THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNDERSTANDING ATTENTION SELECTION IN DRIVING

FROM LIMITED CAPACITY TO ADAPTIVE BEHAVIOUR

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Understanding attention selection in driving: From limited capacity to adaptive behaviour

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Abstract

Accident analysis studies have consistently identified attention-related failures as key factors behind road crashes. However, less is known about *how* such failures lead to accidents. Traditionally, one reason for this knowledge gap has been a lack of sufficiently detailed data from the pre-crash phase, although this situation is currently changing with the advent of naturalistic driving studies. However, a remaining issue is the lack of an adequate conceptual model of attention selection applicable in natural driving situations. Existing attention models applied in the driving domain are generally based on the notion of attention as a resource with limited capacity, subject to overload in demanding conditions. Such models have mainly focused on dual task interference in experimental situations and but have put less emphasis on aspects central to attention selection in everyday driving such as expectancy and anticipatory attention allocation. The general objective of the present thesis was to obtain a better understanding of the relation between attention, performance and crash risk in real driving situations. To this end, a general conceptual framework for understanding attention selection in natural driving was developed, based on the view of attention selection as a form of adaptive behaviour rather than a consequence of limited information processing capacity. This also involved the development of a specific model of attention selection mechanisms and a series of empirical studies to support the model development. The main objective of these studies was to better understand the effects of working memory (or cognitive-) load on driving performance and the key mechanisms behind expectancy and proactive attention scheduling in driving. A key finding was that working memory load appears to selectively affect aspects of driving performance that can be characterised as *controlled*, while leaving reflexive and habitual, *automatic*, behaviours largely unaffected, an idea that resolves several inconsistent findings in the existing literature. Based on the proposed model, precise definitions of attention, expectancy, driver inattention and driver distraction were proposed. The thesis also suggests a general conceptualisation of the relation between attention selection and crashes. Finally, practical applications of the present findings in the areas of accident and incident analysis, countermeasure development and evaluation methods are discussed.

Keywords: Attention, adaptive driver behaviour, driving performance, expectancy, accