eta_p^2=0.472$. Whereas the speed in the non-braking condition was not affected by event urgency, participants drove significantly slower at path 0 in the urgent braking condition (M=28.19, SD=0.60) than in the non-urgent braking condition (M=31.94, SD=1.17). From path +1, this effect was no longer significant, $F(1,34)=0.901$, $p=.349$, $\eta_p^2=0.026$. No other significant and practically relevant effects of the urgency of the braking were found. It can therefore be concluded that the urgency of the braking event had a small effect at the braking path itself, but that this effect did not extend past the event path.

Some unexpected results were found as well. At path -1, speeds in the different urgency conditions were significantly different, $F(1,34)=7.159$, $p=.011$, $\eta_p^2=0.111$. A similar effect was seen at path +3, $F(1,34)=4.290$, $p=.046$, $\eta_p^2=0.112$. In both cases, the speed in the urgent braking condition was higher than in the non-urgent condition, although these paths were not (and in the case of path -1 could not have been) influenced by the braking event in any other way.

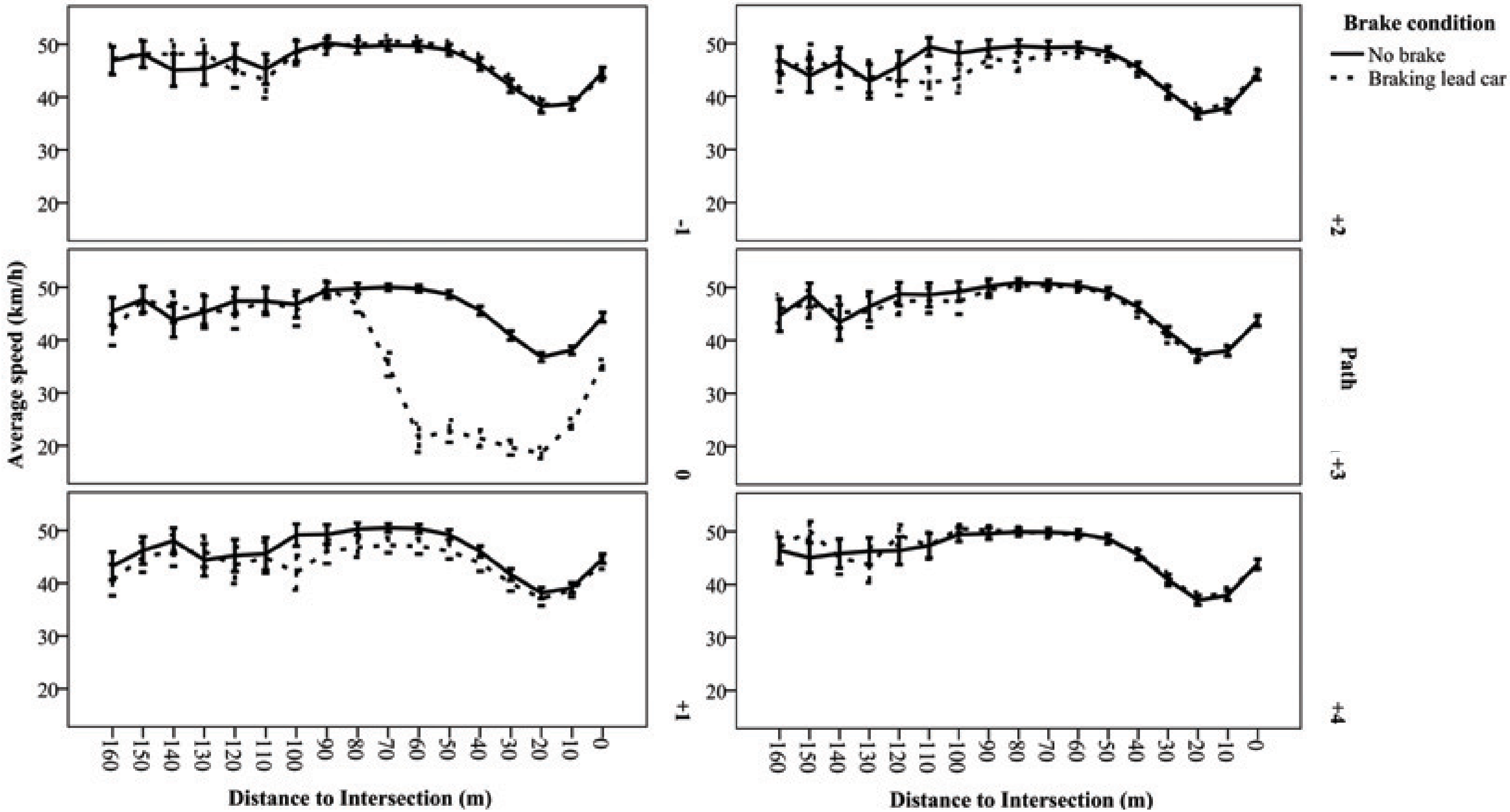

Figure 5.6 Speed per DTI for both braking conditions at paths -1 to +4

Table 5.5 Speed approach pattern - comparison between both braking conditions at paths 0 to +2

Path	DTI	Average (95%-CI) non-braking (km/h)	Average (95%-CI) braking (km/h)	F(1,34)	p-value	Effect size (η_p^2)	Observed power
0	0 m	44.29 (43.20, 45.39)	35.38 (34.19, 36.57)	179.918	<.001	0.841	1.000
	10 m	38.09 (37.25, 38.93)	24.16 (22.93, 25.39)	492.579	<.001	0.935	1.000
	20 m	36.78 (35.84, 37.72)	18.69 (17.59, 19.79)	786.164	<.001	0.959	1.000
	30 m	40.92 (39.86, 41.98)	19.74 (18.31, 21.18)	801.447	<.001	0.959	1.000
	40 m	45.62 (44.67, 46.57)	21.51 (19.95, 23.07)	761.687	<.001	0.979	1.000
	50 m	48.67 (47.68, 49.48)	22.86 (20.63, 25.00)	496.768	<.001	0.936	1.000
	60 m	49.78 (49.09, 50.47)	21.58 (18.81, 24.35)	440.223	<.001	0.928	1.000
	70 m	49.99 (49.35, 50.64)	35.28 (32.96, 37.60)	160.386	<.001	0.825	1.000
	80 m	49.73 (48.71, 50.75)	46.78 (45.43, 48.12)	11.559	.002	0.254	0.910
	90 – 150 m			(ns)	(ns)	<0.200	
	160 m	45.51 (43.42, 47.61)	42.10 (38.58, 45.61)	4.115	.050	0.108	0.504
+1	≤30 m			(ns)	(ns)	<0.200	
	40 m	45.98 (44.69, 47.27)	43.84 (41.89, 45.80)	4.242	.047	0.111	0.516
	50 m	49.17 (48.12, 50.22)	46.12 (44.08, 48.17)	9.466	.004	0.218	0.848
	60 m	50.32 (49.36, 51.28)	47.01 (45.03, 49.00)	13.670	.001	0.287	0.949
	70 m	50.45 (49.56, 51.33)	47.20 (45.30, 49.10)	14.182	.001	0.295	0.955
	80 m	50.18 (49.07, 51.29)	46.80 (44.75, 48.85)	11.556	.002	0.254	0.910
	90 m	49.30 (47.67, 50.94)	45.49 (42.96, 48.02)	6.399	.016	0.162	0.690
	100 m	49.09 (46.90, 51.29)	40.80 (37.40, 44.20)	20.926	<.001	0.388	0.993
	≥110m			(ns)	(ns)	<0.200	
+2	≤70 m			(ns)	(ns)	<0.200	
	80 m	49.50 (48.31, 50.68)	46.59 (44.90, 48.23)	11.133	.002	0.247	0.900
	90 m	49.00 (47.50, 50.51)	47.18 (45.68, 48.68)	(ns)	(ns)	<0.200	
	100 m	48.17 (46.17, 50.17)	43.15 (40.17, 46.13)	7.076	.012	0.172	0.734
	110 m	49.39 (47.48, 51.29)	42.53 (39.80, 47.37)	20.046	<.001	0.371	0.992
	≥120m			(ns)	(ns)	<0.200	

5.6.2.2 Headway

This section describes the effect of the braking event and its urgency on headway, averaged either per complete road section or per 10-metre cell. The average headway per road section or per cell was calculated by dividing the sum of the recorded headway values (100 Hz) by the number of recorded values. This means that headway values recorded at lower speeds might be more pronounced in the calculation. Section 3.4.2 elaborates the ways in which average values were calculated for different variables; possible effects of this calculation will be discussed in Section 5.9, together with the question whether this has led to an over- or underestimation of the headway results.

General effect of the braking event

An ANOVA for Repeated Measures was performed on a number of paths during and after the braking event. As can be seen from Table 5.6 and Figure 5.7, the headway indeed changed as a result of the braking event. Apparently, the decrease in headway due to the braking lead car was first neutralized at path +1 before the absolute increase became apparent at paths +2 and +3.

Some of the results have a very low observed power, but since the effect sizes of these results are generally also very low, we expect that no practically relevant type II errors are made.

Table 5.6: Effects of the braking event on the average headway per path

Path	Average (95%-CI) non-braking (km/h)	Average (95%-CI) braking (km/h)	F(1,33)	p-value	Effect size (η_p^2)	Observed power
-1	15.82 (14.48, 17.16)	15.69 (14.24, 17.15)	0.092	.764	0.003	0.060
0	16.38 (14.94, 17.81)	11.37 (10.49, 12.24)	148.233	<.001	0.818	1.000
+1	16.69 (15.22, 18.17)	16.34 (15.13, 17.56)	0.444	.510	0.013	0.099
+2	16.67 (15.14, 18.19)	18.21 (16.89, 19.53)	6.106	.019	0.156	0.670
+3	16.15 (14.69, 17.61)	17.32 (15.85, 18.79)	5.811	.022	0.150	0.648
+4	16.71 15.32, 18.10)	17.41 (15.87, 18.94)	1.749	.195	0.050	0.250
+5	16.99 (15.57, 18.40)	17.14 (15.53, 18.76)	0.094	.762	0.003	0.060

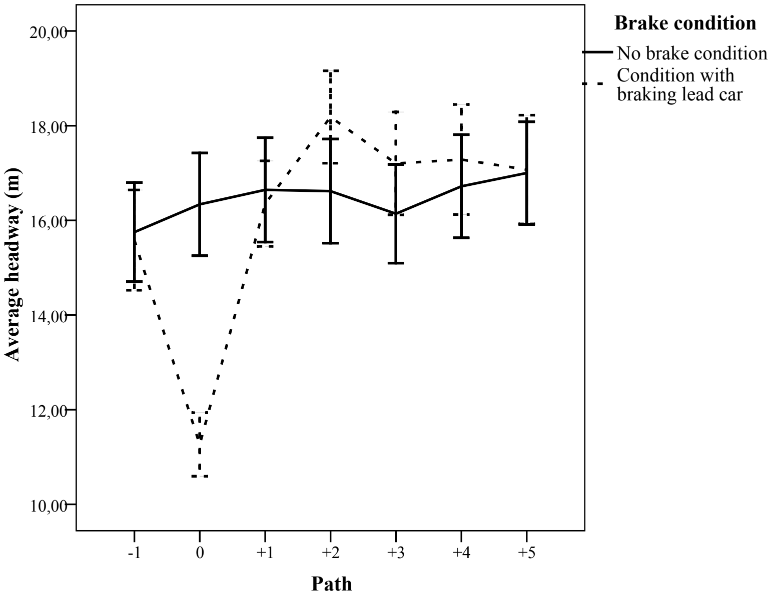

Figure 5.7: Average headway (m) at paths -1 to +5

Distance headway approach pattern

Distance headway decreased rapidly during the braking event, and did not return to its original value until approximately 120 metres before the next intersection at path +1. It then continued to increase, until the difference reached its peak at 70 metres before the intersection at path +2, and remained elevated until the effect of the braking event finally disappeared at path +4. The effect of the braking event was therefore visible for two paths after path +1, as was also concluded from the average distance headway values per path (Table 5.6).

The approach pattern itself also changed: at paths +1 to +3, the distance headway increased over the first 100 metres of each path, until approximately 60 metres before the next intersection (see Figure 5.8, next page). Remember that at 60 metres before the intersection the lead car decelerated slowly (equivalent to taking the foot off the gas pedal) in order to have a good overview of the intersection. This change in distance headway pattern over the first 100 metres of the path was not seen in the reference condition. We determined whether this relative increase per path was statistically significant by subtracting the headway at 60 metres from the headway at 160 metres, and comparing both braking conditions. The development of the distance headway over the path changed significantly as a result of the braking event. Drivers increased their headway over a certain stretch of the path at which they drove after they had encountered an unexpected braking event. At path +1 and +2, the relative change in distance headway over the path in the braking condition was significantly larger (positive) than the change in the reference condition. This change in behaviour disappeared after these two paths. At this point, the pattern at which they drove (development of headway over the path) was no longer significantly different, but the distance headway itself was still larger than in the reference condition.

Summarizing, two behavioural changes were seen: a change in the development of distance headway over the first 100 metres of the two paths directly after the braking event, and an absolute increase in headway which was revealed from the second path after the braking event, lasting for two paths.

Table 5.7 shows the results of the comparison between the distance headway values at 160 metres and 60 metres before a number of intersections (development of headway) in both braking conditions. Table 5.8 (next page) presents the results of the comparison between both braking conditions for each stretch of 10 metres at paths 0 to +3.

Table 5.7 Effects of the braking event on the headway development in the first 100m of each path (paths -1 to +4)

Path	Average (95%-CI) non-braking (m)	Average (95%-CI) braking (m)	F(1,33)	p-value	Effect size (η_p^2)	Observed power
-1	0.23 (-0.41, 0.86)	0.46 (-0.28, 1.20)	0.263	. 611	0.008	0.079
0	0.10 (-0.67, 0.87)	-6.91 (-8.37, -5.44)	101.551	<.001	0.755	1.000
+1	-0.26 (-1.05, 0.53)	4.02 (2.81, 5.22)	34.198	<.001	0.509	1.000
+2	-0.52 (-1.26, 0.22)	1.44 (0.56, 2.32)	15.209	<.001	0.315	0.966
+3	-0.09 (-0.94, 0.77)	0.14 (-0.77, 1.05)	0.229	.636	0.007	0.075
+4	0.20 (-0.49, 0.89)	0.17 (-0.49, 0.82)	0.012	.912	0.000	0.051

Table 5.8 Headway per 10-metre cell - comparison between both braking conditions at paths 0 to +3

Path	DTI	Average (95%-CI) non-braking (m)	Average (95%-CI) braking (m)	F(1,33)	p-value	Effect size (η_p^2)	Observed power
0	0 m	17.11 (15.64, 18.58)	10.72 (9.77, 11.66)	114.168	<.001	0.776	1.000
	10 m	15.03 (13.54, 16.53)	7.72 (6.92, 8.53)	124.237	<.001	0.790	1.000
	20 m	13.36 (11.87, 14.84)	6.05 (5.31, 6.)79)	138.798	<.001	0.808	1.000
	30 m	13.42 (12.09, 14.76)	7.01 (6.22, 7.81)	127.995	<.001	0.795	1.000
	40 m	14.79 (13.49, 16.09)	8.80 (7.88, 9.72)	124.127	<.001	0.790	1.000
	50 m	16.28 (14.94, 17.61)	10.68 (9.76, 11.59)	103.236	<.001	0.758	1.000
	60 m	17.31 (15.92, 18.70)	10.63 (9.63, 11.63)	138.643	<.001	0.808	1.000
	70 m	17.68 (16.21, 19.15)	12.30 (11.20, 13.41)	125.627	<.001	0.792	1.000
	80 m	17.59 (16.07, 19.11)	15.67 (14.45, 16.89)	21.308	.002	0.392	0.994
	90 m+			(ns)	(ns)	<0.200	
+1	≤ 110m			(ns)	(ns)	<0.200	
	120 m	17.73 (16.07, 19.38)	16.13 (14.84, 17.42)	6.287	.017	0.160	0.682
	130 m	17.75 (16.07, 19.43)	15.76 (14.48, 19.43)	10.26	.003	0.237	0.875
	140 m	17.77 (16.06, 19.48)	15.39 (14.13, 16.66)	14.395	.001	0.304	0.957
	150 m	17.81 (16.08, 19.54)	14.97 (13.73, 16.21)	20.507	<.001	0.383	0.993
	160 m	17.83 (16.15, 19.52)	14.43 (13.24, 15.62)	29.234	<.001	0.470	0.999
+2	≤ 20m			(ns)	(ns)	<0.200	
	30 m	13.30 (11.80, 14.79)	14.87 (13.54, 16.20)	5.647	.023	0.146	0.636
	40 m	14.76 (13.31, 16.21)	16.73 (15.42, 18.04)	9.655	.00	0.226	0.854
	50 m	16.39 (14.90, 17.89)	18.73 (17.36, 20.10)	13.009	.001	0.283	0.938
	60 m	17.57 (16.03, 19.10)	20.21 (18.77, 21.65)	15.500	<.001	0.320	0.969
	70 m	18.06 (16.47, 19.65)	20.83 (19.33, 22.33)	15.651	<.001	0.322	0.970
	80 m	18.09 (16.49, 19.70)	20.70 (19.19, 22.20)	13.466	.001	0.290	0.945
	90 m	18.04 (16.45, 19.64)	20.28 (18.80, 21.75)	10.215	.003	0.236	0.873
	100 m	18.04 (16.46, 19.63)	19.90 (18.46, 21.34)	7.369	.010	0.183	0.750
	110 m	18.06 (16.49, 19.64)	19.55 (18.12, 20.98)	5.002	.032	0.132	0.584
	120m+			(ns)	(ns)	<0.200	

Table 5.8 Headway per 10-metre cell - comparison between both braking conditions at paths 0 to +3 (continued)

Path	DTI	Average (95%-CI) non-braking (m)	Average (95%-CI) braking (m)	F(1,33)	p-value	Effect size (η_p^2)	Observed power
+3	0 m	16.42 (15.17, 17.68)	17.48 (16.08, 18.89)	4.782	.036	0.127	0.565
	10 m	14.43 (12.99, 15.87)	15.38 (13.84, 16.92)	4.667	.033	0.131	0.581
	20 m	12.83 (11.36, 14.30)	13.77 (12.26, 15.28)	5.186	.029	0.136	0.599
	30 m	13.04 (11.66, 14.41)	13.89 (12.55, 15.23)	4.408	.043	0.118	0.531
	40 m			(ns)	(ns)	<0.200	
	50 m	16.03 (14.54, 17.53)	17.08(16.66, 18.51)	4.272	.047	0.115	0.519
	60 m	17.12 (15.51, 18.72)	18.38 (16.84, 19.91)	4.994	.032	0.131	0.583
	70 m	17.58 (15.89, 19.27)	19.01 (17.37, 20.64)	5.445	.026	0.142	0.620
	80 m	17.63 (15.93, 19.33)	19.11 (17.42, 20.80)	5.439	.026	0.141	0.619
	90 m	17.52 (15.86, 19.19)	18.99 (17.29, 20.69)	5.285	.028	0.138	0.607
	100 m	17.39 (15.77, 19.00)	18.82 (17.12, 20.52)	5.113	.030	0.134	0.593
	110 m	17.26 (15.68, 18.83)	18.64 (16.92, 20.36)	4.909	.034	0.129	0.576
	120 m	17.16 (15.62, 18.71)	18.51 (16.78, 20.24)	4.850	.035	0.128	0.571
	130 m	17.09 (15.54, 18.65)	18.42 (16.68, 20.15)	4.840	.035	0.128	0.570
	140 m	17.08 (15.50, 18.65)	18.32 (16.57, 20.07)	4.226	.048	0.114	0.514
	150 m +			(ns)	(ns)	<0.200	

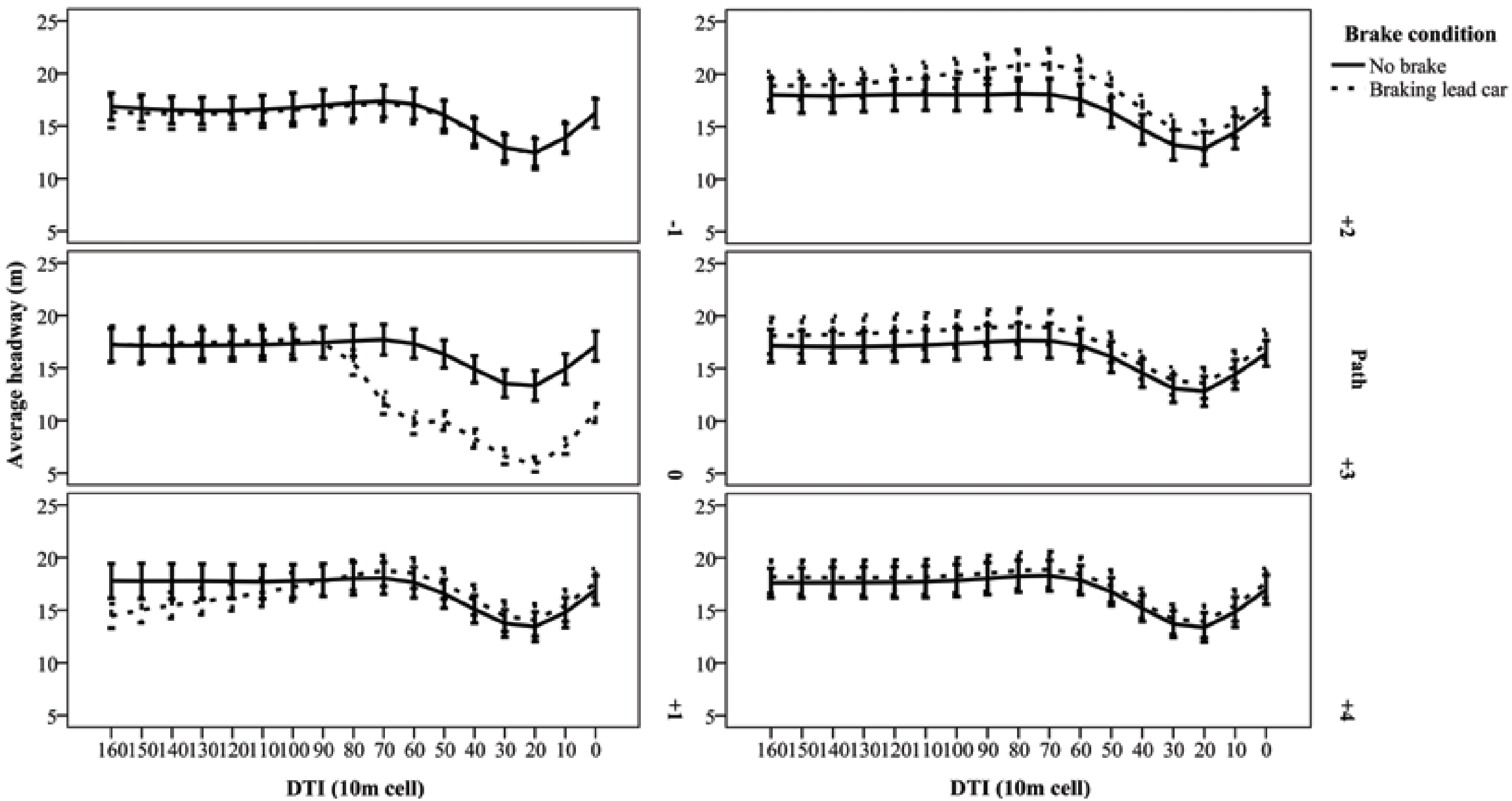

Figure 5.8 Headway per 10-metre cell in both braking conditions at paths -1 to +4

Effects of urgency

No significant effect of urgency was found on average headway per road section or the headway approach pattern (per 10-metre cell), nor were there any interaction effects with urgency of the braking event. There was an interaction effect of urgency and braking condition at path 0, but this effect was very small, $F(2,66)=3.373$, $p=.040$, $\eta_p^2=0.093$. This interaction effect was not seen at any of the paths after the braking event. It can therefore be concluded that the urgency of a braking event did in practice not affect the headway during or after the event.

5.6.2.3 Time headway

Average time headway per path was calculated by averaging all recorded values for the headway over one single road section or per 10-metre cell. Since the time headway is the ratio of the participant's speed and the distance between the two vehicles, this value can grow to extremely large numbers at low speeds. To avoid corruption of the average time headway values by these extreme numbers, any time headway values over 10 seconds were coded as missing values. Due to the (often) low speeds at the braking path, there were less degrees of freedom at path 0 than at the other paths.

General effect of the braking event

Time headway increased significantly at path 0 due to the braking event, but this increase was no longer visible at path +1. However, at paths +2 and +3, the increase was apparent and statistically significant again, after which the effect died out. Table 5.9 gives the results of the ANOVA for Repeated Measures that were performed for paths -1 to +5.

Table 5.9: Effects of the braking event on time headway at paths -1 to +5

Path	**Average (95%-CI) non-braking (s)**	**Average (95%-CI) braking (s)**	**F**	**p-value**	**Effect size (η_p^2)**	**Observed power**
-1	1.23 (1.11, 1.35)	1.21 (1.08, 1.35)	F(1,34)=0.595	.446	0.017	0.116
0	1.32 (1.16, 1.49)	1.67 (1.47, 1.87)	F(1,23)=20.882	<.001	0.476	0.992
+1	1.29 (1.17, 1.41)	1.34 (1.22, 1.46)	F(1,34)=1.147	.292	0.033	0.180
+2	1.30 (1.18, 1.42)	1.46 (1.34, 1.58)	F(1,34)=10.910	.002	0.243	0.894
+3	1.26 (1.13, 1.38)	1.36 (1.23, 1.48)	F(1,34)=5.775	.022	0.145	0.646
+4	1.32 (1.20, 1.44)	1.35 (1.22, 1.48)	F(1,34)=0.639	.430	0.018	0.122
+5	1.35 (1.23, 1.47)	1.36 (1.21, 1.51)	F(1,34)=0.102	.751	0.003	0.061

When looking at time headway per 10 metres, the effect of the braking situation did become apparent at path +1. Time headway was shorter at the start and larger at the end of path +1 in the brake condition than in the reference condition, $F(3.197,108.686)=14.118$, $p<.001$, $\eta_p^2=0.293$. At path +2, time headway was longer for each 10-metre cell in the brake condition as compared to the reference condition. Figure 5.9 gives an overview of the time headway patterns at each DTI for both brake conditions.

Effects of urgency

No main effects of urgency were found. At path 0, there was an interaction effect between brake condition and event urgency, with the more urgent braking event leading to a larger change in time headway as compared to the reference condition, $F(1,23)=5.325$, $p=.030$, $\eta_p^2=0.188$. Table 5.10 shows the average values and 95% confidence intervals for the four conditions. No other effects of event urgency on time headway or headway pattern were found.

Table 5.10 Average values and 95%-confidence intervals for the interaction effect of brake condition and event urgency

Urgency level	Average (95%-CI) non-braking (s)	Average (95%-CI) braking (s)
Non-urgent	1.32 (1.13, 1.50)	1.49 (1.27, 1.71)
Urgent	1.33 (1.06, 1.60)	1.85 (1.52, 2.17)

5.6.2.4 Average and standard deviation of lateral position

Lateral position was measured in metres from the centre of the lane in which the participant drove. A negative value represents driving more to the outside of the lane, whereas a positive value entails driving more to the left, and therefore more to the centre of the road (close to centre lane markings). The standard deviation of lateral position represents the level of swerving. Swerving is an indication of unsafe driving, so a high standard deviation of lateral position suggests that driving performance is impaired. Average lateral position was calculated by dividing the sum of all recorded values by the number of recorded values.

General effect of the braking event

No effects of the braking event on average lateral position were found. When looking at an effect over 6 intersections (paths -1 to +4), swerving (standard deviation of lateral position) was indeed affected by the braking event: $F(1,33)=6.169$, $p=.018$, $\eta_p^2=0.158$. However, when focussing at the braking path (path 0) and the paths directly following this braking location, it becomes clear that this difference is mostly attributable to the event location itself. Table 5.11 (next page) presents the results of the comparison between brake conditions on swerving at paths -1 to +2. As can be seen from this table, swerving at path 0 differs greatly between the braking condition and the non-braking condition, but one path later, this difference already returns to being non-significant (although a somewhat larger SDLP can still be identified in the braking condition). It can therefore be concluded that braking had an effect on swerving, but only for a short while (2 road sections).

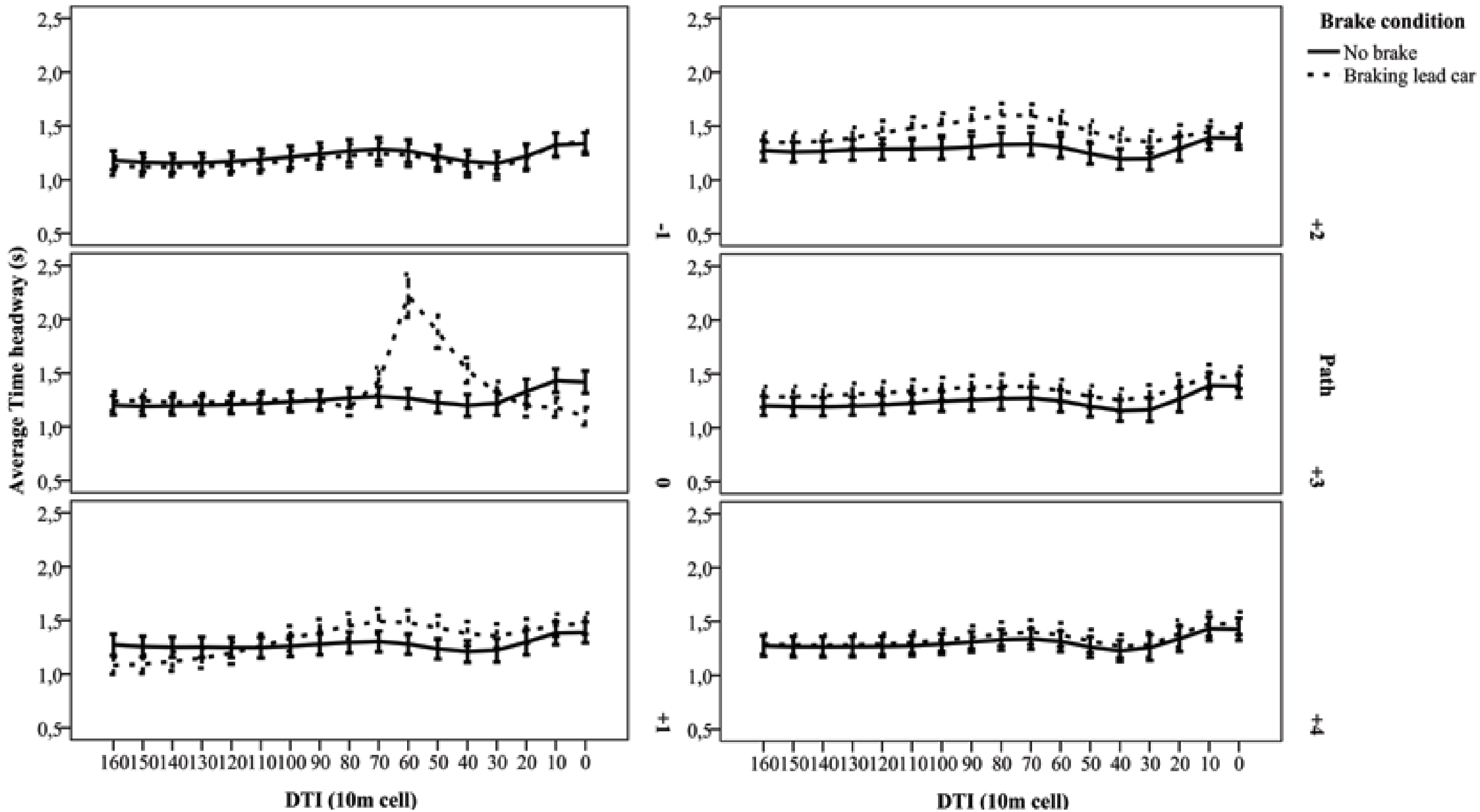

Figure 5.9 Time headway per 10-metre cell in both braking conditions at paths -1 to +4

Table 5.11: Effects of the braking event on swerving (standard deviation of lateral position) at paths -1 to +2

Path	Average (95%-CI) Non-braking (s)	Average (95%-CI) braking (s)	F(1,33)	p-value	Effect size (η_p^2)	Observed power
-1	0.07 (0.06, 0.07)	0.07 (0.06, 0.07)	0.007	.934	0.000	0.051
0	0.06 (0.05, 0.07)	0.07 (0.06, 0.08)	11.998	.001	0.267	0.919
+1	0.06 (0.06, 0.07)	0.07 (0.07, 0.08)	3.868	.058	0.105	0.480
+2	0.06 (0.05, 0.07)	0.06 (0.06, 0.07)	0.196	.661	0.006	0.071

Effects of urgency

No effects of urgency were found at path 0 on either average lateral position, F(1,33)=0.369, p=.548, η_p^2=0.011, or standard deviation of lateral position (swerving), F(1,33)=0.037, p=.845, η_p^2=0.001. The same was true for all other paths after the braking event.

5.6.2.5 Lateral speed

Lateral speed describes a driver's lateral movement over a certain period of time. A negative value for lateral speed describes a movement to the right (to the outside of the lane), whereas a positive lateral speed describes movement to the left, so more to the centre of the lane. Lateral speed is recorded in (m/s).

General effect of the braking event

The braking event only had an effect on lateral speed at the path of the braking itself, and this effect was rather small. At path 0, participants moved more to the outside of their lane in the braking condition (M=-0.002, SD<0.001) than in the reference condition (M=0.002, SD<0.001): F(1,34)=5.272, p=.028, η_p^2=0.134. At all other paths, no effect of braking on lateral speed was found.

Effects of urgency

No effects of event urgency were found on path 0, F(1,33)=1.198, p=.282, η_p^2=0.035. The same was true for the paths following the braking event. Additionally, no significant effects of urgency of braking were found after selection of only the most urgent event. It can therefore be concluded that the urgency of the braking event had no effect on lateral speed during or after sudden braking. This is according to our expectations.

5.6.3 Effects of varying mental workload on driving behaviour

In this section we determine whether mental workload had a significant effect on driving behaviour. Furthermore we study whether a further increase in mental workload led to a more apparent or stronger change in driving behaviour. Interaction effects between mental workload and the braking event will be described in the subsequent section.

In determining the effects of mental workload level on general driving behaviour, only data were used in which 'normal driving behaviour' was displayed: parts of the experimental drives without any braking events. For the analyses in the following sections, 10 paths in the middle of the non-braking condition were used.

5.6.3.1 Speed

Average driving speed over the 10 tested road sections was not affected by varying mental workload, $F(2,70)=0.361$, $p=.698$, $\eta_p^2=0.010$. However, the speed approach pattern did change significantly with mental workload level (interaction effect of mental workload condition and distance to intersection), although the effect size was only minimal, $F(16.667,58.336)=1.699$, $p=.040$, $\eta_p^2=0.040$. The effect was mostly attributable to the locations farthest away from the intersection, i.e. directly after passing through an earlier intersection, where the speed was higher in conditions with increased mental workload than in normal driving.

5.6.3.2 Headway

Average headway changed significantly as a result of varying mental workload, $F(2,68)=5.586$, $p=.006$, $\eta_p^2=0{,}141$. The headway approach pattern also changed significantly over the mental workload conditions, $F(2,68)=5.887$, $p=.004$, $\eta_p^2=0.148$. Headway in the driving only condition (M=18.20, SD=1.58) was significantly larger at every single DTI than headway in the easy task condition (M=15.37, SD=1.64), but neither of these mental workload conditions differed significantly from the difficult task condition (M=16.50, SD=1.78). Figure 5.10 shows the average headway for the three mental workload conditions; Figure 5.11 displays the headway approach patterns per 10-metre cell for each mental workload condition.

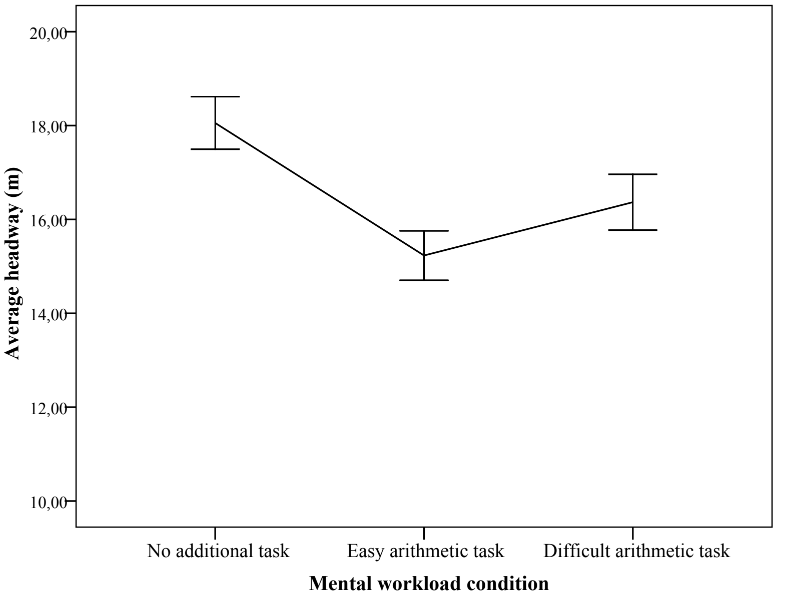

Figure 5.10 Average headway in each mental workload condition

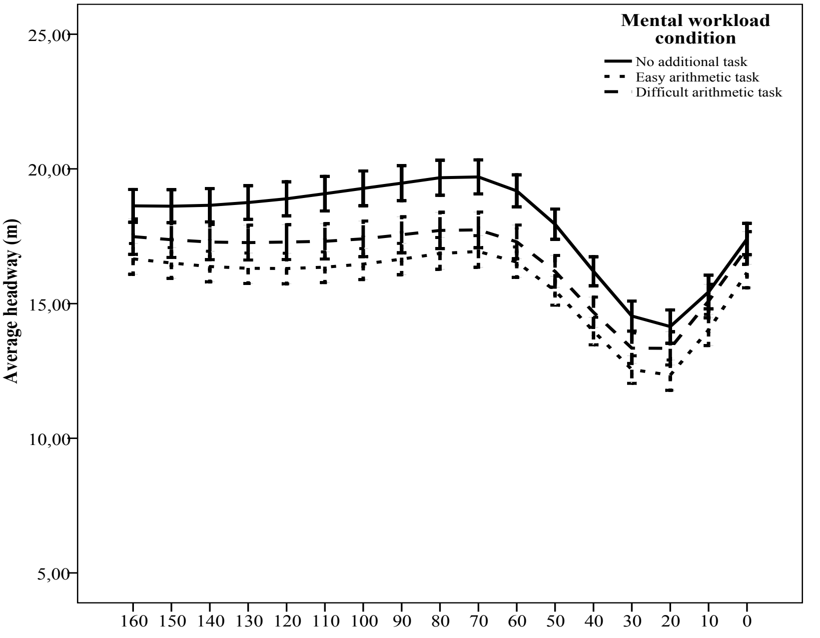

Figure 5.11 Headway patterns per 10-metre cell in each mental workload condition

5.6.3.3 Time headway

Average time headway changed significantly due to varying mental workload, $F(1.810,66.960)=6.371$, $p=.004$, $\eta_p^2=0,147$. Average time headway in the driving only condition (M=1.40, SD=0.14) was significantly longer than in the easy task condition (M=1.17, SD=0.13), but there was no difference between the difficult task condition (M=1.27, SD=0.09) and any of the other two mental workload conditions.

5.6.3.4 Average and standard deviation of lateral position

Lateral position did not change significantly as a result of varying mental workload. However, a trend was seen, although its effect was very small: with increasing mental workload, participants drove slightly more to the left side of their lane, $F(2,68)=2.830$, $p=.066$, $\eta_p^2=0.077$. Figure 5.12 shows this effect. Swerving was affected by the level of mental workload, as was already discussed in Section 5.6.1.1 and Table 5.3.

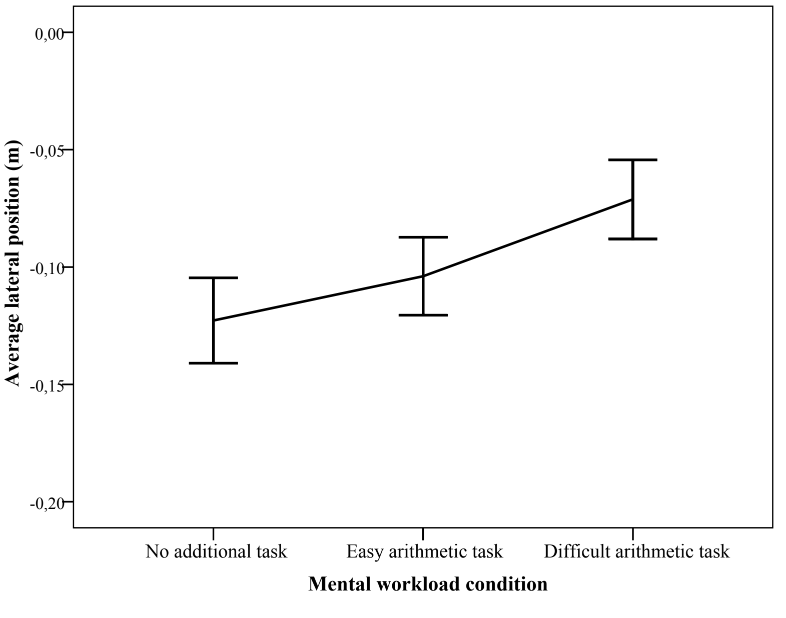

Figure 5.12 Average lateral position in each mental workload condition

5.6.3.5 Lateral speed

In the difficult task condition, participants moved significantly more to the inside of their lanes (M=-0.070, SD=0.05) than when driving only (M=-0.125, SD=0.13) or driving with an easy arithmetic task (M=-0.125, SD=0.05), $F(1.771,60.226)=4.714$, $p=.016$, $\eta_p^2=0.122$. The easy task condition and driving only did not differ significantly, based on pairwise comparisons.

5.6.4 Interaction effects: braking, urgency and level of mental workload

In this section we determine whether there were any interaction effects between the braking events, the urgency of the events, and the level of mental workload.

5.6.4.1 Speed

There was no difference of approach pattern between mental workload conditions over the last 100 metres of the braking path (interaction effect of mental workload condition and DTI), $F(7.166,114.660)=0.351$, $p=.931$ $\eta_p^2=0.021$. Only the speeds at 20 metres before the intersection differed significantly between mental workload conditions, $F(2,15)=4.883$, $p=.023$, $\eta_p^2=0.394$. At this location the speed in the easy arithmetic task condition was significantly lower than in other conditions. Summarizing, participants driving with an easy arithmetic task showed a slightly more profound approach pattern than in the other conditions, but since this effect only shows at one location, it is difficult to draw a conclusion on the whole approach pattern.

We also determined the interaction effects of mental workload level and braking event after selection of only one of the two urgency groups. With the urgent event, the interaction effect of mental workload condition and location was significant for the complete approach pattern, $F(7.394,133.089)=1.130$, $p=.348$; however, speeds at 40 metres and 60 metres before the intersection were significantly different for the three mental workload levels, with $F(2,17)=7.015$, $p=.006$ at 40 metres and $F(2,17)=4.504$, $p=.027$ at 60 metres. At both locations, speed in the driving only condition was significantly lower than in the other conditions, with medium (40 metres) and large (60 metres) effects. In other words, participants drove with a more profound pattern without an additional task, and with a smoother pattern when performing the difficult additional task. The approach patterns of participants driving with an easy additional task were in between. For both situations, the approach pattern was smoother for participants driving with the difficult arithmetic task than for the other participants. However, although we did expect smoother patterns for participants with higher workload, we also hypothesized that this smoothness would be 'broken' by the most severe braking situations. The fact that the smoother approach pattern was not broken by the most urgent event could indicate that our most urgent braking event was 'not urgent enough' to pass a certain threshold in order to bring a behavioural change in participants with high mental workload. Figures 5.13a and 5.13b displays the speed approach pattern per 10-metre cell for both the non-urgent braking event (Figure 5.13a) and the urgent braking event (Figure 5.13b). The figure zooms in at the last 100 metres before the intersection, where the actual approach took place.

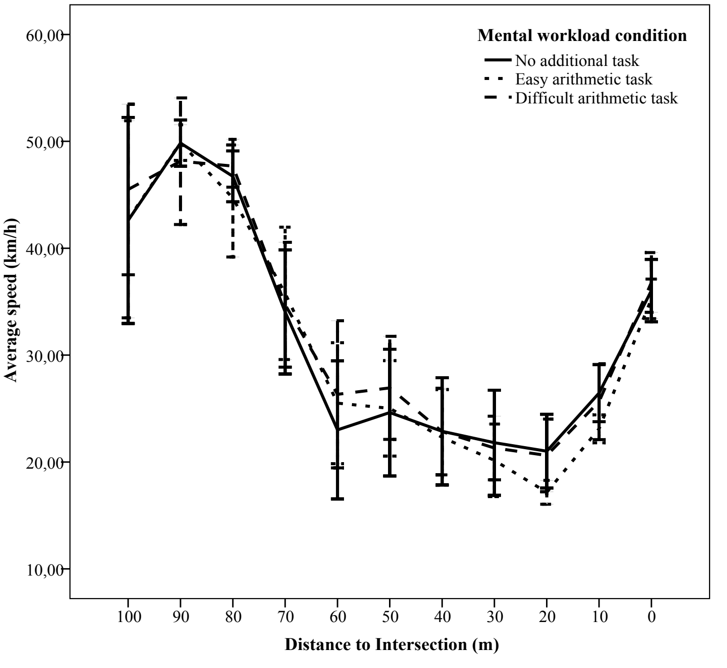

Figure 5.13a Speed pattern at path 0 for each level of mental workload (non-urgent)

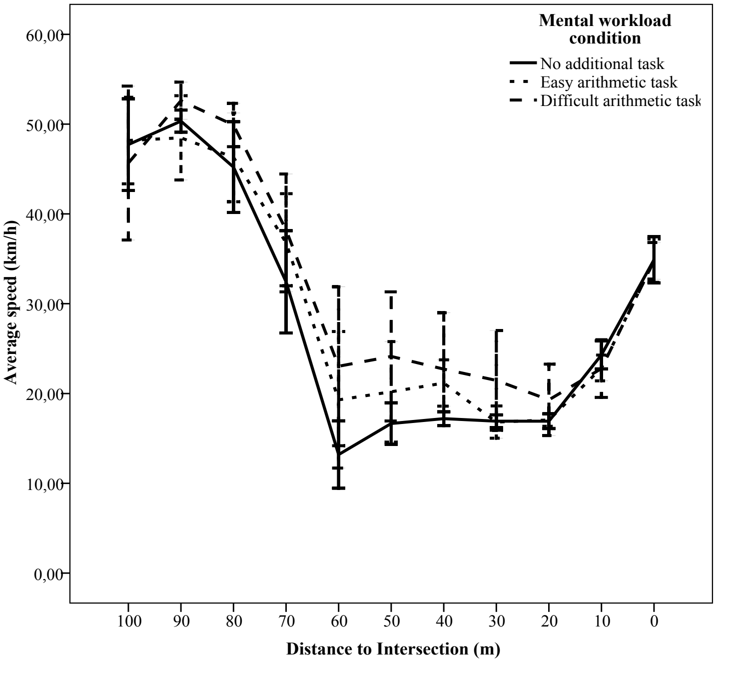

Figure 5.13b Speed pattern at path 0 for each level of mental workload (urgent)

A set number of Paired Samples t-tests were performed to compare the speeds in the reference and brake conditions for each level of mental workload. As can be seen from Table 5.12, the speed in each mental workload condition decreases for two paths as compared to the reference condition, and there is no difference between the duration lengths of these changes.

Table 5.12: Effects of the braking event on average speed per path, for each level of mental workload

Mental workload condition	Path	t-value (df=35)	p-value	Effect size (*r*)	Proportion of variance explained
No additional task (driving only)	-1	0.450	.665	.076	0.6%
	0	23.976	<.001	.971	94.3%
	+1	2.183	.018	.346	12.0%
	+2	1.460	.077	.240	5.8%
	+3	1.102	.144	.183	3.3%
	+4	0.315	.253	.053	0.3%
	+5	0.436	.333	.073	0.5%
Easy arithmetic task	-1	0.140	.889	.023	0.1%
	0	20.814	<.001	.962	92.5%
	+1	2.180	.018	.346	12.0%
	+2	0.776	.222	.130	1.7%
	+3	-0.325	.747	.055	0.3%
	+4	-0.719	.277	.121	1.5%
	+5	-0.912	.368	.152	2.3%
Difficult arithmetic task	-1	-2.371	.023	.372	13.8%
	0	17.362	<.001	.947	89.7%
	+1	3.707	<.001	.531	28.2%
	+2	-0.257	.799	.043	0.2%
	+3	0.670	.254	.113	1.3%
	+4	-1.596	.119	.260	6.8%
	+5	-0.380	.707	.064	0.4%

5.6.4.2 Headway

The duration lengths of headway adaptations to the braking event differed largely between mental workload conditions. In all mental workload conditions, the braking event had a statistically significant and large-sized effect on the headway at the path of the braking (see Table 5.13), but this did not lead to an effect lasting after this one path in either the driving only condition or the difficult task condition. Only in the easy task condition did the braking event have a compensatory effect on driving behaviour after the event. Participants in this condition appeared to need some time to recuperate from the decreased headway (path +1), but after driving one path they reached a larger headway which remained elevated for the duration of two paths. After these two paths the significant effect disappeared, although a small trend could still be identified at path +4. The difference between additional task conditions could be explained by participants giving up the most difficult task (refer to

Section 5.6.1.1 on secondary task performance). It appears that participants could go for seconds without giving their next answer, which would allow them to drive as they would in the driving only condition. Table 5.13 shows the results of the Paired Samples t-test comparison between braking conditions for each level of mental workload.

Table 5.13: Effects of the braking event on average headway (m) per path, for each level of mental workload

Level of mental workload	Path	t-value (df=34)	p-value	Effect size (*r*)	Proportion of variance explained
No additional task (driving only)	-1	1.051	.301	.177	3.1%
	0	8.528	<.001	.825	68.1%
	+1	0.576	.293	.098	0.9%
	+2	-1.435	.080	.239	5.7%
	+3	-0.922	.152	.156	2.4%
	+4	-1.723	.047	.283	8.0%
	+5	-0.334	.370	.057	0.3%
Easy arithmetic task	-1	-0.453	.654	.077	0.5%
	0	5.159	<.001	.663	44.0%
	+1	-0.709	.242	.121	1.5%
	+2	-2.098	.022	.339	11.5%
	+3	-2.773	.005	.429	18.4%
	+4	-1.394	.086	.233	5.4%
	+5	-0.779	.221	.132	1.7%
Difficult arithmetic task	-1	0.363	.719	.062	0.4%
	0	5.945	<.001	.714	51.0%
	+1	0.939	.354	.159	2.5%
	+2	-1.050	.151	.177	3.1%
	+3	0.190	.851	.032	0.1%
	+4	1.310	.199	.219	4.8%
	+5	0.538	.594	.092	0.8%

At the road section of the braking event (path 0), a small but significant interaction effect of mental workload condition and braking condition was seen on the headway development over 100 metres at the braking path, $F(2,66)=3.373$, $p=.040$, $\eta_p^2=0.093$. This effect did not last after path 0. Figure 5.14 shows the differences for each condition at path 0. Finally, Figure 5.15 gives an overview of the different headway patterns for each mental workload condition at the road sections around the braking event (next page).

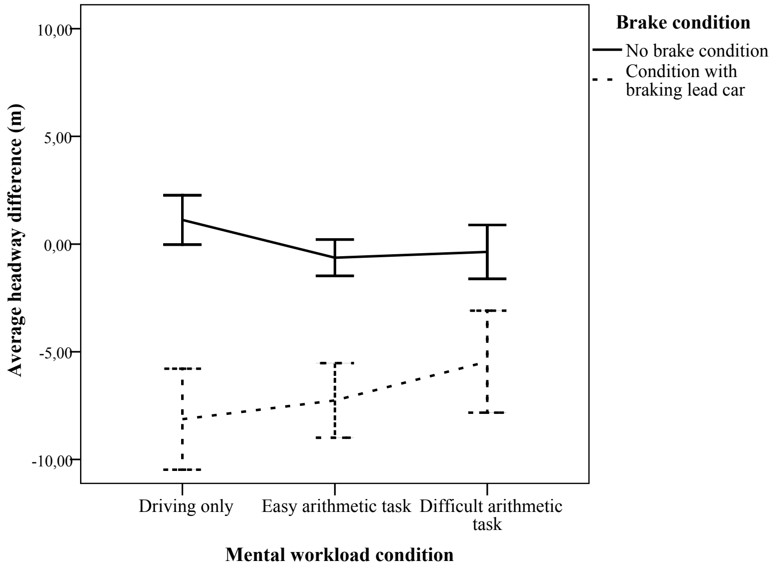

Figure 5.14 Headway change over 100m (headway at 60 metres minus headway at 160 metres from next intersection) at path 0

5.6.4.3 Average and standard deviation of lateral position

There was no significant and relevant interaction effect of workload with braking condition or braking urgency on average lateral position. At path 0, there was a very small effect of workload on average lateral position, with a higher level of mental workload leading to a lateral position more to the inside of the lane, F(2,66)=3.457, p=.037, η_p^2=0.095. This effect did not occur at any point before or after path 0, and no other effects on lateral position were found, not when taking into account both urgencies nor when focussing only on the most urgent braking event.

No significant interaction effects on swerving were found. At the braking path (path 0), workload had a non-significant effect on the standard deviation of the lateral position, F(2,66)=2.530, p=.087, pointing to a slight decrease in swerving for the easy task condition as compared to the other two conditions. This could be in line with the results found on workload and impaired driving behaviour described earlier in Section 5.6.1.

5.6.4.4 Lateral speed

No significant interaction effects between braking, event urgency and/ or mental workload condition on lateral speed were found.

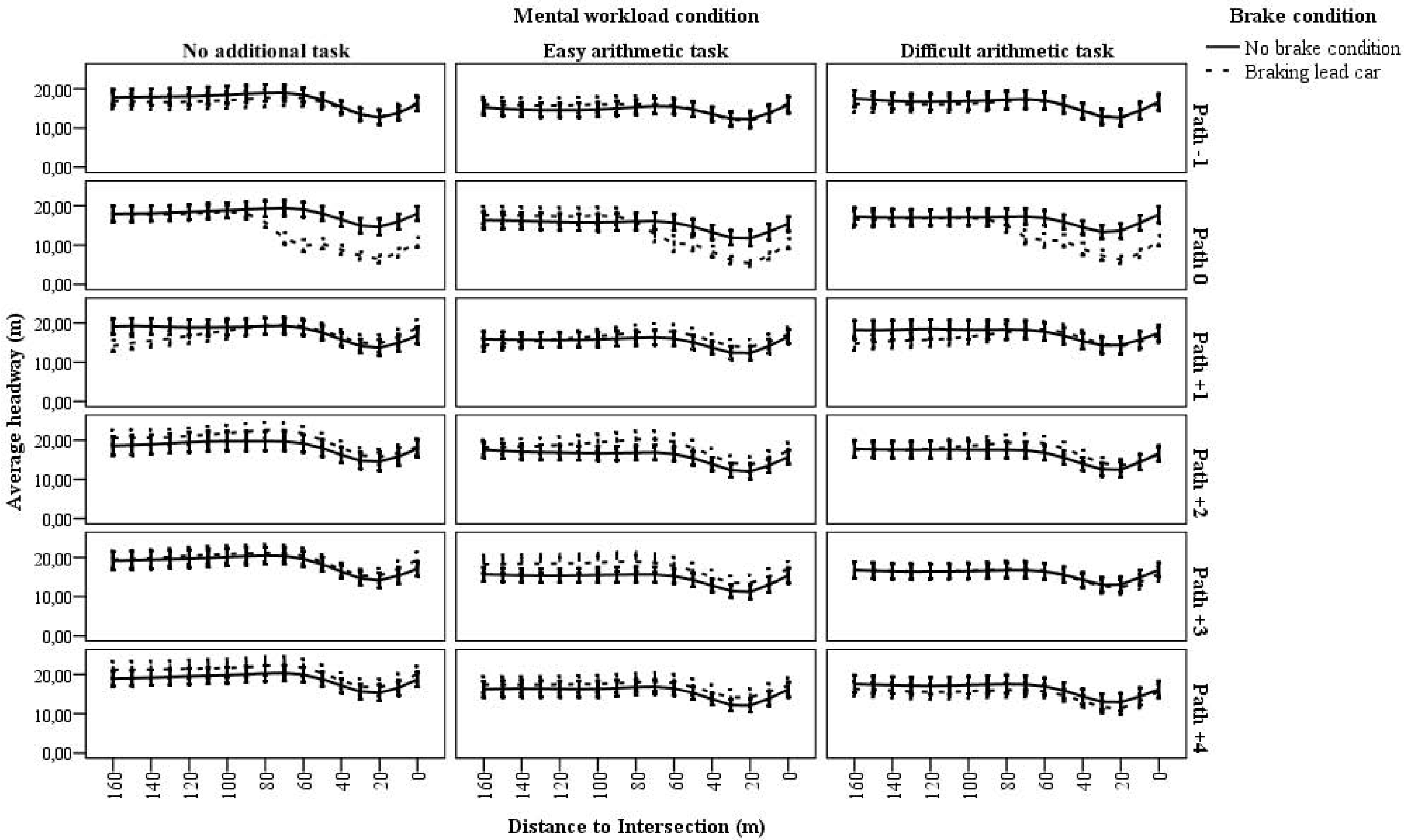

Figure 5.15 Headway patterns at paths -1 to +4 in all three mental workload conditions

5.7 Overview of results

In order to determine whether the hypotheses, listed at the start of the current chapter, were supported by the experimental results, these results are summarized in this section. Chapter 6 (Discussion) will discuss the interpretation, relevance and validity of these results.

Effects of the braking event:

- Drivers modified their speed for one path after a sudden braking event, when looking at average driving speed over one complete path.
- Speed was lowered over the complete path of the braking event (path 0). One path ahead, speed between 40 and 100 metres before the intersection had changed, and on the path after this, this change was only apparent between 80 and 110 metres before the intersection. The speed effect wore off after this.
- There was no speed modification at more than 100 metres from the intersection at any of the paths after the suddenly braking lead car (indicating an effect on anticipation and intersection approach).
- The urgency of a braking event did not affect the speed at which people drive after a braking event, nor did it affect drivers' speed approach pattern.
- Drivers first returned to driving at their original headway after a braking event, but the headway pattern at the path changed immediately as a result of the braking event. This pattern change (present over two paths) transferred into an increase in average headway for the duration of two paths, after which the effect died out again.
- Urgency did not affect headway after the braking event.
- During the braking event, drivers had a tendency to drive more to the outside of their lane than in the reference condition (although the resulting behavioural change was very small).

Effects of workload:

- When driving only, participants kept a larger headway than when driving with an easy arithmetic task. Driving with a difficult arithmetic task resulted in a headway that remained in between these other two conditions.
- Drivers with high mental workload drove more to the inside of their lane than their counterparts driving without an additional task. However, this trend was not found to be significant.

Interaction effects:

- At the path of the braking event, drivers without an additional task changed their headway approach pattern more (larger difference between beginning of path and 60 metres before the intersection) than drivers with an additional task, and this change decreased with task difficulty.
- After a braking event, drivers without an additional task adjusted their headway, whereas drivers driving with an additional task did not (independent of the level of task difficulty).

5.8 Discussion of experimental setup

This section discusses the effects of the current experimental setup for the results found in this experiment. It first elaborates the number of unexpected events and the criticality levels, and then discusses the chosen benchmarks for the effect sizes.

5.8.1 Criticality levels and number of unexpected events

Some of the results related to the effects of criticality levels did not support our hypotheses with regard to the effects of different criticality levels. In fact, a few of the found effects indicated that the criticality levels of the events at hand were not severe enough. For instance, participants drove with a more profound pattern without an additional task, and with a smoother pattern when performing an additional task, as was expected. However, we also expected that participants would be startled by the most serious braking event and would thus be pulled out of their inattentive driving style. According to our hypotheses, this would then lead to more profound deceleration curves. The more profound deceleration curves were not found, on the contrary: the effects resulting from the most critical event were actually anticipated for the least critical event. This could indicate that our most urgent braking event was 'not urgent enough' to pass a certain threshold in order to bring a behavioural change in participants with high mental workload.

Another issue related to the criticality of the events is the number of unexpected events for one participant. The total number of braking events for each participant in this experiment was three, as opposed to one in the previous experiment. Furthermore, Experiment 1 included three complete trials in which no braking event happened, compared to none in the current experiment. Since events which occur more often can be anticipated to, this might result in a less critical experience and thus an outcome which could indicate less critical events.

The differences between the results from two experiments and the implications for the urgency of the events presented will be discussed in Chapter 6 (Discussion).

5.8.2 Effect sizes

We used the benchmarks for Partial Eta Squared (η_p^2) as provided by Cohen (1992) and Keppel and Wickens (2002) for the interpretation of our effect sizes (see Section 3.4.4). These benchmarks are set as follows: 0.20 entails a small effect size, 0.50 a medium effect size, and 0.80 a large effect size. There have been some different interpretations about the benchmarks for η_p^2. For instance, Kittler, Menard and Philips (2007) use benchmarks of 0.01, 0.06 and 0.14 for small, medium and large effect sizes, respectively. The latter study was concerned with human weight, a very different discipline, but it shows that the benchmarks for η_p^2 are not carved in stone. Their interpretation may therefore be related to the discipline studied and could remain subject to discussion. However, we decided to use the aforementioned benchmarks for η_p^2, since no other rules of thumb were found regarding the effect sizes in driving behaviour data.

5.8.3 Motion sickness

As was noted in Section 5.3, 17% of the total number of participants did not finish the experiment due to motion sickness. After the previous experiment, in which 13% of the total number of participants had fallen ill, a number of changes had been made to the experimental setup. The resolution of the screen projection was increased, as was the distance to projected objects, and the motion input from the simulator was tuned to the visual input participants received by using the moving base simulator. However, these improvements did not lead to a lower percentage of participants suffering from motion sickness, on the contrary, the percentage of participants fallen ill with simulator sickness increased. Although this increase might be a result of chance and a smaller sample size, the results might also explained by looking into the experimental setup used for this current experiment.

The specific type of motion sickness participants of these experiments experienced is often referred to as Visually Induced Motion Sickness (VIMS); common symptoms are nausea, drowsiness and salivation (Kennedy, Drexler & Kennedy, 2010). Earlier studies into VIMS show that it can be induced by two types of factors: factors related to the stimuli, and factors related to the person experiencing the stimuli (Golding, 2006). For instance, sex and age are two factors that appear to be highly related to motion sickness susceptibility, as are certain psychological variables such as mood and anxiety (Golding, 2006). There is a link between the duration of the exposure to visual motion stimuli and the severity of experienced VIMS (Stanney, Kingdon, Nahmens & Kennedy, 2003).

A number of explanations for the higher percentage of ill participants can be found in these factors. For instance, all participants had to perform additional tasks during four out of the in total six sections of which the experiment consisted. This increased mental workload might have lead to stress and possibly anxiety, which can lead to a higher susceptibility to motion sickness (Golding, 2006). Furthermore, while the total duration of this current experiment was not higher than the previous experiment, the individual trials were longer, so participants were presented with visual motion stimuli for longer periods at a time. Since longer exposure to motion stimuli might increase the susceptibility to motion sickness (Stanney et al., 2003), this might also be a factor in explaining the relative increase in ill participants. Concluding, despite the actions taken to prevent simulator sickness, there were factors that might have increased the participant’s susceptibility for simulator sickness in the final experiment.

Chapter 6

Discussion

The two driving simulator experiments revealed that drivers react differently to situations dependent of their state, the criticality of the situation, and the type of compensation required. However, there were some differences between the findings in both experiments. The current chapter discusses these differences and their underlying causes. It then discusses the main results in the light of the hierarchical model of the driving task (Michon 1971, 1985) and other theories relevant for driving in risky and/ or unexpected situations. The chapter concludes with a discussion of the implications of our findings for the human-centred development of Advanced Driver Assistance (ADA) Systems.

6.1 Recapitulation: an overview of relevant results

Both the first experiment into task level interaction and the final experiment into the adaptation of driving behaviour to unexpected braking events yielded a number of results, which will be reviewed in this section. For an elaboration of the results, please refer to the chapters on the specific experiments.

6.1.1 Experiment 1: initial hypotheses

The first experiment revealed a number of interesting results. First of all, it was found that the two different types of unexpected events induced different compensation behaviour. In theory, adequate or safe compensation to the braking event would require lowering speed, while the acceleration event would require a combination of deceleration and moving to a safer lateral position. In fact, drivers lowered their driving speed for some time after the braking event, but no change on speed was found after the acceleration event. Lateral position did not change significantly as a result of any of the events.

The event criticality (defined as minimum headway after an unexpected braking event) turned out to be a better predictor of behavioural adaptation to a braking event than the original event urgency, which was related to the duration time of braking. Criticality had a significant effect on drivers' minimum speed, on the location of this minimum speed (end of deceleration as part of intersection approaching), and on the way in which participants decelerated, with lower criticality leading to more passive deceleration (by means of releasing the gas pedal) and the highest criticality level leading to active braking.

The most striking effects were seen in the interactions between the braking event and the level of mental workload. It was found that, when controlling for incident criticality, participants in both mental workload conditions had similar initial headway reactions to the braking lead car, but different reaction durations. After the first road section following the braking, drivers with high workload normalized their headway immediately, whereas regular drivers continued to drive with an increased headway for some time. In other words, drivers with high mental workload initially responded as cautiously as normal drivers, but returned to their original driving behaviour much faster then drivers who completely focussed on driving. This indicates that drivers with high mental workload did not pay as much attention to their driving task and their surroundings (viz., a suddenly braking lead vehicle) as drivers without other things to do than driving. Further evidence for this relationship between elevated mental workload and reduced attention for the driving task was found when event criticality was included in the analyses. The threshold for increasing the headway after an unexpected braking event was lifted for drivers performing an additional task as compared to normal driving. Whereas regular drivers reacted to both medium and high criticality events by increasing their headway, drivers with high workload only responded to the most serious event category. Apparently, only the most serious braking event triggered this latter group to change their driving behaviour.

Finally, mental workload level was shown to be of great influence on driving behaviour before, during and after all unexpected events. Elevated mental workload levels led to smoother speed approach patterns and resulted in vehicle positions more to the left side of the lane. Also, speed adjustment resulting from the braking event was different for groups with different mental workload levels: while drivers without an additional task did not drive at a different speed in the reference drive than in the drive with the braking lead vehicle, those who experienced higher mental workload due to the additional task drove significantly faster in the reference trial than in the event trial. Adding to this result, drivers with higher mental workload drove at a smoother pattern when encountering less urgent events, whereas the highest event urgency was related to a more profound deceleration curve. There were no significant differences in speed patterns for the drivers with normal mental workload levels which could be attributed to event criticality.

6.1.2 Experiment 2: additional hypotheses

The hypotheses for the final experiment, based on the first experiment, were as follows:

- Drivers driving with high mental workload pay less attention to the driving task, leading to a more inattentive style of driving. In other words, they are driving in an automatic fashion.
- Drivers have a more defensive driving style after encountering a safety-critical situation when they can focus their full attention to the driving task. When this is not the case, for instance when driving with the pressure of high mental workload, this defensive driving behaviour diminishes quickly.
- Although drivers quit their defensive driving style when driving under pressure, the defensiveness re-emerges even stronger when the unexpected event reaches a certain threshold of safety-criticality. In other words, startled drivers can get pulled out of their inattentive driving style if the level of event criticality is high enough.

A fourth hypothesis, which was based on an assumption resulting from the hierarchical task model by Michon (1971, 1985) and which was already studied in Experiment 1, concerns the type of compensation and the related changes in driving behaviour, resulting from bottom-up influence between the driving tasks.

- The type of compensation (longitudinal, lateral, or a combination) required to safely handle an unexpected, safety-critical event determines the type of any (temporary) behavioural effect.

The following results regarding these hypotheses were found.

ad 1. *Drivers driving with high mental workload pay less attention to the driving task, leading to a more inattentive style of driving.*

Swerving, an important driving performance measure, was not affected by mental workload. This result does therefore not support the hypothesis. Furthermore, no significant effect was found on lateral position, although a trend could be identified, showing that drivers do have a tendency to drive more to the left side of their lane when dealing with high demand tasks. As we discussed in Section 4.7.1, driving to the left side of the lane can be seen as either driving more cautiously (trying to see farther upstream in the opposing traffic) or as less cautious behaviour (having less regard for possible head-on conflicts). When looking specifically at the effects on safety boundaries, driving closer to the centre line leads to a smaller distance to other road users, in this case the road users from the opposite direction. This is especially the case for our experimental setup in which the opposing traffic was programmed to drive at a fixed lateral position in their lane. However, since the current effect was not found to be either significant or relevantly large for real-life situations, this result will not be regarded as supporting the hypothesis.

Moreover, the result from the previous experiment which showed that participants drove faster and that their speed approach patterns were less pronounced when mental workload was elevated, was not reproduced in this experiment. The speed values were significantly higher at certain locations farther away from the next upcoming intersection, but this does not necessarily point to less attentive driving.

However, the hypothesis was supported when looking at headway and time headway adaptation. The combination of a shorter (time) headway and a higher speed translates to smaller safety margins, which can be explained as less cautious or inattentive driving.

Driving with a difficult arithmetic task resulted in a headway that remained in between the values for the other two conditions. It appears as though the difficult task condition did not lead to the same amount of change as the easy task condition. We will get to this finding later in this section.

ad 2. *Drivers have a more defensive driving style after encountering a safety-critical situation when they can focus their full attention on the driving task. When this is not the case, for instance when driving with the pressure of high mental workload, this defensive driving behaviour diminishes quickly.*

The first part of this hypothesis was supported by both headway and speed changes seen after the braking event. Drivers driving under normal workload circumstances showed a more defensive driving style after the safety-critical event than before. They drove at a lower speed, temporarily kept a larger average headway, and started the next road section after the headway increase had died out at a larger headway than before the safety-critical braking event. So even though the average headway over a complete road section did not change, drivers were still cautious at the start of a new road section, translating into a larger headway at this location.

The second part of this hypothesis was also supported when looking at headway adaptation. After a braking event, drivers without an additional task adjusted their headway, whereas drivers driving with an additional task did not (independent of the level of task difficulty). And at the path of the braking event itself, drivers without an additional task changed their headway approach pattern more (larger difference between beginning of path and 60 metres before the intersection) than drivers with an additional task, and this change decreased with task difficulty. In other words, there was a clear change in headway during and after the braking incident for drivers with normal mental workload, and a significantly smaller change for drivers with increased mental workload.

Drivers had a tendency to drive more to the outside (right side) of their lane during the braking event than in a reference condition. They kept a larger distance to the opposing traffic, which was driving at a fixed lateral position on the opposing lane. This effect of the braking event was significant, but due to its small effect size, it might be less relevant for real-life situations.

As was expected, driving speed was lowered during the braking event. When we investigated one and two paths ahead, the driving speed was first lowered between 40 and 100 metres before the intersection, and then only between 80 and 110 metres before the intersection. The speed effect died out after this. This means that the speed change was not apparent at the intersection itself, nor directly after the intersections. Only around the locations where the braking event had actually happened did drivers adjust their speeds.

ad 3. *Although drivers quit their defensive driving style when driving under pressure, the defensiveness re-emerges even stronger when the unexpected event reaches a certain threshold of safety-criticality. In other words, drivers can get startled out of their inattentive driving style.*

This hypothesis was not supported by the data from this experiment. The urgency of a braking event used in this experiment did not affect average speed, drivers' speed approach pattern, or headway. This might mean that either the hypothesis is false, or that the event urgency used in the current experiment was too low. The levels of urgency adopted in this experiment will be elaborated in Section 6.1.4.

ad 4. *The type of compensation (longitudinal, lateral, or a combination) required to safely handle an unexpected, safety-critical event determines the type of any (temporary) behavioural effect.*

As was explained before, the differences between two types of compensation behaviour and their respective effects on behavioural adaptation were already studied in the first driving simulator experiment. It was found that two different types of unexpected events, requiring different combinations of compensatory actions, have different behavioural effects. The current elaboration concerns only these behavioural effects of longitudinal compensatory actions.

The safety-critical situations under investigation in this experiment were unexpected braking actions from the participant's leading vehicle. They required compensation in the longitudinal direction from the participants, specifically in the form of lowering speed; no lateral compensation was required. The longitudinal effect was indeed found. Participants lowered their speed and adapted their headway, and this was a strong effect. However, drivers also had a tendency to drive more to the outside of their lane during the braking manoeuvre than in reference conditions. Although the size of this effect on lateral actions was very small (rendering the effect almost negligible), this means that the longitudinal compensation was not done without any effect on lateral behaviour. Apparently, a longitudinal event triggers drivers to show a short-term reaction in more than only a longitudinal manner. However, no behavioural adaptation was seen in the drivers' lateral behaviour after the braking events.

Other findings

i. Task prioritization

The results show that in situations where the high task demands rise above a certain level, drivers change their task prioritization in order to focus on the main driving task, at the expense of other, less relevant tasks. This was reflected in the headway changes in the three mental workload conditions. In the easy task condition, drivers decreased their headway as compared to normal driving without any additional tasks. The increased task demands led to a situation in which drivers apparently shared their attention between the secondary task and the primary driving task. A decrease in safety margins is generally considered less safe. However, when the task demands increased further, drivers normalized their headway to accommodate these increased demands, and apparently turned their focus back to the driving task. This was done at the expense of the additional task, as was shown in the secondary task performance. It appears as though mental workload and distraction were both elevated in the easy task condition, but that motivation and prioritization played a role in reducing distraction while keeping mental workload elevated in the difficult task condition.

ii. Switching between driving in an automatic fashion and conscious control over the driving task

Results from both experiments suggest that drivers perform certain subtasks in a less conscious manner, when driving with an additional task. These subtasks include decelerating before an intersection, keeping right, and maintaining an appropriate speed and distance to a leading vehicle. These results point in the direction of driving in an automatic fashion, or a habitualized driving style. Since the experimental setups of both experiments included many situations that all appeared similar, it would seem reasonable that drivers would get used to the situations, develop expectations about them, and thus develop a habit of driving though them in the optimally efficient manner. This habit could be maintained for some time, until a safety-critical situation occurred. It was seen that drivers started to exert more conscious control over the driving task after an unexpected situation, and showed more active involvement in the driving task and the traffic situation. The results furthermore show that the level of safety-criticality of a braking event changes the way in which drivers decelerate; higher criticality events evoke a more active way of deceleration (i.e., through braking) than less critical events, after which drivers more often release the gas pedal.

Both experiments show that level of criticality, or the urgency of the braking event, does not influence the speed pattern of drivers with normal mental workload levels. However, other aspects of their driving behaviour did change as a result of the safety-critical breaking event. The results indicated that participants drive more slowly after the braking event, if only temporarily. Drivers in the first experiment also kept larger headways after the unexpected and safety-critical braking event.

6.1.3 Possible under- or overestimation of results

As was already discussed in the light of the first experimental results (Chapter 4), the manner in which the data for both experiments were recorded might have had some influence on the outcome of our analyses. The raw data were recorded with fixed sampling rates (256 Hz for the first experiment, and 100 Hz for the final experiment), and this strict time interval between recorded data values resulted in an overrepresentation of values for periods of time in which participants drove slower. Since all variables other than speed variables were averaged over the total number of recorded values, some effects might have been over- or underestimated.

At lower speeds, drivers usually have smaller deviations of their lateral positions; swerving effects might therefore have been underestimated in both experiments. The final experiment showed no significant results for swerving effects, other than a small increase of swerving at the path of the braking event. This increase might have been bigger than indicated in the analyses, especially since the speeds during the braking event were rather low (some participants even came to a full stop in reaction to the braking lead vehicle). A trend of increased swerving was identified at path +1, but its effect size was too small to be of relevance, based on the current analyses. However, the power of the related test was rather small (0.480), and combined with the supposition of underestimation of swerving values this could indicate that the results were actually larger than found in the current analyses.

The averaging method might furthermore have led to an underestimation of relative headway increases and an overestimation of headway decreases, but only when they coincide with lower speeds. The decrease in headway seen for driving while performing the secondary task was not affected by the averaging method, since it coincided with faster rather than lower driving speeds. Since there was no overrepresentation of lower speeds, these values of decreased headway are not expected to be overestimated. There was however an increase in headway related to slower speeds at the path directly following the braking events in the easy task condition in the second experiment. The effect on headway was not significant, but since the speeds were lower in that part of the experiment, it might be the case that this effect was underestimated. Furthermore, drivers driving under normal workload circumstances showed a more defensive driving style after the safety-critical event than before; they also drove more cautiously at the start of a new road section as compared to the reference situation. This effect might have been underestimated, since lower speeds are often related to smaller (time) headway values, and in this case the lower speed contrarily coincided with larger (time) headway values. So maybe the values were even larger.

Concluding, some of the results that did not appear to be very strong might actually have been more prominent and/ or relevant than concluded from the current analyses.

6.1.4 Differences explained

There were a number of differences between the findings in the first experiment and the ones arising from the second experiment. This section describes the most prominent deviating results and subsequently elaborates on their possible underlying causes. Given that the final experiment was designed to optimally answer the final research questions, the set of results from that experiment will be used as guidelines for our conclusions (Chapter 7).

i. Compensation behaviour and safety margins after the most serious braking event

Experiment 1

In all situations but the one with the most urgent braking event, smoother approach patterns were seen for drivers with elevated mental workload than for those without. Only after the most urgent event did the drivers with increased workload show a more profound speed pattern. Furthermore, drivers without high workload increased their headway after the braking events if these were medium or highly critical; drivers with high workload only adapted their headway after the most serious event. Concluding, when driving with high workload, only the most serious event triggered drivers to change their driving style

Experiment 2

After the most urgent event, participants with a difficult additional task drove with a smoother pattern than those without. The approach patterns of participants driving with an easy additional task were in between. The urgency of a braking event did not affect drivers' headway.

Explanation

The results indicate that the experienced criticality of the second set of experimental situations were not as high as the situations in the first experiment. There were some alterations in setup

of Experiment 2 as compared to Experiment 1 that might explain this difference. For instance, there were more braking events in a shorter time span; these braking events were all caused by the same leading vehicle; and other vehicles' behaviours were not influenced by the braking event.
A very different explanation might lie in the fact that the moving-base simulator was used, giving participants the feeling of movement in addition to the view of a braking event. This might have given them a stronger sense of control, rendering the need to react less important.

The criticality of an event is partly determined by the experience of drivers. We expect that this is the reason why startled drivers reacted more profoundly to the most serious event than in a situation when they are less (or not at all) startled. Strongly related to the experienced criticality of the events is the number of unexpected events presented to one participant. The total number of presented braking events for each participant in this experiment was three, as opposed to one in Experiment 1. Furthermore, the first experiment included three trials in which no braking event happened out of the total four. This might have given participants stronger expectations about situations to come: only at one out of 80 intersections did this severe braking event occur. When comparing this to the second experiment, in which both trials included at least one unexpected situation and three events were presented over a total of 120 road intersections, the difference is apparent. The ratio of unexpected situations per intersection encountered is much lower in the first experiment (1:80) than in the second experiment (3:120). Furthermore, there was no variation in the causes for the unexpected event. Since events which occur more often can be anticipated to, specifically if they also have similar causes, drivers might have had a less critical experience in the final experiment. However, this is hard to verify.

Referring to the results for the previous experiment, another indication of the events' criticality levels was found on the means of deceleration after braking. In the first experiment, the level of safety-criticality of a braking event had a significant effect on the means of deceleration, with higher criticality being related to a more active approach to decelerating (braking) than less critical events (releasing the gas pedal). In order to investigate whether the current most urgent event was similarly different from the non-urgent event, we determined the correlation (Spearman's ρ) between the number of times the brake was applied, the time during which the gas pedal was released, and the two criticality levels. These analyses show that the criticality was positively correlated to the number of times the brake pedal was applied (more serious entails more active braking), $\rho=.161$, $p=.029$. The time the gas pedal was released and the criticality levels were negatively correlated (less critical entails more time released), $\rho=-.048$, $p=.008$. In other words, there was indeed a relationship between the level of activity of decelerating and the criticality levels, and this was similar to the relationship found in the previous experiment: the level of criticality changed the way in which drivers moved towards their more defensive driving style.

A last explanation for a difference in experienced criticality might lie in the way the leading vehicle's speed choice was programmed, and its effects on the braking events. In the final experiment, the leading vehicle remained within a time headway range of between 1.5 and 2.5 seconds during normal driving. The distance between the two vehicles in Experiment 1 remained in a range of between 18 and 48 metres. Remember that a headway value of 48 metres is equivalent to a time headway of 3.5 seconds at a speed of 50 km/h, and to an even longer time headway at lower speeds. If the leading vehicle was often at the high end of the range of possible distances, a sudden braking event resulting in a final distance of less than 18 metres (highest criticality) would have been a large difference. It could be argued that such a large change could result in a more startling situation than a change in time headway from 2.5 seconds to 0.8 seconds.

We can therefore conclude that the events which were intended as more critical were indeed more critical than others, as was already concluded from the programmed behaviour of the leading vehicle. However, it appears from the results that the most serious event in the final experiment was not as serious and/ or unexpected as the most serious event in Experiment 1. Therefore, we cannot be completely certain that the level of criticality was high enough to prompt the level of behavioural change found in the first experiment.

ii. Initial response to the braking events

Experiment 1

Drivers with high mental workload initially responded as cautiously as normal drivers, but returned to their original driving behaviour much faster than drivers who completely focussed on driving.

Experiment 2

At the path of the braking event itself, drivers without an additional task changed their headway approach pattern more (larger difference between beginning of path and 60 metres before the intersection) than drivers with an additional task, and this change decreased with task difficulty. The initial change was therefore not similar between groups of different mental workload levels. However, drivers without an additional task adjusted their headway after the braking event, whereas drivers driving with an additional task did not. This is similar to the findings in the first experiment.

Explanation

The supposed lower event criticality might also have had an influence on this response. The perception of a lower criticality event might result in less startled drivers, who then might show a smaller response. This might also be related to the predecessor's speed choice and the related difference in (time) headway before and after the braking events.

6.2 Interpretation of results

This section describes the meaning of our findings in the light of earlier studies and varying theories regarding driving behaviour. It specifically focuses on dynamic versus steady-state driving situations, on the implications of our findings for the hierarchical model of the driving task (Michon, 1971, 1985), on task prioritization, on conscious control versus driving in an automatic fashion, and on risk handling.

6.2.1 Mental workload and the driving task: dynamic vs steady-state situations

Other researchers have also investigated the relationship between mental workload and driving behaviour. One of the conclusions drawn in many of these studies was that driving in dual-task conditions is often related to safety precautions, for instance a decrease in speed and an increase in safety margins (e.g., Dingus et al., 1997; Ranney, Harbluk & Noy, 2005; Strayer, Drews & Johnston, 2003). This implies that drivers with high workload levels often drive with larger (time) headways and at lower speeds, which can be explained as driving more cautiously. At first glance, our results seem to contradict these earlier findings: we found that drivers with elevated mental workload drive closer to their leading vehicle and road users from the opposite direction and have higher speeds than their counterparts without elevated mental workload. However, when looking more closely to the differences between our experiment and some of these earlier studies, an explanation for the different findings presents itself.

There are a number of other studies that support our found results that drivers tend to increase their speed and decrease their safety margins in high mental workload level situations. For instance, Lesh and Hancock suggested that drivers overestimate their own capabilities and performance, indicating that an (intentional) compensatory strategy involving an increase in safety margins is unlikely (Lesh & Hancock, 2004). Furthermore, Charlton (2004) found that drivers who were driving while talking on the phone became less responsive to primary task demands, leading to an increase in speed and longer reaction times.

Earlier studies finding that drivers decrease their speed and increase their safety margins with elevated mental workload were often based on car-following, and often in a highly controlled environment. Brookhuis, De Waard and Mulder (1994) presented a way to measure impairing effects of external factors on driving behaviour using the car-following task. Participants were required to follow a leading vehicle at a safe and constant distance in real traffic. The leading vehicle's speed was preset by the researchers, and would fluctuate within a preset range of speeds. Reaction times and coherence and phase shift of the driver's response to the lead vehicle's changing speed were recorded and used as a measurement of impaired driving. It was found that the ability to adaptively follow a car in front was a good indicator of (attention and perception related) driving performance. In other experiments investigating dual-task effects on safety margins that found evidence for compensatory strategies, the driving scenarios were all steady-state scenarios in which many decisions were taken away from the drivers: route choice, speed choice, the choice to maintain a certain constant distance, the choice whether or not to overtake, and the overall goal of the trip. Furthermore, the encountered traffic situations were often rather simple, without any crossing traffic, opposing traffic, in a relatively simple environment without multiple relevant features - in other words, no response to other traffic or aspects of the traffic situation would be required. The only remaining subtask was car-following, and this setup generally resulted in increased safety margins in dual-task conditions (e.g., Dingus et al., 1997; Ranney, Harbluk & Noy, 2005; Strayer, Drews & Johnston, 2003).

Horrey and Simmons (2007) questioned the conclusion that drivers always increase their safety margins when driving with elevated workload. They described the aforementioned car-following task as steady-state car-following. The authors performed two concurrent experiments in order to investigate whether normal driving behaviour resembles driving behaviour in these steady-state tasks. Normal, or 'tactical' driving behaviour, according to the researchers, involves monitoring multiple aspects of the driving environment and adapting to changing goals. Their first experiment involved performing a steady-state car-following task; in the second experiment, drivers were given what the researchers call a 'tactical' driving assignment. Drivers were requested to drive on a simulated highway and drive as they normally would, although specific instructions were given to avoid excessive speeding. Drivers drove two similar experimental blocks, one while driving only and one while performing an additional task. They were free to overtake slower moving vehicles, but could also remain behind another vehicle or drive at their own pace. The researchers divided the blocks into sections of car-following and the sections of overtaking, and compared the results. They found that drivers indeed adaptively increase their safety margins in dual-task conditions while following their predecessor. However, drivers did not increase (and sometimes even decreased) their safety margins in other (tactical) tasks. The authors therefore concluded that during the performance of tactical tasks, so while moving through a complex traffic environment at their own pace, drivers do not adapt their safety margins as was expected based on other studies.

A similar conclusion can be drawn based on our experiments. Instead of presetting a high number of subtasks, drivers could choose their own driving speed, driving style and safety margins, and could prioritize their additional tasks. The instructions for the participants in both our experiments stated that drivers should drive ‘as they normally would’. They furthermore described how other road users might appear in the experiment, such as opposing traffic or cars driving in the same lane as the participants, but did not prescribe how to interact with them. Instead, participants were requested to drive at a self-chosen speed and distance to other road users, but to prioritize safe driving over other tasks. The instructions did not read that drivers could not overtake other vehicles; however, overtaking was made impossible in both scenarios by either the acceleration of the lead vehicle or the high number of opposing traffic.

Horrey and Simmons (2007) argued that the stretches of time in which drivers stayed behind their predecessor can still be categorized as steady-state car following. This was not the case in our experiment, which consisted of only tactical driving in the parts which were used for measurement. Our participants continuously faced tactical tasks and challenges, all related to driving in an urban setting, and met with crossing and opposing traffic and busy infrastructure. They furthermore had to cross 60 intersections per trial, which largely consists of tactical driving. Participants in Horrey and Simmons’s (2007) study, in contrast, drove on a highway with all the encountered traffic moving in the same direction. In situations where drivers decide to follow, tactical choices are ignored; this is not the case in our experimental setting. In other words, whereas drivers in the study by Horrey and Simmons could temporarily ignore or forget their tactical tasks and engage in steady-state car-following, this was not an option in our experiment.

We therefore conclude that our results support the findings of Horrey and Simmons (2007), in that drivers do not increase necessarily their safety margins in dual-task conditions when they perform tactical driving actions. In challenging situations in which their driving is not restricted by instructions, viz. in tactical driving situations, drivers do not increase their safety margins; they may even decrease them. This is valuable new knowledge for increasing the understanding of driving with elevated mental workload.

6.2.2 Michon’s (1971, 1985) hierarchical model of the driving task

As was described in Chapter 2 (Theoretical Framework), Michon (1971) proposed a hierarchical model of the driving task consisting of three task levels. These three levels are the strategic level, at which destination, departure time, route and mode choices are made; the tactical level, dealing with interaction with the road and other road users; and the operational level, which consists of driving tasks related to handling the vehicle. In normal driving, these task levels interact in a hierarchical, top-down manner: route choices made at the strategic level have their effect on the turns needed to arrive at the chosen destination, and operational actions are required to steer the vehicle in the appropriate direction at the appropriate speed. There are however situations in which the interaction between task levels can be bottom-up, for instance in unexpected situations. Due to the required compensation behaviour, often at lower levels, choices which were made earlier can sometimes become obsolete or have to be changed (Michon, 1985).

The hierarchical model of the driving task (Michon, 1971, 1985) was intended both as a description of the (structure of the) driving task and as a framework for a comprehensive driver model. We therefore wanted to determine to what extent the model could describe and frame the actions of drivers in specific situations. Our first driving simulator experiment was aimed at finding more information on the ways in which compensation behaviour to unexpected, safety-critical situations influenced both short-term and long-term driving behaviour. The subsequent experiment focussed on testing hypotheses arising from the findings in Experiment 1. Some of the results described in Chapters 4 and 5 indicate that a directional change in task level interaction can indeed have both a short-term and a long-term effect on driving behaviour, and that this can be seen during and after unexpected events. For instance, compensation behaviour to a longitudinal, safety-critical event was clearly found to have an effect on longitudinal driving behaviour after that event. However, the results also indicate that using the model as a framework for a comprehensive model of driving behaviour poses some difficulties, that the model in itself has some limitations, and that there are a number of uncertainties that first need to be clarified before the model could possibly be used in that manner.

The first uncertainty arises with the fixed number of three levels of the driving task. On the one hand, it is questionable whether certain strategic subtasks, such as choosing a transport mode and determining trip goal, are part of the actual driving task. After all, if travellers strategically decide to use the train as their transport mode, there is no driving task to be executed. Trip goal and personal demands concerning the time, price and comfort of a trip are a factor in determining a transport mode. One could argue that the driving task only starts after these choices have been made in favour of using the car as transport mode, and that these tasks therefore should not be considered an integral part of the driving task. Following this line of reasoning, the outcome of tasks at the strategic level could be considered a constraint for driving (including the related route and time demands), and the actual driving task could be reduced to the two levels that actually take place while driving a car, the tactical and operational level. This raises a question related to situations in which route, time or goal have to be reconsidered (bottom-up interaction): Is this reconsideration part of driving, or is it checking the constraints and demands related to the choice of whether or not to drive? On the other hand, arguments for expanding the driving task to include an additional fourth level also exist. Higher motivations and personal skills play a role in many every-day situations, including driving. Michon’s (1971, 1985) model has therefore been expanded by Hatakka, Keskinen, Glad, Gregersen and Hernetkoski (2002) to contain a fourth level which does not strictly contain primary driving tasks but which directly influences all other levels, namely ‘Goals for life and skills for living’. This level describes how drivers’ higher motivations and personal skills also determine certain aspects of how they drive. Should this influential fourth ‘level’ be taken into account when looking at the three levels of the driving task itself, and does it have an influence on the way the three driving task levels interact? Do drivers’ motivations play a role in their adaptation to certain situations, and how? Can the driving task be considered a separate task that can be studied distinctive from these higher motivations, or do decisional and motivational aspects also play a role in driving? Although these motivations and skills are not solely related to the driving task, they do say a lot about the way drivers handle this task. It can therefore also be argued that the driving task does not consist of three, but even of four levels. Concluding, the fixed number of three driving task levels can be disputed.

Also, the classification of different tasks in the three levels of the driving task poses some theoretical challenges. In this study, we classified most tasks in which hand or foot movements were involved as an operational task. This also involves the amount of pressure put on the gas pedal. We considered keeping a certain speed, which also involves the estimation and evaluation of current speed, a tactical task, since it was related to the interaction with the other road users and the road. Finally, choosing an average goal speed, by estimating travel time and desired time of arrival, was considered a strategic task. However, this classification is subject to interpretation. For instance, Bellet and Tattegrain-Veste (1999) classify keeping speed as an operational task, since it is a low-level task that involves actions with durations of less than a second. On the other hand, Koppa (1990) states that speed control (especially when adapting speed to a car in front) is a tactical-level task, since it involves reacting to the environment and other road users' behaviour and is dynamic. Finally, Brookhuis, De Vries and De Waard (1991) also state that normal speed choice can be related to the tactical level; however, the authors say that excessive speeding is also, and maybe even mainly, related to the strategic level. Other reasons in favour of classifying speed choice as a strategic task can also be given, since speed choice is almost always related to reaching a certain destination within a certain time span. Michon does not mention speed choice and speed control as a separate task, but focuses on overtaking and stopping (Michon, 1985); these tasks both involve speed control, and they are both categorized as being tactical level tasks. When developing a model based on a strict classification of subtasks among different levels, the classification of tasks to certain levels should not be subject to interpretation. Furthermore, the question arises whether it is possible to talk about strictly separate subtasks in a primary task in which every action at every single moment is dictated by a number of subtasks and goals. Can the different actions in driving be separated to the extent needed for making computations between the different levels? And is the separation into levels the optimal way to model the interaction between different driving tasks, or would it be more realistic to model different types of distinctions between different types of subtasks, which are all interrelated?

Finally, the results of Experiment 1 showed that different characteristics of unexpected events may lead to varying types and sizes of change after these events. The two cases that we studied led to very different results, and it would be difficult to draw a generalized conclusion based on these two events. It is unclear whether adding a third or a fourth type of unexpected event would lead to more varying results, or would fall under the category of one of the studied examples. It is however already clear from these two different types of events that it cannot be stated that unexpected events in general lead to a certain directional change in task level interaction. The longitudinal braking event led to changes in longitudinal driving behaviour, but the acceleration event, requiring both longitudinal and lateral compensation, did not bring about any significant changes. It is therefore not even clear whether a certain type of compensation behaviour will lead to a certain (similar or different) type of behavioural change in driving. In short, we cannot draw any solid conclusions on the type of change after unexpected events in general. It is probably the case that this model has a specific realization for different types of events, or even for different specific events.

Concluding, using the model as a framework for modelling the way in which drivers handle the driving task in practice poses some challenges, and a number of other limitations also exist for the model as representation of the driving task. Moreover, further research is needed to clarify the uncertainties that were identified. These uncertainties and difficulties are mostly related to the delimitation of the task and the number of levels constituting the driving task, to whether or not these levels are strictly divided or partly overlapping, and to the division of the different tasks over the task levels. The model with its current setup is useful for providing insight into the different aspects that constitute the driving task. The underlying (sub)tasks, although very different, together constitute the overall driving task. These subtasks have different time frames and different roles in the realization of car driving. The hierarchical ordering of the task levels clarifies how car driving involves continuous creation, execution and control of goal-directed plans and related feedback loops. This hierarchical ordering is inspired by architectures of human cognition modelling (e.g., SOAR, see Lehman, Laird & Rosenbloom, 2006, or ACT-R, see Anderson, 1995), in which a goal is set at a higher level and passed on to the next lower level during conscious control of the task. Feedback loops guide the execution of the plan. Furthermore, the hierarchy shows how an increasingly larger amount of information is needed for the successful execution of tasks at each higher order task level. Although reservations about the general setup of the model are in order, the hierarchical structure does provide insight into a number of important aspects of the driving task. With the mentioned uncertainties and theoretical problems solved, the altered version of the hierarchical driving task model (Michon, 1971, 1985) could serve as a guideline for modelling the cognitive aspects of the driving task in situations in which conscious control and goal management are involved.

6.2.3 Task prioritization

When determining the safety effects of additional tasks on driving performance, the first step is to understand the prioritization of tasks and subtasks. After all, if a possibly distracting task is completely ignored in favour of safe driving, its effects are much smaller than when drivers fully engage in the distraction, regardless of the level of mental workload or task demands. But how does this prioritization take place in actual traffic situations? Do drivers still pay as much attention to safe driving when they concurrently do something else? Do they actively prioritize safe driving at the expense of their secondary task? Or could driving in a situation with increased mental workload turn out to be detrimental to safety?

Even without instructions, drivers distinguish between different types of subtasks. As was described in Chapter 2 (Theoretical Framework), Cnossen, Meijman and Rothengatter (2004) found that drivers prioritize safe driving at the expense of lower-priority secondary tasks. Our experiments revealed similar results. Both driving simulator experiments showed that an increase in mental workload changes drivers' behaviour. Drivers paid less attention to their speed and speed approach pattern and maintained a smaller headway when engaged in certain levels of the secondary task, specifically the easy arithmetic task.

Prioritization of the primary driving task at the expense of the secondary task occurred when the level of mental workload reached a threshold, which occurred while performing the difficult arithmetic task in both experiments. This was indicated by the larger behavioural effects for the easy arithmetic task than the difficult task. Furthermore, when participants were asked to perform only the difficult and not the easy task (Experiment 1), the difficult task did not interfere with behavioural variables. This also indicates prioritization of safe driving in high demand situations. Finally, driving task prioritization was also indicated by drivers' performance on the two secondary tasks. Participants performed much better on the easy than the difficult version of the task, with 2.4 times more answers and only one third of the proportion of wrong answers. This ratio could suggest that participants abandoned the difficult arithmetic task in order to focus on the primary task of safe and attentive driving.

Concluding, drivers do not only prioritize when instructed to (De Waard, 1996), they also prioritize safe driving over distracting tasks when the external tasks are not relevant for safe driving (Cnossen et al., 2004), or when the combined task demands exceed a certain threshold (our results).

6.2.4 Conscious control versus driving in an automatic fashion

Driving is a task in which both automatic performance of subtasks and conscious task execution play a role. Such learned automatic (sub)tasks can allow drivers to save attentional resources. When fewer resources are invested, task execution will be done in a more automatic or habitual fashion. When drivers drive in an automatic fashion and thus do not exert conscious control over every single subtask, this habitual behaviour can show in different ways and on different levels of the driving task. The automatic fashion in which drivers handle the driving task in these automaticity situations can be compared to the supervision task when supported by certain ADA Systems. This type of support can have positive effects on the reduction of stress and negative affect (Cottrell & Barton, 2011). However, there needs to be an adequate balance between automaticity and conscious control. When it is safe and possible to perform (part of) the driving task in an automatic fashion, automaticity can indeed be positive, but the driver needs to remain alert in order to switch back to conscious control when necessary. If this switch back to an active driving mode is initiated too late drivers may not respond in a timely fashion, and safety-critical situations might occur.

In our experiment, we found a relationship between the level of criticality of a situation, the level of automaticity at which a task is performed, and the level of mental workload in the driver. It was shown that drivers pay less attention to certain crucial aspects of the driving task in dual-task situations. Specifically, our first experiment showed that drivers perform certain subtasks, such as decelerating before an intersection, keeping right, and maintaining an appropriate speed, in a more automatic fashion when driving with an additional task. Furthermore, our second experiment showed that participants kept a larger headway when they could focus all of their attention on driving, than when they were driving with an arithmetic task. To a large extent this reflects the way in which people drive when they perform their driving task in an automatic fashion: habitually and without high levels of conscious control and/ or decision-making. It appears that a high level of mental workload pushes drivers in the direction of an automatized driving mode. The link between mental workload and automaticity seems reasonable, since automatization is strongly related to the efficient allocation of attentional resources.

Switching task execution from a habitual, skill-based performance level to a more conscious, rule- or knowledge-based performance level is a mechanism that is related to compensation for a situation that does not fit within the normal patterns (Rasmussen, 1987). In other words, the task needs to be executed at a different performance level. This could be characterized as a directional switch within the SRK-framework (Rasmussen, 1987), with performance levels moving from skill-based (automatized, habitual) towards rule-based or even knowledge-based (conscious control over the driving task). This directional switch is strongly related to the way in which the driving task hierarchy responds to unexpected situations (Michon, 1985; also refer to Section 2.2.1). When drivers actually make this switch onto a lower level of automaticity and thus start to exert more conscious control over the driving task after an unexpected situation, one would expect more active involvement in the driving task and the traffic situation. The results of the first experiment indeed confirm this expectation. It was found that the level of safety-criticality of a braking event changes the way in which drivers decelerate; higher criticality events evoke a more active way of deceleration (i.e., through braking) than less critical events, after which drivers more often release the gas pedal.

The results furthermore indicate that the switch from automatic to conscious control is mostly restricted to specific levels of the driving task. This can be clarified by showing the different responses between people with high mental workload and people who could focus all of their attentional resources on the driving task. In situations where the task demands are not very high (normal driving), drivers do not change all aspects of their driving behaviour after a safety-critical situation. For instance, both experiments showed that level of criticality, or the urgency of the braking event, does not influence the speed pattern of regular drivers. So even though a safety-critical situation occurred, drivers did not change their habitual speed approach pattern. However, other aspects of their driving behaviour did change as a result of the safety-critical breaking event. Both experiments showed that participants drove more slowly after the braking event, if only temporarily. Drivers in the first experiment also kept larger headways; one could argue that they temporarily drove at a defensive or cautious driving style as a result of a safety-critical braking event. It seems as if the approach pattern to an intersection is a very habitual behaviour that is not easily changed from automatized to conscious performance, whereas general speed and distance keeping do appear to change as a result of more conscious control. This could be explained by the fact that an approach pattern is largely connected to operational tasks such as brake and gas pedal control. Earlier studies have shown that it is very difficult to unlearn these tasks (e.g., Korteling, 1994; also refer to Section 2.2.1.2). However, subtasks on a higher level, for instance tactical subtasks such as distance keeping and speed maintenance, are more easily performed consciously. In other words, it can be concluded that a directional switch in skill-level mostly occurs in tactical level driving tasks, and less in operational subtasks.

Concluding, our results indicate that the level of mental workload has a link with the level of automaticity, and that drivers become more actively involved in their task and drive in a less automatic manner after an unexpected situation. Mental workload appears to drive people into automaticity and the directional switches between performance levels and task levels appear to be linked. Our results also revealed another interaction between mental workload, situation criticality and automaticity.

If drivers face an unexpected and safety-critical situation while they are driving in an automatic manner, it is recommendable to switch back to a higher level of conscious control in order to handle the situation actively and safely. This is the case for all drivers, whether or not they are driving with elevated levels of mental workload. Our results show that drivers with increased mental workload are very reluctant to switch back from their habitual driving style. If they do change their driving mode, it is only when the situation is highly safety-critical and urgent, and their response also lasts shorter than a response from normally loaded drivers. Apparently it takes more to get people with high mental workload from their automatized driving style into conscious driving than it does for people with normal workload levels. This is reflected in the results for both experiments. The first experiment showed that, while drivers with normal workload levels switch back from habitual driving to a more active and cautious driving style, drivers who have to divide their attention between driving and an additional task either do not show this defensive driving style, or quit this driving style sooner. This divide between the two mental workload groups in the first experiment was also reflected in the fact that drivers with high mental workload only respond to the most critical events, whereas drivers under normal circumstances respond to all levels of events. The second experiment confirmed these results, showing that drivers without an additional task adjusted their headway after a braking event, whereas drivers driving with an additional task did not (independent of the level of task difficulty).

When drivers with elevated mental workload levels do finally respond to a highly critical situation, they show a stronger reaction, as if they are startled more strongly than their normally loaded counterparts. Their regained active engagement in the driving task even reflects in the operational level of the driving task, as they even change their approach patterns to intersections, in both speed and headway (based on results from both experiments).

In other words, our results point towards a three-way interaction between levels of mental workload, levels of automaticity, and levels of safety-criticality.

Safe driving requires an appropriate balance between conscious driving (in which the driver is alert and invests cognitive effort) and driving in an automatic fashion (during which cognitive effort can be saved). Many studies have shown that both very low and very high task demands can lead to a high level of mental workload, and that this might impair driving behaviour (for a review of studies on mental workload and task demands, please refer to Section 2.4.3). The current study furthermore showed that the level of conscious or habitual driving is also related to mental workload.

Further research could focus more deeply on the relationship between mental workload, task prioritization, automaticity and driving performance. Some of our current findings seem to contradict at first glance (on the one hand prioritizing the primary task in high mental workload situations and on the other hand going into a more or less automatized driving mode). However, it might be that both findings describe drivers' strategies to relieve some of the burden of extremely high mental workload, especially since they did not explicitly show other compensation strategies such as increasing their safety margins. This thesis has already attempted to uncover the differences and similarities between distraction and mental workload (Chapter 2). Further untangling the relationship between mental workload and possible strategies for workload relief would strongly improve the knowledge about ways to improve driving performance by protecting drivers from their 'bad habits'. Since previous studies have shown that drivers overestimate their performance and there is little chance that they consciously adopt a strategy to increase their driving performance (Lesh & Hancock, 2004). It would also be very interesting to know more about the role of conscious decision making and strategy forming in this context. Further research should therefore focus on these interrelations.

6.2.5 Risk handling

The participants of the two experiments were placed in safety-critical situations, which lead to a behavioural adaptation to this risk. We compared our results to the theories on risk handling that were described in Chapter 2 (Theoretical framework): the Risk Homeostasis theory (Wilde, 1982), the Zero-risk theory (Näätänen & Summala, 1976; Summala & Näätänen, 1988) and the Task-Capability Interface model (Fuller, 2000). Our experiments were not directed towards finding the (internal) reasons for drivers' actions, so the results are not appropriate for supporting or falsifying any of the theories described. It has however become clear that the ways in which drivers cope with safety-critical situations can be related to the level at which they are actively engaged in their driving task, an aspect of behavioural adaptation to risk that is not explicitly included in all of the theories of risk handling.

The fact that encountering risk in a traffic situation leads to behavioural adaptation is not controversial. Risk handling theories mostly focus on explaining why behavioural adaptation takes place, rather than how. All the theories on risk handling described in Chapter 2 (Theoretical Framework) can explain the results in their own way. For instance, the finding that drivers lowered their speeds for a number of intersections directly following a safety-critical braking event (Experiment 1) would be explained by the Risk Homeostasis theory (Wilde, 1982) as originating from a perceived increase of risk. This new risk level presumably exceeded the personal acceptable level of risk which could be successfully attained until the braking event occurred. As a result, the drivers' perceived utility of their driving behaviour was no longer optimal, leading to a decrease in speed. However, this result would be explained differently when basing the explanation on the Zero-risk model (Näätänen & Summala, 1976; Summala & Näätänen, 1988). Based on this Zero-risk model, it could be argued that drivers felt in control (zero risk) until the lead car braked. Whereas they might not have continuously monitored the risk level of the situation before the braking event, they apparently did feel the need to adapt their behaviour afterwards in order to accommodate for the perceived occurrence of risk. The drivers therefore adjusted their behaviour by means of control mechanisms, leading to a decrease in speed and/ or an increase in safety margins. After some time, they regained their trust in the situation and their perceived risk returned to zero. Finally, a third explanation from the viewpoint of the Task-Capability-Interface (Fuller, 2000) would say that the difficulty of the task increased due to the unexpected behaviour of the lead car, resulting in a situation where the (new) task demands exceed the drivers' capabilities. Therefore, drivers could react by doing one of two things: either invest more effort with the aim of increasing their own capability, or decrease the task demands. Decreasing task demands could involve dropping an external or secondary task, but could also be achieved by lowering the demands from the driving task itself. Since driving is mostly a self-paced task, lowering their driving speed would give drivers more time to perceive possible hazards and make adequate decisions, therefore decreasing task difficulty.

It is our recommendation that further research be done into the ways in which behavioural adaptation to risky situations (including the reasons for this adaptation) is influenced by the level of mental workload and by the extent to which drivers are actively engaged in driving.

6.3 Design considerations for ADA Systems

As was already explained in Chapter 1, ADA Systems can be designed based either on technological advancements or on a human-centred design process. With such a human-centred design process, driver needs are at the starting point for system development. A way to accomplish human-centred design is to comply with a number of ergonomic design principles, such as transparency of the system's actions, adjusting to individual situations and requirements (an adaptive system), and intelligibility of the operator's role. Transparency means that the system's responses to certain traffic situations should be 'understandable' for drivers. To this end, the system could for instance mimic the drivers' natural optimal (safe) responses, or compensate for unsafe responses while accompanied by some type of explanation (information or warning).

An adaptive system could adapt the systems' reactions to foreseen actions from drivers, in addition to using the cues about the environment available to sensors. Our results show that drivers' reactions to safety-critical situations differ according to their level of mental workload and/ or distraction. By adaptively reacting to the drivers' current state, ADA Systems can give the best appropriate response. For instance, the objectively measured criticality of a situation and the related experience of a driver turn out to differ due to the driver's state. This has an effect on the duration and size of the intervention that drivers perform. Moreover, given that a risky situation is highly safety-critical, all drivers show an immediate reaction to the situation, but their response is much shorter in dual-task conditions (such as driving while handling the interface of a support system). In addition to this, the total sum of task demands and the related level of mental workload also determine the priorities that drivers give to primary driving tasks and other possibly distracting secondary tasks. Mimicking the driver's safety response in normal circumstances (increasing the response duration until some time after the actual event) might possibly lead to higher acceptance rates. More research is needed to determine whether this is actually the case.

As the actions performed by ADA Systems should be transparent to drivers, so should be the drivers' own responsibilities. Drivers need to be aware of the relative priority for handling and complying with the ADA System as compared to focusing on their normal driving tasks. This is especially true when the main aim of the ADA System is to increase driver comfort rather than traffic safety. Drivers' prioritization of tasks (both primary and external) and, related, the relative relevance of external tasks, are important indicators of the impairing effects of mental workload. Driver training feedback during driving could make drivers (more) aware of the relative relevance of using ADA Systems as compared to regular driving tasks. Of course, not overloading the driver with information remains an important concern, especially in situations of high mental workload, so more research is needed to establish the optimal way to provide this information to drivers.

Moreover, researchers and developers of ADA Systems need to be aware that a 'tipping point' exists for the impairing effects of increased mental workload. Below a certain threshold of mental workload, drivers allow themselves to be distracted, resulting in impaired driving behaviour. When the level of mental workload exceeds this threshold, drivers appear to realize that the task demands exceed their capabilities, and they put their focus back on safe driving. Unfortunately, this tipping point is not always situated where researchers and developers would wish it was, viz. before the impairment of driving performance. Studies into the effects of ADA Systems should therefore not only focus on possible increases or decreases of mental workload levels involved with using the system. They should also determine what effects the system has on task prioritization, distraction, and the overall traffic safety resulting from possible changes in driving behaviour.

With these recommendations and our findings on driver distraction and mental workload in mind, we proposed a promising direction for the development of safety-enhancing ADA Systems. This could lead to a group of safety-enhancing ADA Systems designed for urban settings. The functions of this group of systems are related to safety enhancement in distracted driving. Based on the findings in this thesis, we recommend that this type of systems would be developed as integrated systems, in order to coordinate all signals given to the driver and adaptively suppress information based on the level of current workload in the driver. This means that it would contain a communication and coordination module, which communicates with all other devices and combines information from sensors to continuously update information on the states of both driver and vehicle. A module for workload estimation could keep track of the state of the driver in terms of mental workload and distraction. This module could for instance combine information about the static road environment, the number of systems and vehicle controls drivers are interacting with, drivers' seat positions, glancing behaviour, or a change in driving style (e.g., Mayser, Piechulla, Weiss & König, 2003). By combining the information about the state of the driver, the vehicle and the environment, this type of systems can constantly be aware of the actual driving situation. The actions of the system can thus be adapted to give the optimal response to this situation.

The proposed direction for development could lead to a group of systems which could be given the generic name DAISy (Distraction Avoidance Integrated System). DAISy has the aim of enhancing drivers' safety during distracted driving in urban settings. Based on the findings presented in this thesis, five recommendations for this new direction of systems are made.

Many safety issues arise from or manifest in the form of inappropriate speeds and safety margins, and adopting these safety boundaries to the current driving situation and the driver state could largely benefit safety. The first recommendation is therefore to establish a safety zone around the vehicle with its boundaries set at safe distances, giving drivers enough time to counter a possible conflict.

We found that drivers might 'allow' their driving to be impaired when their mental workload is elevated but still stays below a certain threshold. Drivers should thus not be presented with unnecessary stimuli when they are driving in safety-critical situations, such as another object entering the safety boundaries. The second recommendation would therefore be to stop the input of non-vital systems and warn the driver when another object enters this safety zone.

We furthermore found that drivers respond later to upcoming conflicts in the case of elevated mental workload. Drivers therefore need to be warned earlier when they are in a high workload situation, so that they can switch their full attention to avoiding a possible conflict. So when it is determined that mental workload is higher than normal, the safety boundaries should be increased to accommodate the decreased attention. This is the third recommendation for this type of systems.

A fourth recommendation would be to adjust the speed or (lateral) direction of the vehicle if the level of mental workload is higher than normal, in order to accommodate the decreased attention.

Finally, when mental workload increases, drivers pay less attention to objects appearing in their peripheral visual field. As a fifth recommendation, we therefore propose that Distraction Avoidance Integrated Systems scan for moving objects in the part of drivers' visual field that overlap with the safety boundaries around the vehicle, such as pedestrians and bicyclists, in situations with elevated mental workload.

In this way, ADA Systems in the DAISy 'family' would meet several of the recommendations based on this thesis. More research is needed to determine how the relative priorities of drivers' own driving actions and interaction with the system can be guided in a safe manner, without overloading the driver with too much information.

Chapter 7

Conclusions

The final chapter of this thesis gives an overview of the findings and conclusions for the studies performed. Recommendations for further research are discussed, based on the findings from the driving simulator studies and the questions raised in discussing them.

7.1 Context and research questions

The central theme in this thesis is the way in which drivers handle unexpected risky situations, and the personal characteristics and circumstances that affect the outcome of their choices and actions. This is related to the change between top-down and bottom-up influence between levels of the driving task, as proposed by Michon (1971). In this hierarchical task level model, three task levels make up the driving task: the strategic, tactical, and operational level. Tasks involving choices about trip destination, departure time, route and other trip goals are part of the strategic level. At the tactical level, tasks involving interaction with the road and other road users are performed. This includes maintaining an appropriate distance to other road users, driving on the correct side of the road, and taking turns according to the trip goals. At the lowest operational level, all interaction with the vehicle controls takes place. This involves, among other tasks, pressing the gas pedal, turning the steering wheel, and checking the mirrors.

These three driving task levels interact, and in normal driving this interaction takes place top-down. Choices about the route involve the turns to be taken, and this determines the angle in which the steering wheel needs to be held. Choices about the desired departure and arrival times (partly) determine the desired speed, which in turn determines how drivers interact with other road users and how far they press the gas pedal. In other words, higher level choices dictate the input for lower level tasks. However, a directional change can take place in the interaction between task levels. Top-down interaction, important in normal driving, can switch to bottom-up interaction in the case of an unexpected situation (Michon, 1985). When drivers' choices do not turn out the way they had anticipated, drivers have to compensate for this unexpected situation by changing certain actions in order to regain control over the situation. For example, a driver driving on a slippery road who would normally act according to top-down route choices, might have to intervene when the car starts to shift, and thus prioritize lower-level tasks (regaining control over the vehicle) over earlier higher-level choices (taking the correct turn, or keeping the appropriate distance to a predecessor). This is what is meant throughout this thesis by the directional change in task level interaction during unexpected situations.

7.1.1 Research questions

This thesis aimed to answer the following research questions:

- How do drivers respond to unexpected, safety-critical events while driving in an urban environment?
- To what extent does the urgency of the event influence this response?
- To what extent does the level of mental workload exert an influence on this reaction?
- To what extent do drivers' basic demographic characteristics, such as gender or age, influence this reaction?
- How do the results relate to the framework presented by the hierarchical model of the driving task (Michon, 1971, 1985)?
- What is the relationship between the findings in our studies and previous studies done into driver distraction, mental workload and other human factors in driving?
- What is the relationship between mental workload and driver distraction?
- Which recommendations can be made for the development of safe ADA Systems?

7.1.2 Research approach

According to the hierarchical model of the driving task (Michon, 1971, 1985), described in Chapter 2, normal driving with its top-down interaction between task levels can switch to compensation behaviour and the related bottom-up interaction in the case of an unexpected situation. The hypothesized change of the direction of interactions between task levels and its effects on driving behaviour were investigated in two driving simulator experiments with the aim of studying the implications of Michon's (1971, 1985) model. By presenting successive similar situations to drivers, without much variation, expectations were created by the drivers. These expectations were subsequently broken by presenting them with unexpected and safety-critical situations. In investigating the drivers' responses, we determined their primary responses during the event, the (temporary) effects on driving behaviour, and the influence of external factors such as mental workload and the urgency of the situation. We furthermore determined whether certain basic demographic characteristics of drivers (e.g., gender, age) have an effect on their reactions.

7.2 Findings: Reactions to unexpected, safety-critical events

7.2.1 Compensation behaviour and driving style

Car drivers adapt their driving style and behavioural responses to the type of situations they encounter, the risk level of encountered situations, and their own level of mental workload. When they experience an unexpected, safety-critical event at the operational level, they generally tend to compensate for it at this operational level (for instance, by braking and/ or steering away), and they might temporarily adapt their (tactical) driving style to accommodate for the risky situation. Depending on the type of situation, the compensatory actions required to divert the immediate traffic conflict and the resulting change in driving style can vary. For instance, a suddenly braking lead vehicle was found to have a different behavioural effect than a suddenly accelerating car from a left side street, although both situations led to approximately equally risky situations in terms of the distance after the event between the two vehicles involved. Not only were the initial compensatory responses different, also the (temporary) behavioural adaptation after the events varied between the two types of events. Encountering the suddenly accelerating car did not seem to affect participants' driving styles, whereas the required compensation to the braking lead vehicle did have an effect on driving speed, speed approach pattern, lateral position on the road, and distance headway.

Driver characteristics such as age and gender were not found to significantly affect these reactions to unexpected and/ or safety-critical events. However, the level of mental workload of the driver does have an influence on the aforementioned reactions. Performing a relatively simple, yet cognitively demanding, arithmetic task elevates mental workload. With this elevated mental workload, the safety of drivers' reactions to the unexpected and safety-critical events deteriorates. On the one hand, drivers with normal workload were found to intervene and adapt their driving style to accommodate for safety-critical situations, also in situations which are not very high-risk. After having gained back control, they maintain a larger distance than before the event, and drive slower. In other words, they try to prevent a similar situation from occurring again by paying more attention to the driving task and their (apparently risky) environment. This indicates a directional change from normal top-down directed driving behaviour to compensation behaviour, which is directed in a bottom-up manner. Regular drivers furthermore drive more cautiously (larger headway) at the start of a road section after the braking event than they do at the end of that particular road section, as if they try to examine the situation. They maintain this cautious behaviour for some time after the braking event. On the other hand, drivers with high levels of mental workload seem to respond only to very serious situations (although this was not supported in both experiments, possibly due to a difference in programming of the severity of the experimental events). They furthermore maintain a shorter distance to other road users (both their predecessor and opposing traffic), drive faster, and return to their normal driving situation much more quickly than drivers who are able to focus their full attention to the driving task. There appears to be a threshold above which drivers abandon their attempt to perform both the primary driving task and the secondary tasks concurrently, and prioritize safe driving at the cost of performance on the secondary task.

Our experiments confirm the premise of the hierarchical model of the driving task (Michon, 1971, 1985) that top-down interaction between task levels temporarily changes into bottom-up interaction as a result of compensation for unexpected and safety-critical situations. This is shown in the temporary behavioural change after unexpected, safety-critical events. Furthermore, our results indicate that the model can be extended when it comes to the impact of conscious attention on the part of the driver. If drivers focus on other things than safe driving, bottom-up interaction occurs only in response to highly dangerous situations in contrast to situations when drivers do pay full attention to driving. Additionally we found that the duration of this behavioural change is dependent on the level of mental workload that drivers have in such double task situations. Section 7.3 reflects on the theoretical issues related to these results and their application in the light of the hierarchical model of the driving task (Michon, 1971, 1985).

7.2.2 Task prioritization

The primary driving task was prioritized at the expense of the secondary task when the level of mental workload reached a threshold, which occurred while performing the difficult arithmetic task in both experiments. Participants performed much better on the easy than the difficult version of the task (more than one would expect based on the task difficulty itself), and their primary task performance increased at the same time. This suggests that participants abandoned the difficult arithmetic task in order to focus on the primary task of safe and attentive driving. In other words, when drivers are faced with increasing task demands which exceed their capabilities, they put safe driving back at the top of their priority list. The increased task demands result in prioritizing safer driving over the performance on the secondary task. Earlier research conducted by Cnossen, Meijman and Rothengatter (2004) already showed that drivers give a lower priority to secondary tasks which are irrelevant for safe driving, such as tuning the radio, than to external tasks which are indeed relevant for driving, such as reading a map. The current research furthermore shows that not only the relevance of the secondary task for driving performance, but also the task demands play a role in drivers' task prioritization. Concluding, drivers do not only prioritize safe driving over distracting tasks when instructed to or when the external tasks are not relevant for safe driving, but also when the combined task demands exceed a certain threshold.

7.2.3 Automatized driving versus conscious control over the driving task

Driving is a task in which both automatic performance of subtasks and conscious task execution play a role. Such learned automatic (sub)tasks can allow drivers to save attentional resources. However, there needs to be an adequate balance between automaticity and conscious control. When it is safe and possible to perform (part of) the driving task in an automatized fashion, automaticity can indeed be positive, but the driver needs to remain alert in order to switch back to conscious control when necessary. When this switch back to an active driving mode is initiated too late, drivers may not respond in a timely fashion, and safety-critical situations might occur.

Findings from this study suggest a relationship between the level of criticality of a situation, the level of automaticity with which a task is performed, and the level of mental workload of the driver. Drivers pay less attention to certain crucial aspects of the driving task, such as decelerating before an intersection, keeping right, and maintaining an appropriate speed and headway, when they have a high level of mental workload. It appears that a high level of mental workload pushes drivers in the direction of an automatized driving mode. Although a switch from conscious control to automatized driving might save attentional resources, switching back to full conscious control over the driving task is required in safety-critical situations. It was found that drivers do make this switch, but mostly at the tactical level of the driving task (strategic level subtasks were not studied).

Drivers with increased mental workload are highly reluctant to switch back from their habitual driving style. If they do change their driving mode, it is only when the situation is highly safety-critical and urgent, and their response also lasts shorter than a response from normally loaded drivers. However, when mentally loaded drivers do finally respond to a highly critical situation, they show a stronger reaction, as if they are startled more strongly than their normally loaded counterparts.

Concluding, our results point towards a three-way interaction between levels of mental workload, automaticity, and safety-criticality.

7.3 Reflections on theoretical framework

The theoretical framework presented in Chapter 2 was based on the three-layered hierarchical model of the driving task (Michon, 1971, 1985), and included references to mental workload and the effects of unexpected situations. This section reflects upon two theoretical aspects of this framework, namely the underlying structure of the hierarchical model and the relationship between mental workload and (latent) driver distraction.

7.3.1 Latent driver distraction and mental workload

According to its definition, driver distraction occurs when there is a secondary task or activity which is given attention by the driver and thus diminishes driving performance. Traditionally, whether or not driving performance was diminished was determined by measuring the level of safety of the current situation. However, being able to respond to an upcoming safety hazard is also a part of safe driving, and this does not necessarily materialize in measurable safety effects within the current situation. Therefore, the concept of latent driver distraction, a form of driver distraction that does not materialize in measurably unsafe driving behaviour but that does impair being able to respond adequately to upcoming safety-critical situations, is introduced in Chapter 2.

The concepts of driver distraction and mental workload appear to have a number of aspects in common. They are both related to task demands; they can both coincide with deteriorating driving performance; and they can occur simultaneously. However, the concepts and processes involved are clearly distinct. Whereas driver distraction can only occur as the result of a distracting task or object; mental workload can also increase due to changing demands from the primary task itself. While decreased driving performance from an increase in mental workload can be countered by investing more task-related effort, distraction always leads to worse performance. And finally, drivers can influence their level of distraction through motivation and task engagement; in other words, through task prioritization. But although using an increase in one of these concepts as a indication of the other is incorrect, the readiness to respond that is affected by latent driver distraction can actually also be measured by one of the tools used for mental workload assessment. It is therefore proposed to use this mental workload assessment tool, the Peripheral Detection Task, to assess latent distraction.

7.3.2 The hierarchical model of the driving task

The results from the current study relate to the hierarchical model of the driving task (Michon, 1971, 1985) as follows. There indeed appears to be a directional change in driving task level interaction as a result of compensation for unexpected and safety-critical situations, although is has not been established what exactly are the constituting factors for these unexpected situations. This directional change in task level interaction requires conscious attention from the driver, and if this attention is not fully available, for instance as result of demanding secondary tasks, the resulting change occurs only in more critical situations and lasts shorter. The behavioural change resulting from the directional change is temporary. Drivers change back to their normal driving behaviour after some time, and this duration is dependent on the level of mental workload that drivers have.

It was found that in challenging, high mental workload situations in which their driving is not restricted by instructions, viz. in real-world tactical driving situations, drivers do not necessarily increase their safety margins; they may even decrease them. This is contrary to what one would expect from compensation behaviour. It seems that longitudinal tasks are easier influenced by compensatory actions than are lateral tasks. Another finding is that the behavioural change resulting from compensatory actions can become visible at the specific location on the road around which the unexpected situation originally occurred, rather than over the complete stretch of road.

However, a few comments can be made about the hierarchical driving task model, based on both theoretical considerations and empirical data. It remains unclear which tasks influence which other tasks in the nearest upper level. Moreover, interpretations of the classification of subtasks over the different levels have differed between researchers, and it remains unclear what the final classification of subtasks should be. The fixed number of three task levels can be disputed, since on the one hand certain subtasks included in the model are not part of driving (e.g, when the train is chosen as the transport mode at the strategic level) and on the other hand, higher level motivations and skills also play a role in the execution of driving tasks. And finally, separating the subtasks of driving into strictly divided different tasks at different levels seems to be an abstract theoretical intervention that does not resemble actual driving behaviour and goal management. Chapter 6 elaborates these reflections on the hierarchical model of the driving task (Michon, 1971, 1985).

However, the model does also provide insight into the hierarchical ordering of different types of tasks within driving. This hierarchy is an important aspect of goal-driven planning and execution of complex tasks, and resembles the way in which human cognition is modelled in a number of architectures (e.g., SOAR, see Lehman, Laird & Rosenbloom, 2006, and ACT-R, Anderson, 1995). Furthermore, different subtasks which bear resemblance in terms of their role within the overall driving task and the time frame involved in their execution are (theoretically) clustered within the different task levels. This clustering is useful for understanding the different types of tasks involved. Furthermore, the model does give insight, however limited, into the stages and durations related to certain driving subtasks and choices, into the fact that actions and external aspects influence each other, and (partly) into the role of expectations, unexpected situations, and compensatory actions.

We therefore conclude that the hierarchical model of the driving task (Michon, 1971, 1985) has a number of theoretical and practical shortcomings, although it is indeed a valuable model for the purpose of describing the complexities and the different types of subtasks that constitute the driving task. Its setup with interacting task levels and the notion that driving subtasks are hierarchically ordered are also valuable for understanding the hierarchical ways in which (driving) plans are created and executed with the help of feedback loops. However, in its current form, it is incomplete as a framework for a comprehensive model of the driving task.

7.4 Human-centred design of ADA Systems

When designing Advanced Driver Assistance (ADA) Systems, it is of the utmost importance to incorporate normal driving behaviour into the development process. This normal driving behaviour does not only cover driving behaviour in predictable circumstances in which drivers can have their complete focus on the driving task. It also concerns behaviour in unexpected situations, compensation effects, temporary or long-lasting changes in driving behaviour resulting from situational circumstances, and the interaction between multiple tasks.

A way to accomplish human-centred design is to ensure transparency of the system’s actions, dynamically adjusting to individual needs, and intelligibility of the operator’s role. Transparency means that the system’s responses to specific situations should be ‘understandable’ for drivers; mimicking drivers’ reactions or explaining before acting could support this goal. By adaptively reacting to the drivers’ current state, ADA Systems can give the best appropriate response. Mimicking the driver’s safety response in normal circumstances (increasing the response duration until some time after the actual event) is a way of responding to critical situations in a more human-like manner, and this might possibly lead to higher acceptance rates. Furthermore, drivers need to be made aware of the relative priority for handling and complying with the ADA System as compared to focusing on their normal driving tasks. And finally, a ‘tipping point’ exists for the impairing effects of increased mental workload. Studies into the effects of ADA Systems should therefore not only focus on possible increases or decreases of mental workload levels involved with using the system; they should also determine what effects the system has on task prioritization, distraction, and the overall traffic safety resulting from possible changes in driving behaviour.

With these recommendations and our findings on driver distraction and mental workload in mind, we proposed a promising direction for the development of safety-enhancing ADA Systems. The proposed direction for development could lead to a group of systems which could be given the generic name Distraction Avoidance Integrated System, DAISy for short. DAISy has the aim of enhancing drivers' safety during distracted driving in urban settings. Based on this thesis, five recommendations for this new direction of systems are made.

The first recommendation is to establish a safety zone around the vehicle with its boundaries set at safe distances, giving drivers enough time to counter a possible conflict. Secondly, when another object enters this safety zone, this thesis recommends that systems following the DAISy guidelines stop the input of non-vital systems and warn the driver. Thirdly, it is recommended to increase the safety boundaries when DAISy determines that mental workload is higher than normal, in order to accommodate the decreased attention. A fourth recommendation is to adjust the speed or (lateral) direction of the vehicle if the driver does not respond in a timely and appropriate manner, in order to avoid a conflict. Finally, Distraction Avoidance Integrated Systems could scan for moving objects in the part of drivers' visual field that overlap with the safety boundaries around the vehicle, such as pedestrians and bicyclists, when the workload estimator establishes elevated mental workload, which is often related to diminished attention for the peripheral visual field.

With the guidelines in this thesis taken into account, this new direction for development could adaptively lead to a group op generic systems which assist the driver in one of the most demanding driving situations: distracted driving in an urban setting.

7.5 Recommendations for further research

One of the aims of this thesis was to determine to what extent the hierarchical driving task model as proposed by Michon (1971, 1985) is suitable as a framework for a model describing and/ or predicting how drivers actually drive. Some findings support the postulation that compensation behaviour influences the directional influence driving task levels have, and that this change is temporary. However, there are some theoretical considerations that need clarification before the model can actually serve as such a framework. Firstly, it has not been fully determined whether separating the subtasks of driving into strictly divided tasks at different levels is an abstract theoretical intervention or a resemblance of actual driving behaviour. Secondly, if such a distinction would be viable, it remains unclear how related subtasks are connected between task levels and how they influence each other. It has also not been determined how other types of unexpected situations and their related compensation behaviour induce behavioural adaptation. Thirdly, interpretations of the classification of subtasks over the different levels have differed between researchers, and it remains unclear what the final classification of subtasks should be. And finally, the question whether and to what extent higher-order skills and attitudes, such as 'Goals for life and skills for living' (Hatakka et al., 2002), are a factor in the hierarchical task model, needs further consideration.

The human-centred design process of ADA Systems could benefit from more research on a number of issues raised in this thesis. Firstly, drivers appear to prioritize safe driving over distracting tasks when the combined task demands exceed a certain threshold. More research is needed to determine whether there exists one threshold that is fixed over drivers and/ or over time, or whether this is an individual and fluctuating threshold. Furthermore, the aspects determining such a threshold require further investigation. Secondly, we postulate that mimicking the drivers' longer-term safety response might lead to higher acceptance rates of in-vehicle support systems. However, this topic needs further investigation in order to establish the preferred timing and level of support given to drivers outside of direct conflict areas, and the optimal ratio between mental workload arising from warnings and acceptance resulting from 'understandable' reactions. Related to this is the question what exactly determines whether or not drivers find an unexpected or safety-critical situation risky, or are startled by them. Our study has shown that this can partly depend on circumstances of mental workload, but possibly also on external circumstances such as the number of previous risky encounters. Clear insight into drivers' perceptions of risk and the factors constituting this perception would help both human factors research and the human-centred design of ADA Systems. And finally, an integrated design with a focus on mental workload estimation and distraction avoidance determines which stimuli drivers receive at which point in time. This means that control is taken away from the driver to a certain level. Will this have an influence on drivers' acceptance levels of such a system, or do drivers prefer to remain in control of their own actions and timing of those actions? Further research should attempt to answer this question.

This study showed that behavioural adaptation to risky situations is influenced by the level of mental workload and by the extent to which drivers are actively engaged in driving. However, researchers still have not come to consensus on the ways in which this influence takes place and the underlying reasons for the behavioural adaptation. We recommend doing further research into the ways in which behavioural adaptation to risky situations (including the underlying reasons for this adaptation) is influenced by mental workload and task engagement.

Finally, driver distraction, mental workload, and the related concepts of task prioritization, automaticity, motivation and effort are important aspects of driving and 'hot topics' in human factors research. Our findings suggests that drivers might adopt different strategies for relieving extremely high levels of mental workload, for instance by driving in a habitualized or automatized manner. It is however not clear whether people actively decide to adopt a strategy for workload relieve, or that this is a reflexive, automatized response to high mental workload. More insight into the relationship between the different concepts could support human factors research in developing countermeasures and mitigating the negative and large impacts of driver distraction and driver overload on traffic safety.

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Appendices

A.1 Annotated code for the first experiment

Lead car starts at 20 metres in front of the participant's car, with initial speed of 20 km/h. Participant's car starts with initial speed of 0 km/h. Route for both participant and lead car is straight at each intersection (N=20 for each trial). Data recording and the PDT start when the participant reaches a speed of 1 km/h for the first time and stops when the participant stops at the last road section.

A1.1 Lead car's speed choice

Normal driving behaviour

```
Do {
        If (Part[MainTarget].DisToLeadCar <18)
[If headway is smaller than 18m, lead car will accelerate to participant's current speed plus 2 km/h]
        {       Part[PNr].Velocity := Part[MainTarget].velocity + 2/3.6;
        }
ElseIf (Part[PNr].DisToLeadCar >48)
[If headway is over larger than 48m, lead car will decelerate to participant's speed minus 3.5 km/h, or drive at 1 km/h if participant has stopped completely]
        {       Part[PNr].MaxVelocity := max(Part[MainTarget].Velocity – 3.5/3.6, 1);
        }
Else    [In all other situations, lead vehicle's desired speed is 50 km/h]
        {       Part[PNr].MaxVelocity := 50/3.6;
}
}
```

Sudden braking (2-BLC)

[At a certain location, i.e. Path Number 18 (directly after the 5th intersection) in trial 2-BLC, regular speed choice behaviour as described above is replaced by anticipation to the braking event. The lead car accelerates or decelerates with the aim of either decreasing or increasing headway to an average value for all participants.]

```
If (Part[MainTarget].PathNr = 18 and
Part[MainTarget].DisToInter > 250 and Part[MainTarget].DisToInter < 240)
        {       If (Part[MainTarget].DisToLeadCar < 18)
                        {       Part[PNr].Velocity := Part[MainTarget].Velocity + 6/3.6;
                        }
                ElseIf (Part[MainTarget].DisToLeadCar > 45)
                        {
Part[PNr].MaxVelocity :=
max(Part[MainTarget].velocity – 3.5/3.6, 1);
                        }
                }
```

[When the participant is driving at 240 metres before the intersection, the lead car starts to decelerate to 10% of the current speed; this deceleration loop could ultimately lead to a full stop. Deceleration continues unless the headway has reached either 14, 10 or 6 metres, related to the three urgency levels]

```
        ElseIf (Part[MainTarget].DisToleadCar > [14 / 10 / 6])
        {
                [Current speed is recorded and braking lights are turned on]
                Currentspeed := Part[PNr].Velocity;
                Part[PNr].Velocity := Currentspeed * 0.9;
                Part[PNr].Brakelight := On;
                [The time of the braking event is recorded, including the urgency level of the
                event]
                Proc(SetEventCode, [1/ 2/ 3]);
                }
        }
```

A1.2 Car from left (4-CfL)

```
[Between 140 and 150 metres before the 7th intersection in trial 4-CfL, a car is created and
placed at 80 metres before the intersection at the road section from the left]
When (Part[MainTarget].DisToInter < 150 and Part[MainTarget].DisToInter > 140;
PNr := CreatePart;
Part[PNr].DisToInter  := 80;

Do
  {
        If ( Part[MainTarget].PathNr = 26 and Part[MainTarget].DisToInter > [15/ 6/ 0] )
[If the participant is at the predefined location and drives at either 15, 6 or 0 metres from the
start of the intersection (related to the three urgency levels), the car from left accelerates]
        {
        [The left car's speed is adjusted so that the two vehicles will reach the intersection
        centre at the same time]
                If (Part[PNr].DisToInter > Part[MainTarget].DisToInter - 4)
                {       Part[PNr].MaxVelocity := Part[PNr].Velocity + 2/3.6;
                }
                ElseIf (Part[PNr].DisToInter < Part[MainTarget].DisToInter - 4)
                {       Part[PNr].MaxVelocity := max( 1, Part[PNr].Velocity - 2/3.6);
                }
                Else
                {       Part[PNr].Velocity := 50/3.6;
                }
        }
[When the participant reaches the intersection, accelerate left car and record event time and
urgency level]
        ElseIf(Part[MainTarget].PathNr = 26 and Part[PNr].OnInterPlane = False )
        {       Part[PNr].Velocity      := 45/3.6;
                Proc(SetEventCode, [1/2/3]);
        }
[Finally, when the participant has passed the intersection centre, end the event by stopping the
car from left]
        ElseIf(Part[MainTarget].PathNr = 26 and Part[MainTarget].DisToInter > - 8)
        {       Part[PNr].Velocity      := 1/3.6;
        }
}
```

A.2 Annotated code for the final experiment

Initialization of the second experiment was similar to the first experiment.

A2.2 Lead car

The section describes the lead vehicle's speed choice.

Normal driving behaviour

[The time headway is calculated as the distance between the centre of the lead car and the centre of the participant's car, divided by the participant's speed. This is possible since the roads at which the lead car's speed choice is regulated are all straight]

```
Define Function TimeHeadWay ( )
{
        TimeHeadWay := ((DisBetween(Part[MainTarget].PartNr, VoorLigger) –
(0.5 * Part[VoorLigger].CarLength) - (0.5 * Part[MainTarget].CarLength)) /
Part[MainTarget].Velocity);
}
```

[The lead vehicle slows down when the time headway is larger than 2.5 seconds and accelerates when the time headway is smaller than 0.8 seconds. The acceleration and deceleration rate are chosen randomly between boundaries.]

```
Do {
        If (TimeHeadWay <0.8)
        {       Part[Voorligger].Velocity := Part[Voorligger].Velocity + rnd(2,5)/3.6;
        }
ElseIf (TimeHeadWay>2.5)
        {       Part[Voorligger].MaxVelocity := Part[Voorligger].Velocity – rnd(2,5)/3.6);
        }
}
```

Sudden braking

[Between 100 and 45 metres from the sixth, seventh or eight intersection in three of the blocks, the speed choice behaviour as described above is replaced by a braking scenario. An event code (200) is recorded. Depending on the location within the experiment, a certain number of previous braking events is used as a condition for starting the braking scenario. The acceleration rate and distance headway after the event vary with urgency. After the braking event, another event code (201) is recorded, to indicate the end of the braking event.]

```
If (Part[Voorligger].PathNr => and Part[Voorligger].PathNr <=8 and
        45 < Part[Voorligger].DisToInter < 100 and < TimeHeadWay < 2.0 and
        1.0 NrRemactie < X)
        { Scen_RemmenVoorligger :=1;
        }
ElseIf (Part[Voorligger].PathNr = 9 and 80 < Part[Voorligger].DisToInter < 90 and
        NrRemactie < X)
        { Scen_RemmenVoorligger :=1;
        }
```

```
Define Action[0]
{
Var { a; }
Start
{
            When (Scen_RemmenVoorligger = 1);
            Part[VoorLigger].MaxDec := X; // varying with event urgency
            Part[VoorLigger].DumVar1 := Part[VoorLigger].MaxVelocity;
            Part[VoorLigger].DumVar2 := Part[VoorLigger].MaxAcc;
            Part[VoorLigger].MaxVelocity := 0;
            Part[VoorLigger].UseBrakeLight := On;
            ControlVoorligger := Off;
            Proc(SetEventCode, 200);
            NrRemactie := NrRemactie + 1;
      }
End
{
            When (TimeHeadWay() <= X or Action[].Duration > X );
            Scen_RemmenVoorligger := 0;
            Part[VoorLigger].UseBrakeLight := Off;
            Part[VoorLigger].MaxVelocity := 50/3.6;
            Part[VoorLigger].MaxAcc := 3.0;
            ControlVoorligger := True;
            Proc(SetEventCode, 201);
      }
```

B.1 Instructions for the first driving simulator experiment (in Dutch)

Hartelijk dank voor uw deelname aan het onderzoek “TRANSUMO” en welkom bij TNO. U gaat zo deelnemen aan een rijsimulator experiment. In dit experiment wordt uw normale rijgedrag gemeten. Het is dan ook van belang dat u rijdt zoals u normaal ook zou doen.

In dit experiment, dat in een stedelijke omgeving plaatsvindt, willen we graag uw normale rijgedrag meten op wegen en kruispunten waar de maximumsnelheid van 50 kilometer per uur geldt, en waar verkeer van rechts voorrang heeft. Het doel van dit experiment is om te bepalen op welk punt automobilisten ondersteuning in de auto kunnen gebruiken. Daarnaast wordt er in sommige ritten bij sommige proefpersonen iets aangepast in de omgeving, om te kijken wat dit voor invloed heeft op uw normale rijgedrag.

In een enkel geval zou ook een onverwachte situatie kunnen ontstaan op de weg. Het is ook in deze situaties van belang dat u rijdt zoals u normaal gesproken ook zou rijden.

Allereerst maakt u een korte introductierit. Deze is bedoeld om u vertrouwd te maken met de rijsimulator en de bediening ervan. Na een korte pauze zal u een aantal korte ritten rijden, waarna u steeds een vragenlijst invult. De ritten duren ongeveer 10 minuten, en het experiment zal in totaal ongeveer 2 uur duren. Tussen twee ritten heeft u steeds ongeveer 10 minuten de tijd voor een vragenlijst en een pauze.

Bedenkt u tijdens het rijden dat u in een rijsimulator rijdt, en niet in een gewone auto, hier moet u mogelijk even aan wennen in het begin. Daarom rijden we straks eerst een korte introductierit.

Het is belangrijk dat u het direct aan de proefleider doorgeeft als u zich draaierig, misselijk of anderszins vervelend voelt. U moet hier niet mee wachten, omdat het de resultaten van het experiment kan beïnvloeden en omdat de ervaring leert dat het vervelende gevoel niet overgaat als u doorrijdt. Bovendien kan het vaak snel onderdrukt worden door een korte pauze te nemen buiten de simulator.

Als u iets niet begrijpt, of vragen heeft over uw taak, kunt u deze voorafgaand aan het experiment en tijdens de pauzes stellen. Tijdens de ritten is er geen mogelijkheid om vragen te stellen. Vragen over het experiment en de uitkomsten kunt u naderhand aan de proefleider stellen.

B.2 Instructions for the final driving simulator experiment (in Dutch)

Hartelijk dank voor uw deelname aan het onderzoek "TRANSUMO – rijgedrag binnen de bebouwde kom" en welkom bij TNO. U gaat zo deelnemen aan een rijsimulator experiment. In dit experiment, dat in een stedelijke omgeving plaatsvindt, willen we graag uw normale rijgedrag meten op wegen en kruispunten waar de maximumsnelheid van 50 kilometer per uur geldt, en waar verkeer van rechts voorrang heeft. Het doel van dit experiment is om te bepalen op welk punt automobilisten ondersteuning in de auto kunnen gebruiken. Daarnaast vragen we u in twee van de drie delen van de rit een extra rekentaak uit te voeren, om te kijken wat dit voor invloed heeft op uw normale rijgedrag. Over deze extra taak krijgt u zo meteen meer uitleg.

Het is in het hele experiment van belang dat u rijdt zoals u normaal gesproken ook zou rijden.

Gedurende het experiment rijdt u vrijwel voortdurend in een stad, en er kunnen dus auto's uit verschillende richtingen komen. Zoals ook in een normale stad gebeurt het meestal dat u achter iemand rijdt die een andere snelheid aanhoudt dan u misschien gewend bent, we willen u vragen om geen ongevallen met tegenliggers te riskeren. In een enkel geval zou er een onverwachte situatie kunnen ontstaan op de weg. Het is ook in deze situaties van belang dat u rijdt zoals u normaal gesproken ook zou rijden.

Allereerst maakt u een korte introductierit. Deze is bedoeld om u vertrouwd te maken met de rijsimulator en de bediening ervan. Halverwege de introductierit krijgt u bovendien de mogelijkheid om met de rekentaak te oefenen. Na een korte pauze zult u twee keer een rit van ongeveer 20 minuten rijden, waarna u een vragenlijst invult over wat u van de rit vond en of u het moeilijk vond. Na de laatste vragenlijst is het experiment afgelopen.

Bedenk tijdens het rijden dat u in een rijsimulator rijdt, en niet in een gewone auto, hier moet u mogelijk even aan wennen in het begin. Daarom rijden we eerst de korte introductierit.
Het is belangrijk dat u het direct aan de proefleider doorgeeft als u zich draaierig, ziek of anderszins vervelend voelt, ook als dit al voorafgaand aan het experiment het geval is. U moet hier niet mee wachten, omdat het de resultaten van het experiment kan beïnvloeden en omdat het vervelende gevoel niet altijd overgaat als u doorrijdt. Bovendien kan het vaak snel onderdrukt worden door een korte pauze te nemen buiten de simulator. Uw vergoeding blijft uiteraard hetzelfde.

U krijgt tijdens het rijden een hoofdband om uw hoofd, met een klein lampje in uw linkerbovenhoek dat aan en uit gaat. Om uw vinger wordt een knopje geschoven dat u kunt indrukken tegen het stuur. Zodra het rode lampje aan gaat moet u dit knopje indrukken. Het is van belang dat u het autorijden niet ondergeschikt maakt aan het reageren op dit knopje, rijdt u dus normaal en laat u niet afleiden door het lampje. Met andere woorden: reageert u zo snel mogelijk, maar besteed er niet meer aandacht aan dan het autorijden toelaat. Ook in de rijsimulator is het van belang dat u zo veilig mogelijk naar uw bestemming rijdt.

Verder krijgt u een borstband om uw borst en elektrodes op uw schouder, borst en heup die uw hartslagfrequentie meten. Dit geeft extra informatie over hoe moeilijk u het vond om de rekentaak en het autorijden te combineren. De band en de elektrodes zijn veilig en hebben geen enkel effect op uw hartslag, ze meten alleen!

Zoals al eerder genoemd krijgt u tijdens delen van deze rit een extra taak. U moet hardop terugtellen vanaf 250 of 350 in stappen van bijvoorbeeld 6. Dit gaat ongeveer als volgt: 250, 244, 238,…etc. U geeft dus antwoord in de vorm van een cijferreeks. De proefleider zal aangeven wanneer deze taak begint en wat de taak precies inhoudt. Maakt u in de terugtelling een vergissing, dan zal de proefleider u het goede antwoord geven en kunt u vanaf dat punt doorgaan. Om te bepalen welke taak u krijgt zal de proefleider na de instructies een oefentaakje met u doen.

U kunt uw cijferreeks op normaal volume uitspreken in de auto, de antwoorden worden via een microfoontje aan de proefleider doorgegeven. U hoeft dus niet extra hard te praten. Het is wel van belang dat u zo snel mogelijk antwoord geeft. Maar ook hier geldt: veilig op uw bestemming aankomen is het allerbelangrijkste!

Mocht u tijdens de rit gedurende langere tijd stil moeten staan op de weg, dan moet het experiment opnieuw worden opgestart. Als u iets niet begrijpt, of vragen heeft over uw taak, kunt u deze voorafgaand aan het experiment stellen. Tijdens de uiteindelijke rit is er geen mogelijkheid om vragen te stellen. Vragen over de uitkomsten kunt u naderhand aan de proefleider stellen.

We gaan nu eerst een introductierit rijden. U kunt nu het proefpersonenformulier ondertekenen en aan de proefleider aangeven dat u klaar bent om te beginnen.

C.1 Questionnaire for the first driving simulator experiment (in Dutch)

U heeft zojuist een experiment binnen een stad gereden. Graag zouden wij uw mening horen over de omgeving waarin u heeft rondgereden, over het rijden in de rijsimulator en over opvallende zaken in het experiment. De vragenlijst bestaat uit drie korte delen. Beantwoordt u de vragen alstublieft zo eerlijk en volledig mogelijk. Aan het eind van de vragenlijst is er ruimte voor extra opmerkingen die niet bij de vragen aan de orde komen.

Deel A. Voor en na het experiment

1. Hoe voelde u zich voor aanvang van het experiment? Geef op onderstaande schaal aan welke term het beste bij uw gevoel past.

a.	Energiek	x	x	x	x	x	Vermoeid
b.	Gespannen	x	x	x	x	x	Ontspannen
c.	Ongezond	x	x	x	x	x	Gezond
d.	Draaierig	x	x	x	x	x	Niet draaierig
e.	Zeker	x	x	x	x	x	Onzeker
f.	Druk	x	x	x	x	x	Rustig

2. Hoe voelde u zich na het experiment? Geef op onderstaande schaal aan welke term het beste bij uw gevoel past.

a.	Energiek	x	x	x	x	x	Vermoeid
b.	Gespannen	x	x	x	x	x	Ontspannen
c.	Ongezond	x	x	x	x	x	Gezond
d.	Draaierig	x	x	x	x	x	Niet draaierig
e.	Zeker	x	x	x	x	x	Onzeker
f.	Druk	x	x	x	x	x	Rustig

Deel B. De omgeving

3. Wat vond u van de omgeving waarin u reed?

a.	Mooi	x	x	x	x	x	Lelijk
b.	Simpel	x	x	x	x	x	Complex
c.	Saai	x	x	x	x	x	Spannend
d.	Onverwacht	x	x	x	x	x	Voorspelbaar
e.	Groot	x	x	x	x	x	Klein
f.	Niet leuk	x	x	x	x	x	Leuk

4. Wat vond u van het andere verkeer dat in de stad rondreed?

a.	Mooi	x	x	x	x	x	Lelijk
b.	Simpel	x	x	x	x	x	Complex
c.	Saai	x	x	x	x	x	Spannend
d.	Onverwacht	x	x	x	x	x	Voorspelbaar
e.	Niet leuk	x	x	x	x	x	Leuk
f.	Veel verkeer	x	x	x	x	x	Weinig verkeer

Deel C. De rijtaak

5. Wat vond u van de taak, namelijk het rondrijden in de stad?

a.	Gemakkelijk	x	x	x	x	x	Moeilijk
b.	Saai	x	x	x	x	x	Spannend
c.	Onverwacht	x	x	x	x	x	Voorspelbaar
d.	Niet leuk	x	x	x	x	x	Leuk

6. Heeft u gereden zoals u normaal ook rijdt in de stad? Licht toe.

……………………………………………………………………………………

7. Wat vond u van het reageren op het rode lampje? Streep door wat niet van toepassing is.

Gemakkelijk / moeilijk

8. Had het reageren op het rode lampje invloed op uw rijgedrag? Licht toe.

……………………………………………………………………………………….

9. Is u verder nog iets opgevallen?

…..................................………………………………………………………………….

Two supplemental questions for participants driving with an additional task [4]

10. Wat vond u van de extra taak (oplossen van wiskundige sommen)? Streep door wat niet van toepassing is.

Gemakkelijk / moeilijk

11. Had de extra taak (het oplossen van wiskundige sommen) invloed op uw rijgedrag? Licht toe.

……………………………………………………………………………………….

[4] These two questions were only included in the questionnaires for participants driving with an additional task.

C.2 Questionnaire for the final driving simulator experiment (in Dutch)

U heeft zojuist een experiment binnen een stad gereden. Graag zouden wij uw mening horen over de omgeving waarin u heeft rondgereden, over het rijden in de rijsimulator en over opvallende zaken in het experiment. De vragenlijst bestaat uit drie korte delen. Beantwoordt u de vragen alstublieft zo eerlijk en volledig mogelijk. Aan het eind van de vragenlijst is er ruimte voor extra opmerkingen die niet bij de vragen aan de orde komen.

De vragen zijn als volgt geformuleerd:

Wat vond u van de omgeving waarin u reed?

Simpel X X X X X Complex

U geeft op deze vraag antwoord door 1 kruisje te omcirkelen. Als u de omgeving erg simpel vond ziet dat er dus als volgt uit:

Simpel (X) X X X X Complex

Dit doet u ook voor elke volgende term.

Op de volgende pagina staat de vragenlijst.

Deel A. Voor en na het experiment

1. Hoe voelde u zich voor aanvang van het experiment? Geef op onderstaande schaal aan welke term het beste bij uw gevoel past.

a.	Energiek	x	x	x	x	x	Vermoeid
b.	Gespannen	x	x	x	x	x	Ontspannen
c.	Ongezond	x	x	x	x	x	Gezond

2. Hoe voelde u zich na het experiment? Geef op onderstaande schaal aan welke term het beste bij uw gevoel past. Per term 1 cirkel aub.

a.	Energiek	x	x	x	x	x	Vermoeid
b.	Gespannen	x	x	x	x	x	Ontspannen
c.	Ongezond	x	x	x	x	x	Gezond

Deel B. De omgeving

3. Wat vond u van de omgeving waarin u reed? Per term 1 cirkel aub.

b.	Simpel	x	x	x	x	x	Complex
c.	Saai	x	x	x	x	x	Spannend
d.	Onverwacht	x	x	x	x	x	Voorspelbaar

4. Wat vond u van het andere verkeer dat in de stad rondreed?

b.	Simpel	x	x	x	x	x	Complex
c.	Saai	x	x	x	x	x	Spannend
d.	Onverwacht	x	x	x	x	x	Voorspelbaar

Deel C. De rijtaak

5. Wat vond u van de taak, namelijk het rondrijden in de stad?

a.	Gemakkelijk	x	x	x	x	x	Moeilijk
b.	Saai	x	x	x	x	x	Spannend
c.	Onverwacht	x	x	x	x	x	Voorspelbaar

6. Heeft u gereden zoals u normaal ook rijdt in de stad? Licht toe.

……………………………………………………………………………………

7. Wat vond u van de extra taak (het opzeggen van de getallenreeks)? Streep door wat niet van toepassing is.

Gemakkelijk / moeilijk

8. Had de extra taak (het opzeggen van een getallenreeks) invloed op uw rijgedrag? Licht toe.

…………………………………………………………………………………

9. Wat vond u van het reageren op het rode lampje? Streep door wat niet van toepassing is.

Gemakkelijk / moeilijk

10. Had het reageren op het rode lampje invloed op uw rijgedrag? Licht toe.

………………………………………………………………………………………….

11. Is u verder nog iets opgevallen?

…...................................……………………………………………………………….

Ruimte voor overige opmerkingen:

………………………………………………………………………………………….

D.1 Detailed results for the first driving simulator experiment

Average speed (km/h)

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	40.0272	36.4447	38.4956	47.6547	40.5308	36.6313
Drive 2	42.9976	41.2981	42.6361	46.5756	44.3816	38.1676
Drive 3	44.0543	41.7835	43.5687	48.5285	49.4622	40.4213
Drive 4	45.0749	41.6551	43.2550	49.9198	49.9196	41.2283

Standard deviation of speed

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	6.1896	7.2366	5.4484	4.9312	6.8453	7.0996
Drive 2	4.8579	5.2971	4.6944	2.9015	6.3802	5.6059
Drive 3	4.2443	5.5803	4.2973	3.1069	4.4477	5.7484
Drive 4	4.4444	5.5488	4.5319	3.6879	3.7123	5.3415

Average distance headway (m)

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	26.8089	31.7328	25.7831	21.5170	25.4200	30.0259
Drive 2	24.6346	27.0289	26.0952	19.4746	21.5375	29.7059
Drive 3	23.8055	26.2031	25.1392	20.2511	21.7155	27.0091
Drive 4	23.8276	26.1492	25.7449	20.5026	20.3937	27.7688

Standard deviation of distance headway

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	6.3629	6.9375	6.8906	5.0284	5.9945	5.5917
Drive 2	5.4193	7.2917	6.7266	3.9694	5.6076	9.9714
Drive 3	5.0528	7.1261	9.1333	4.1949	4.8643	5.1750
Drive 4	5.7263	7.7299	7.5491	4.0038	4.5986	6.1904

Percentage of time driven with minimum headway (< 19 m) (%)

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	18.6872	5.8906	20.6826	47.4637	13.2420	5.5783
Drive 2	25.5623	19.8430	20.4713	70.4058	52.3204	9.4258
Drive 3	32.8839	19.2405	21.6318	48.1464	44.0339	11.7270
Drive 4	34.1816	43.5169	24.7617	46.9346	56.1309	16.5987

Percentage of time driven with maximum headway (> 47 m) (%)

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	6.1700	8.6493	2.8733	0.7757	2.5139	4.9457
Drive 2	3.2061	4.1720	2.5285	0.2490	1.1268	4.3664
Drive 3	4.7287	2.6860	1.7503	0.3160	0.3677	2.3648
Drive 4	4.6911	2.2151	1.7184	0.6336	0.4797	3.7597

Average lateral position (m)

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	-0.1019	-0.4054	-0.2999	0.0610	0.2236	-0.0297
Drive 2	-0.1175	-0.4275	-0.4401	-0.0542	0.3553	-0.1580
Drive 3	-0.1617	-0.4609	-0.5188	0.0153	0.4053	-0.2315
Drive 4	-0.0333	-0.5020	-0.4900	-0.0063	0.3400	-0.0651

Standard deviation of lateral position

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	0.9116	0.9385	0.7941	0.7189	0.7808	0.5888
Drive 2	0.8516	0.8517	0.7066	0.6589	0.8847	0.7824
Drive 3	0.8879	0.9680	0.7700	0.6791	0.7935	0.7122
Drive 4	0.8546	0.9418	0.7346	0.6897	0.8569	0.6740

Average lateral acceleration (m/s2)

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	-0.0114	-0.0260	-0.0463	-0.0433	-0.0366	-0.0280
Drive 2	-0.0085	-0.0494	-0.0390	-0.0357	-0.0469	-0.0415
Drive 3	-0.0361	-0.0484	-0.0322	-0.0393	-0.0659	-0.0300
Drive 4	-0.0168	-0.0423	-0.0193	-0.0584	-0.0658	-0.0371

Standard deviation of lateral acceleration

	No additional workload			Additional workload		
	Mild	Medium	Hard	Mild	Medium	Hard
Drive 1	0.1766	0.1679	0.1955	0.2276	0.1903	0.1810
Drive 2	0.2035	0.2313	0.1800	0.1942	0.2058	0.1955
Drive 3	0.2055	0.2090	0.1968	0.1843	0.2381	0.1626
Drive 4	0.1956	0.2149	0.1755	0.2142	0.2459	0.1700

D.2 Detailed results for the final driving simulator experiment

Average speed (km/h)

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	45.9334	46.4391	46.3886	46.6158	47.5703	46.3886
Non-urgent	43.9211	46.9761	45.6634	44.5464	44.2937	45.1681
Urgent	44.3900	45.2015	45.0505	43.3707	45.2567	45.5729

Standard deviation of speed

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	7.1602	7.5770	7.9746	7.2320	5.9518	7.4191
Non-urgent	10.6011	10.2922	8.7699	8.7561	9.4101	9.0882
Urgent	10.7467	10.2165	10.7898	10.1710	10.3360	10.7645

Average distance headway (m)

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	19.3612	16.8121	15.6190	17.1448	13.9086	18.3930
Non-urgent	18.9422	12.4894	15.8229	18.1064	19.4994	15.7755
Urgent	15.5645	14.3004	15.8595	18.3320	15.1290	13.8030

Standard deviation of distance headway

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	5.9192	6.6664	5.7279	6.6324	4.7306	5.7677
Non-urgent	7.0873	4.4424	5.8361	6.4014	6.8784	5.9053
Urgent	5.9024	5.3289	5.6176	6.6269	5.8924	5.9527

Average time headway (s)

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	1.5533	1.3440	1.2558	1.3757	1.0599	1.4614
Non-urgent	1.6511	0.9917	1.2828	1.5010	1.6268	1.3151
Urgent	1.3412	1.2080	1.3526	1.5787	1.2674	1.1305

Standard deviation of time headway

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	0.5331	0.5730	0.5930	0.5963	0.3576	0.5113
Non-urgent	0.7730	0.3962	0.5281	0.5675	0.6309	0.5785
Urgent	0.6711	0.6959	0.6918	0.5940	0.6680	0.6575

Average lateral position (m)

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	-0.1228	-0.1093	-0.0657	-0.1249	-0.0964	-0.0729
Non-urgent	-0.0860	-0.0588	-0.0892	-0.1314	-0.0893	-0.0798
Urgent	-0.1261	-0.0996	-0.0879	-0.1426	-0.1313	-0.1260

Standard deviation of lateral position

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	0.1893	0.1760	0.1756	0.2177	0.1451	0.1625
Non-urgent	0.1933	0.1050	0.1566	0.1472	0.1300	0.1707
Urgent	0.1966	0.1234	0.1469	0.2010	0.1826	0.2012

Average PDT reaction time (ms)

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	476.7632	703.9293	721.1339	501.6523	646.8817	669.3837
Non-urgent	507.4741	634.30081	769.8309	539.0470	740.3438	773.8162
Urgent	451.4472	670.6519	648.4776	457.9257	630.5175	725.5185

Standard deviation of PDT reaction time

	Trial 1			Trial 2		
	Driving only	Easy task	Difficult task	Driving only	Easy task	Difficult task
No braking	231.0332	405.4883	392.1251	276.4681	363.7348	357.3102
Non-urgent	277.5164	307.4040	402.8719	289.9747	405.6547	411.9988
Urgent	284.8046	361.1798	378.0401	222.8776	357.8870	387.3518

Driving behaviour in unexpected situations: Summary

Driving can be very demanding, especially in an urban environment. The road network in cities is often more complex than outside these cities, and it hosts many different road users: cars, pedestrians, cyclists, busses, trams, et cetera. Advanced Driver Assistance (ADA) Systems may contribute to making driving safer, road use more efficient and the trip more comfortable. These systems support drivers in their driving task, preventing accidents by for instance warning drivers when exceeding the speed limit, or maintaining a safe distance to other road users. The development of ADA Systems is mainly technology-driven, but designers could also benefit from understanding what drivers need and how they interact with the technology, additionally allowing for human-centred development. For human-centred development of ADA Systems, it is crucial to understand driving behaviour both in normal circumstances and in reaction to unexpected and/ or dangerous situations. This thesis attempts to add new knowledge to what is already known about this by studying the ways in which people drive on urban roads.

A challenging aspect of driving in an urban environment is that drivers have to do many things at the same time: know where they are going and how to get there, watch their speed, take turns, press the gas pedal and the brake, et cetera. Understanding how people drive also entails understanding how these different subtasks are organized and handled. An influential model developed in the early seventies of the previous century (Michon, 1971) describes the structure and characteristics of the driving task. According to this model, the driving task consists of three hierarchically ordered layers of subtasks.
Strategic: concerned with trip goal and organization (e.g., destination, route, time planning, target speed),

- Tactical: related to interaction with the road and road users (e.g., making turns, overtaking, merging)
- Operational: concerned with operating the vehicle (e.g., braking, shifting gear, steering)

In normal driving, subtasks at one level are transferred top-down into subtasks at the nearest lower level.

Later Michon extended the model with bottom-up interaction between task levels, which supposedly occurs in reaction to unexpected situations (Michon, 1985). For instance, when a road is slippery and the car does not react normally to the steering wheel movements, regaining control over the car (operational) is temporarily much more important than taking the planned turn (tactical) or getting to the destination in time (strategic). This operational compensation can lead to changes at higher levels. Although the hierarchical model of the driving task (Michon, 1971, 1985) has been used by many to describe the structure of the driving task, research into this bottom-up influence between levels of the driving task is not widespread. We aim to extend the current knowledge with this thesis. In the remainder of this summary, the hierarchical model of the driving task (Michon, 1971, 1985) is referred to as 'the model' or 'the model of the driving task'.

The thesis focuses on the question how drivers react to unexpected situations in an urban environment, and the effects of external aspects such as event urgency and mental workload. This was examined in two large driving simulator experiments.

First experiment

The first large experiment tried to answer the question how people react to unexpected situations in an urban environment. In order to create these unexpected situations, it was first necessary to make sure that the participants had formed expectations about the situations to come. This experiment consisted of four drives, or trials, in each of which drivers crossed twenty intersections. Drivers were asked to go straight on each intersection. The traffic situations at all but two intersections looked very much alike. As a result of this repetition, drivers built expectations about the route to follow, the interactions with the other road users and the road, and how to respond to these repeating traffic situations. This showed in their driving behaviour and in their answers to questionnaires given to them after each trial.

At two out of the eighty intersections, something unexpected happened. In one situation, a car from a left side street suddenly accelerated onto the road; in the other, the lead car braked suddenly. The seriousness of these safety-critical situations was varied between participants by deceleration force and distance between the vehicles after the event. The experiment was made more demanding for half of the participants. Their mental workload was increased by having them perform a difficult arithmetic task (serial subtraction) out loud while driving. The driving simulator recorded the driving behaviour of the participants in terms of driving speed, distance to other road users and location on the road. Their mental workload was recorded using the Peripheral Detection Task.

The model of the driving task (Michon, 1971, 1985) predicts that drivers compensate for the unexpected situations at the operational level, and that this translates into a change in tactical subtasks. In other words, participants would have to switch from operational to tactical level in order to accurately brake or steer away to avoid an accident from happening, and this would temporarily lead to an adjusted driving style based on the type of compensation.

Unexpected situations and compensation behaviour

Participants indeed stated in the questionnaires that the trials with the unexpected situations were much less predictable than the regular trials, and their driving behaviour also included compensation behaviour to the unexpected situations. They would brake hard and would drive more to the outside of their lane during both unexpected situations. Furthermore, participants lowered their speed and increased the distance between them and the car in front of them for some time after that car had startled them by braking suddenly. In other words, they temporarily stayed in the tactical mode to drive more cautiously after encountering an unexpected braking event. A more critical braking situation temporarily led to a more cautious driving style than a less critical braking event, and was also accompanied by more active braking than less critical events.

The effects of mental workload

The most striking effects were seen in the effects of mental workload. Drivers with high mental workload decelerated less than regular drivers when approaching an intersection. Unlike drivers without elevated mental workload, they drove in their habitual style after the less serious situations, and only reacted to situations that were very critical or unsafe. And when they did respond, they initially reacted in the same cautious manner as did normal drivers, but fell back to their normal driving behaviour much faster than drivers who could completely focus on driving. Finally, drivers with high workload also drove more to the left (in)side of their lane. These results all suggest the same: that drivers with higher workload are more occupied with their additional task and therefore pay less attention to the traffic situation, which leads to a more habitual driving style. They also do not respond noticeably to mildly urgent situations. However, when an unexpected situation is “urgent enough”, its effect appears to come through more strongly in mentally loaded drivers than in regular drivers.

Final experiment

The first experiment revealed some highly interesting results, which led to a number of additional hypotheses about the effects of elevated mental workload on (the size and duration of) a change in driving style towards more defensive driving, and the effect of the urgency of safety-critical events. These additional hypotheses were tested in a final large driving simulator experiment.

This second experiment was adjusted as compared to the first experiment. The four trials of the first experiment were extended and combined into two drives consisting of three blocks of twenty intersections each. As described, the first experiment only contained difficult subtraction tasks to strongly elevate the mental workload of some of the drivers. To distinguish more specifically between the effects of different levels of mental workload, an additional level was added to the setup. All participants had to perform one easy and one difficult subtraction task while driving. They all encountered the same type of safety-critical event, a braking lead vehicle, and this happened three times in total for each participant. To keep the experiment manageable, only two levels of urgency were set for the events.

Behavioural adaptation to the suddenly braking lead car

It was found that drivers temporarily modified their speed after the sudden braking events, and that the urgency of the event did not affect this. When drivers could focus all of their attention on driving, they temporarily also increased the distance to the (sometimes suddenly braking) lead car. However, while they were focussing on their subtraction task (no matter how difficult or easy this task was), they did not take these precautions.

Task prioritization: keeping safe driving manageable

We found interesting differences in behavioural response to the varying levels of mental workload. The intermediate level of mental workload that was added to the setup of this experiment (easy subtraction task) gave rise to the largest effects on unsafe driving. Drivers with this easy subtraction task drove much closer to their predecessor than drivers that could focus all of their attention on driving. Driving with the difficult task resulted in a headway that remained in between these other two conditions. Drivers generally performed well on the easy subtraction task and much less on the difficult subtraction task (in terms of numbers of answers given and percentage of mistakes). This underperformance at the difficult subtraction task, combined with their safer driving behaviour when doing the difficult task, indicates that they dropped effort in the difficult task and prioritized safe driving over performing well on the secondary task. Earlier studies had already shown that drivers might prioritize safe driving over secondary tasks when instructed to (e.g., De Waard, 1996) and when the external tasks are not relevant for safe driving (Cnossen et al., 2004). In addition to these findings, our experiments show that drivers also give priority to safe driving over external secondary tasks when the combined task demands are too difficult to handle.

Additional conclusions

Having drawn conclusions from both individual experiments, we also looked at the combination of the two experiments and the related theory. This provided some additional conclusions on conscious driving versus automatic driving style, latent driver distraction, and the model of the driving task (Michon, 1971, 1985).

Conscious control versus driving in an automatic fashion

With sufficient experience, some daily multi-tasking activities can be performed in an automatic, habitual fashion, although they might sometimes still require conscious attention. This is also the case with driving. Performing (sub)tasks in an automatic manner may allow drivers to save attentional/ mental resources and become less tired. However, there always needs to be a good balance between automaticity and conscious control.

Drivers were found to pay less attention to certain crucial aspects of the driving task and drive in a more habitual manner when they are cognitively loaded. If any driver, cognitively loaded or not, faces an unexpected and safety-critical situation while driving in such an automatic manner, he or she should switch back to a more conscious control for the sake of safety. Our results show that drivers with increased mental workload are highly reluctant to drop their habitual driving style. If they do finally change their driving style, it is only when the situation is highly safety-critical and urgent, and their cautionary response also lasts shorter than a response of normal drivers. Apparently it takes more to get people with high mental workload to abandon their automatic driving style and return to conscious driving than it does for people with normal workload. A certain reluctance to totally drop all effort in the secondary task was noticeable in our experiments, which mimics everyday situations such as drivers on their (mobile) phone. The experiments also showed that the switch from automatized performance to conscious control is mostly restricted to tactical driving tasks, and occurs less in (generally highly automatized) operational subtasks.

Latent driver distraction

According to its definition, driver distraction occurs when there is a secondary task or activity which is given attention by the driver, through which driving performance diminishes.

Traditionally, safety was determined by measuring the level of safety of the current situation, for instance by using surrogate safety measures. However, this neglects the fact that being able to respond to an upcoming safety hazard is also a part of safe driving. This thesis therefore introduces the concept of latent driver distraction, a form of driver distraction that does not materialize in directly measurable unsafe driving behaviour, but does impair an adequate response to upcoming safety hazards. We propose using the Peripheral Detection Task to assess this readiness to respond and thus latent distraction.

Reflections on the model of the driving task (Michon, 1971, 1985)

Our experiments confirm the premise of the model of the driving task (Michon, 1971, 1985) that top-down interaction between task levels temporarily changes into bottom-up interaction as a result of compensation for unexpected and safety-critical situations. However, it has not been established what exactly constitutes these unexpected situations and how unexpected or safety-critical these situations need to be. Our conclusions emphasize the relevance of this factor.

Some of our results indicate that the model can be extended when it comes to the impact of conscious attention on the part of the driver. If drivers focus on other things than safe driving, bottom-up interaction occurs only in response to highly dangerous situations in contrast to when drivers do pay full attention to driving. Additionally we found that the duration of this behavioural change is dependent on the level of mental workload that drivers have in such dual-task situations.

In addition to describing the driving task, the model was initially also proposed as a framework for a comprehensive driver model including cognition (Michon, 1985). A few comments can be made about using the model for this purpose. Researchers have to this point not agreed on the ways in which subtasks should be classified over the different task levels, and some subtasks seem to belong to more than one task level (e.g., speed control). Moreover, motivations and characteristics of drivers are not included in the model but do play a large role in the way people perform their driving task. Some researchers have therefore suggested adding a fourth level to the model, containing ‘goals for life and skills for living’ (Hatakka et al., 2002). In addition to this, it remains unclear how related subtasks are connected between task levels and how they influence each other.

We therefore conclude that the hierarchical model of the driving task (Michon, 1971, 1985), at this point only partly describes how people drive. A a framework for a comprehensive model of driving behaviour, the model of the driving task is incomplete for the time being. However, with the aforementioned additions, the model still remains valuable for describing both the driving task itself and its complexity.

Rijgedrag in onverwachte situaties: Samenvatting

Autorijden kan erg veeleisend zijn, met name in een stedelijke omgeving. Het stedelijke weggennet is complex en er zijn veel verschillende typen weggebruikers: auto's, fietsen, bussen, trams, et cetera. Geavanceerde bestuurdersondersteunende systemen, ook wel *Advanced Driver Assistance* (ADA) Systemen genoemd, zouden een bijdrage kunnen leveren om autorijden veiliger te maken, de weg efficiënter te benutten en de reis comfortabeler te maken. Deze systemen ondersteunen autobestuurders in hun rijtaak, waarbij ze aanrijdingen voorkomen door bijvoorbeeld een waarschuwing te geven als bestuurders te hard rijden of een veilige afstand tot andere weggebruikers aan te houden. De ontwikkeling van ADA Systemen wordt voornamelijk gestimuleerd door ontwikkelingen in de technologie. Indien ontwerpers van deze ADA Systemen zouden begrijpen wat bestuurders nodig hebben en hoe ze met de technologie omgaan, zou de gebruikersgerichte ontwikkeling van de systemen hiervan kunnen profiteren. Voor een gebruikersgerichte ontwikkeling is het cruciaal om te weten hoe mensen rijden, zowel in normale omstandigheden als in reactie op gevaarlijke en/ of onverwachte verkeerssituaties. Dit proefschrift doet een poging kennis toe te voegen aan wat al bekend is over deze gebruikersgerichte ontwikkeling van ADA systemen, door te bestuderen hoe mensen op stedelijke wegen rijden.

Een uitdagend aspect van autorijden in een stedelijke omgeving is dat bestuurders veel dingen tegelijk moeten doen. Ze moeten weten waar ze zijn, waar ze naartoe gaan en hoe ze daar moeten komen, hun snelheid in de gaten houden, de juiste afslag nemen, het gaspedaal en de rem bedienen, et cetera. Begrip over hoe mensen rijden vindt mede zijn basis in kennis over de organisatie en uitvoering van deze verschillende soorten subtaken. In de jaren '70 is er een invloedrijk model voorgesteld dat de structuur en een aantal eigenschappen van de rijtaak omschrijft (Michon, 1971). Volgens dit model bestaat de rijtaak uit drie hiërarchisch geordende niveaus van subtaken:

- Strategisch: heeft betrekking op doel en organisatie van de reis (bijvoorbeeld bepalen van bestemming, route, en doelsnelheid)
- Tactisch: heeft betrekking op de interactie met de weg en andere weggebruikers (bijvoorbeeld een afslag nemen, inhalen, invoegen)
- Operationeel: heeft betrekking op het besturen van het voertuig (bijvoorbeeld remmen, schakelen, sturen)

Bij normaal autorijden worden subtaken op een bepaald niveau top-down doorvertaald naar taken op het dichtstbijzijnde lager gelegen niveau.

Michon breidde het model later uit met bottom-up interactie tussen de taakniveaus, hetgeen volgens de verwachting zou gebeuren in reactie op onverwachte situaties (Michon, 1985). Als een weg bijvoorbeeld glad is en de auto niet normaal reageert op de stuurbewegingen, is het tijdelijk veel belangrijker om weer controle over de auto te krijgen (operationeel) dan om de geplande afslag te nemen (tactisch) of om op tijd op de bestemming aan te komen (strategisch). Deze operationele compensatie kan leiden tot veranderingen op hogere taakniveaus. Hoewel het model veelvuldig toegepast wordt om de structuur van de rijtaak te omschrijven, is er nog geen uitgebreid onderzoek gedaan naar deze bottom-up invloed tussen de taakniveaus van de rijtaak. Dit proefschrift doet een poging de huidige stand van kennis hierover uit te breiden. In de rest van deze samenvatting noemen we dit model het model van de rijtaak.

Dit proefschrift richt zich op de vraag hoe bestuurders reageren op onverwachte situaties in de stad, en welke effecten externe aspecten, zoals mentale werkbelasting en de ernst van de onverwachte situatie, hierop hebben. Dit is onderzocht aan de hand van twee grote rijsimulator experimenten.

Eerste experiment

Het eerste grote rijsimulator experiment was bedoeld om een antwoord te vinden op de vraag hoe mensen reageren op onverwachte verkeerssituaties in de stad. Om ervoor te zorgen dat er onverwachte situaties ontstonden, moesten we eerst zorgen dat proefpersonen verwachtingen vormden over de situaties waarin zij reden. Dit experiment bestond uit vier ritten waarin elke keer twintig kruispunten na elkaar werden overgestoken. Aan de deelnemers werd gevraagd om elke kruispunt rechtdoor over te steken. Op twee na leken alle tachtig kruispunten sterk op elkaar. Door deze herhaling bouwden de deelnemers verwachtingen op over de te volgen route, de interacties met de andere weggebruikers en de weg, en over hoe te reageren op deze zich herhalende situaties. Dit bleek in hun rijgedrag en in de antwoorden die ze gaven op de vragenlijst die na elke rit aan ze werd gegeven.

Op twee van de tachtig kruispunten gebeurde iets onverwachts. In de ene situatie trok een auto uit een linker zijstraat snel op en reed de weg op; in de andere remde de voorligger plotseling hard. De ernst van deze situaties werd tussen proefpersonen gevarieerd. Het experiment werd voor de helft van de proefpersonen nog moeilijker gemaakt. Hun mentale werkbelasting werd verhoogd doordat ze hardop ingewikkelde rekensommen moesten maken (herhaald een getal van een ander groot getal aftrekken). De rijsimulator registreerde het rijgedrag van de proefpersonen: hun rijsnelheid, afstand tot andere weggebruikers en locatie op de weg. De mentale werkbelasting werd gemeten met behulp van de Perifere Detectie Taak.

Het model van de rijtaak (Michon, 1971, 1985) voorspelt dat bestuurders op operationeel niveau compenseren voor de omschreven onverwachte situaties, en dat dit zich zou doorvertalen naar een verandering in tactische subtaken. In andere woorden, proefpersonen moesten de operationele taken laten doorwerken in de tactische rijtaken om op een zodanige manier te remmen of weg te sturen dat ze een aanrijding zouden voorkomen, en dit zou zich tijdelijk vertalen in een aangepaste rijstijl, afhankelijk van het type compensatie-acties.

Onverwachte situaties en compensatie gedrag

Proefpersonen gaven inderdaad aan dat ze de ritten met de onverwachte situaties een stuk minder voorspelbaar vonden dan de normale ritten. Hun rijgedrag liet ook zien dat ze compenseerden voor de onverwachte situaties. Ze remden hard en reden meer aan de buitenkant van hun rijbaan tijdens beide onverwachte situaties. Na de plotselinge remactie van de voorligger pasten de proefpersonen bovendien tijdelijk hun snelheid naar beneden aan en lieten ze een grotere afstand tussen henzelf en de auto voor hen bestaan. Met andere woorden, ze bleven tijdelijk voorzichtiger rijden na deze onverwachte situatie. Na een ernstiger situatie reden mensen nog voorzichtiger dan na een minder ernstige situatie, en bovendien remden bestuurders dan ook vaker.

De effecten van mentale werkbelasting

De opvallendste resultaten waren te zien bij de effecten van mentale werkbelasting. Bestuurders die een hoge mentale werkbelasting hadden remden minder af als ze een kruispunt naderden dan normale bestuurders. Anders dan bestuurders die met normale werkbelasting reden, bleven ze na minder ernstige situaties met deze uit gewenning ontstane rijstijl rijden, en ze reageerden alleen op situaties die erg kritiek of onveilig waren. En als ze toch reageerden deden ze dat initieel wel op dezelfde voorzichtige manier als gewone bestuurders, maar vielen ze sneller weer terug naar hun eerste rijstijl dan diezelfde normale bestuurders. Ten slotte bleek ook dat bestuurders met hoge mentale werklast meer aan de linker (binnen)kant van hun rijbaan reden. Deze resultaten wijzen allemaal in dezelfde richting: dat bestuurders die een hoge mentale werkbelasting hebben mentaal bezig zijn met de belastende taak en hun rijstijl meer op gewenning baseren omdat ze hun aandacht aan andere zaken dan autorijden en hun directe omgeving besteden. Ze reageren ook niet zichtbaar op situaties die niet erg kritiek zijn. Als een onverwachte situatie echter "onveilig genoeg" is, lijkt het effect daarvan echter toch door te dringen, en zelfs sterker dan bij autobestuurders die geen hoge mentale werklast hebben.

Tweede experiment

Het eerste experiment leverde enkele zeer interessante resultaten op, die leidden tot een aantal hypotheses over de effecten van verhoogde mentale werkbelasting op (de grootte en duur van) een voorzichtiger rijstijl, en de effecten van de ernst van een onveilige situatie. Deze aanvullende hypotheses zijn vervolgens getest in een tweede uitgebreid rijsimulator experiment.

De opzet van dit uiteindelijke experiment werd aangepast ten opzichte van het eerste experiment. De vier ritten uit het eerste experiment werden uitgebreid en gecombineerd tot twee ritten, bestaand uit drie delen met elk twintig kruispunten. Zoals omschreven bevatte het eerste experiment alleen een moeilijk taakniveau voor de rekentaak. Om onderscheid te kunnen maken tussen de effecten van verschillende niveaus van mentale werkbelasting werd een extra moeilijkheidsniveau toegevoegd aan de opzet. Proefpersonen moesten nu een gemakkelijke en een moeilijke rekentaak uitvoeren in elke rit. Ze kwamen nu allemaal dezelfde onverwachte situatie tegen, namelijk een plotseling remmende voorligger, en dit gebeurde in totaal drie keer voor elke deelnemer. Om het experiment beheersbaar te houden werd er gekozen voor twee vaste niveaus van ernst voor alle gebeurtenissen.

Gedragsaanpassing na de plotseling remmende voorligger

Uit de resultaten bleek dat deelnemers tijdelijk hun snelheid aanpasten na de plotselinge remsituaties, en dat de ernst van de situaties hierop geen effect hadden. Als bestuurders hun volledige aandacht op het autorijden konden richten lieten ze ook tijdelijk wat meer afstand tussen henzelf en de auto voor hen (die dus af en toe plotseling remde) vallen. Als ze echter een rekentaak moesten uitvoeren, ongeacht hoe moeilijk deze taak was, namen ze deze voorzorgsmaatregelen niet.

Prioriteren van taken: hanteerbaar houden van veilig rijden

We ontdekten in onze resultaten een aantal interessante verschillen in gedrag tussen de verschillende niveaus van mentale werkbelasting. Het middelste niveau van mentale werklast dat was toegevoegd aan de experimentele opzet ten opzichte van het eerste experiment (gemakkelijke rekentaak) bleek de grootste effecten op onveilig rijgedrag te hebben. Deelnemers met deze gemakkelijke rekentaak reden veel dichter bij hun voorligger dan deelnemers die zich volledig op het autorijden konden richten. Autorijden met de moeilijke rekentaak leidde er toe dat deelnemers een afstand aanhielden die het midden hield tussen volledig gefocust autorijden en autorijden met de gemakkelijke rekentaak. Over het algemeen presteerden de autobestuurders goed op de gemakkelijke rekentaak en een stuk slechter op de moeilijke rekentaak (gemeten als het aantal gegeven antwoorden en het percentage gemaakte fouten). Deze onderprestatie op de moeilijke extra taak, gecombineerd met het feit dat ze met die moeilijke taak veiliger reden dan met de gemakkelijke taak waar ze beter op presteerden, wijst er op dat ze minder energie stopten in het uitvoeren van hun moeilijke rekentaak en veilig autorijden ten koste lieten gaan van hun prestatie op die extra taak. Uit eerdere studies was al gebleken dat autobestuurders veilig autorijden boven externe taken laten gaan als ze daartoe geïnstrueerd worden (De Waard, 1996) en als de externe taak niet relevant is voor veilig autorijden (Cnossen et al., 2004). In aanvulling hierop hebben onze experimenten aangetoond dat autobestuurders ook voorrang geven aan veilig rijden boven het uitvoeren van een externe taak indien de taken samen te moeilijke worden om te hanteren.

Aanvullende conclusies

We hebben onze conclusies niet slechts gebaseerd op de resultaten van de afzonderlijke experimenten, maar hebben ook gekeken naar de combinatie van beide experimenten en de theorie die er achter zit. Dit leverde een aantal aanvullende conclusies op, over aandacht voor het rijden tegenover autorijden uit gewenning, over latente afleiding tijdens het rijden, en over het model van de rijtaak (Michon, 1971, 1985).

Bewuste controle versus automatisch rijgedrag

Met voldoende oefening kan een groot aantal dagelijkse bezigheden die uit meerdere handelingen bestaan vrijwel automatisch worden uitgevoerd, terwijl andere handelingen bewust aandacht nodig hebben. Dit geldt ook voor autorijden. Taken uitvoeren op een automatische manier kan er voor zorgen dat bestuurders minder mentale capaciteit gebruiken en minder vermoeid worden. Er moet echter altijd een goede balans blijven tussen automatisch gedrag en bewuste controle.

We vonden in onze resultaten dat bestuurders de neiging hebben om minder aandacht te besteden aan bepaalde cruciale rijtaken en meer gewoontegedreven rijgedrag vertoonden als ze mentaal belast zijn. Voor elke bestuurder, cognitief belast of niet, geldt dat het aan te bevelen is om bewuster de controle over de rijtaak te nemen wanneer er een onverwachte, gevaarlijke situatie gebeurt, om zo de situatie veilig en efficiënt af te handelen. Onze resultaten laten zien dat bestuurders met verhoogde mentale werkbelasting hun gewoontegedrag niet snel loslaten. Als zij hun rijstijl dan uiteindelijk veranderen, is dat alleen bij een situatie die zeer kritiek en urgent is, en hun voorzichtige reactie duurt ook korter dan als ze niet mentaal belast zouden zijn. Blijkbaar vergt het nog meer van mensen met een hoge mentale werkbelasting om hun automatische rijstijl om te zetten naar bewust autorijden dan het vraagt van mensen die niet mentaal belast zijn. Onze experimenten lieten zien dat mensen niet erg geneigd zijn om helemaal geen energie meer in de extra taak te steken. Dit lijkt overeen te komen met hoe het gaat in echte situaties, zoals wanneer bestuurders (mobiel) aan het bellen zijn. Ten slotte laten de experimenten ook zien dat de overgang van rijden op de automatische piloot naar bewuste controle met name voorbehouden is aan tactische rijtaken, en minder voorkomt in (over het algemeen zeer sterk geautomatiseerde) operationele taken.

Latente afleiding tijdens het rijden

Volgens de definitie ontstaat afleiding tijdens het rijden wanneer er een externe taak of activiteit is die aandacht krijgt van de bestuurder, waardoor de bestuurder minder goed gaat rijden. Traditioneel werd er bij het vaststellen van of de bestuurder minder goed reed gekeken naar de veiligheid van de huidige situatie. Dit laat echter buiten beschouwing dat een onderdeel van veilig autorijden ook is om veilig te reageren op een mogelijke gevaarlijke situatie. Dit proefschrift introduceert daarom een nieuw concept, latente afleiding tijdens het rijden, een vorm van afleiding die niet direct meetbaar tot uiting komt in onveilig rijden maar in een beperkte mogelijkheid om adequaat te reageren op een mogelijke gevaarlijke situatie. We stellen voor om de Perifere Detectie Taak te gebruiken voor het vaststellen van deze mogelijkheid om te reageren, en dus van latente afleiding tijdens het rijden.

Het hiërarchische model van de rijtaak (Michon, 1971, 1985)

Onze resultaten bevestigen de premisse van het model van de rijtaak (Michon, 1971, 1985) dat top-down interactie tussen taakniveaus tijdelijk verandert naar bottom-up interactie wanneer een bestuurder moet compenseren voor een onverwachte situatie. Het is echter nog niet duidelijk wat precies de bepalende factoren zijn van deze onverwachte situaties, en hoe onverwacht ze dienen te zijn om dit effect te hebben. Onze conclusies benadrukken de relevantie van deze factor.

Enkele van onze resultaten wijzen er op dat het model van de rijtaak uitgebreid kan worden waar het gaat om de impact van bewuste aandacht van de bestuurder. Wanneer bestuurders bezig zijn met andere dingen dan veilig rijden ontstaat bottom-up interactie alleen bij zeer ernstige situaties, in tegenstelling tot normale bestuurders. Hoe lang deze wijziging duurt is afhankelijk van het niveau van mentale werkbelasting van de bestuurder in dit soort dubbeltaaksituaties.

Behalve het omschrijven van de rijtaak was het model initieel ook bedoeld als raamwerk voor een allesomvattend model van hoe mensen autorijden (Michon, 1985). Een aantal opmerkingen hierover is op zijn plaats. Om te beginnen zijn wetenschappers het niet eens over hoe de verschillende subtaken over de taakniveaus verdeeld moeten worden, en lijken sommige taken binnen meer dan één taakniveau thuis te horen (bijvoorbeeld snelheidsgedrag). Bovendien spelen motivaties en eigenschappen van autobestuurders in de praktijk een grote rol in hoe ze rijden, maar zijn deze niet opgenomen in het model. Het is daarom door anderen voorgesteld om een extra niveau bovenop het strategische niveau toe te voegen, dat 'Levensdoelen en lange termijn vaardigheden' omvat (Hatakka et al., 2002). Daarnaast is het nog niet duidelijk hoe vergelijkbare taken tussen verschillende taakniveaus verbonden zijn en door elkaar beïnvloed worden.

We concluderen daarom dat het hiërarchische model van de rijtaak (Michon, 1971, 1985) in de huidige staat slechts ten dele omschrijft hoe mensen autorijden. Het model is bovendien in zijn huidige staat een incompleet raamwerk voor een allesomvattend model. Met de toevoegingen aan het model die in het proefschrift zijn voorgesteld kan het model wel waardevol zijn in het omschrijven van de rijtaak en zijn complexiteit.

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Nina
Den Haag, december 2011

About the Author

Trijntje Willemien (Nina) Schaap was born in Leeuwarden, the Netherlands, on August 3 1979. She graduated from the Stedelijk Gymnasium in Leeuwarden in 1997 (pre-university degree) on a combination of nine subjects including exact sciences, Latin, and Philosophy. In 1998 Nina started her academic education at the University of Groningen with a propaedeutic year in Psychology. She then went on to study Cognitive Science and Engineering and took the opportunity to take extracurricular courses in Philosophy of Science (University of Groningen) and Ethics (VU University Amsterdam).

During her time in university, Nina was an active member of multiple student associations. As a member of the debating society 'Current Affairs' (Actualiteiten), part of the Dutch United Nations Student Association, she organized a number of debates on international relations. She was also the initiator and chair of the organizing committee for a career event on development cooperation, 'Develop Your World', which has since been repeated successfully every year. Furthermore, Nina was a teaching assistant for six courses, among others on Human Development & Adolescence, Observation Techniques, and Interview Techniques.

Nina obtained her Master's degree in 2005. Her Master's thesis focused on visual searching strategies and resulted in a newly developed layout for mobile telephone keyboards. Later that year, Nina joined the Centre for Transport Studies (University of Twente) as a Ph.D. candidate. She conducted her research as a part of Knowledge centre AIDA (Applications of Intelligent Driver Assistance), a cooperation between the Centre for Transport Studies and the Netherlands Organization for Applied Scientific Research (TNO). Nina was awarded two prizes for her scientific work, and was nominated for two other awards. In addition to her research work, she reviewed international conference papers, gave lectures at AIDA courses, and supervised Bachelor and Master students.

Since August 2010, Nina is employed by the Netherlands Institute for Transport Policy Analysis (KiM) in The Hague. As an independent institute within the Ministry of Infrastructure and the Environment, KiM carries out transport policy studies and analyses which are used to strengthen the strategic knowledge base for policy-making. Nina participates in studies concerning behavioural aspects of mobility.

Although she greatly enjoys her professional life, Nina also has other interests. She loves spending time with family and friends, discussing ethical issues, playing board games, and watching The West Wing on DVD, as well as exploring foreign cuisines and having new culinary experiences. She lives together with her partner Roel in The Hague, and they are planning their wedding.

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Summary

Do car drivers change their driving style after compensating for safety-critical events? What are the effects of mental workload? And how do drivers prioritize their driving (sub)tasks? This thesis aims to answer these questions by describing two large driving simulator experiments. The results show that drivers temporarily change their driving style after a safety-critical event; the duration of this change is affected by mental workload level. Drivers with increased mental workload drive less cautiously and respond only to highly safety-critical events, but they do prioritize safe driving when this workload gets too high.

About the Author

T.W. (Nina) Schaap performed her doctoral research within Knowledge centre AIDA, a cooperation between the Centre for Transport Studies at the University of Twente and TNO. She is currently employed by the Netherlands Institute for Transport Policy Analysis (KiM), where she is involved in studies concerned with mobility behaviour. Nina holds a Master's degree in Cognitive Science and Engineering from the University of Groningen.

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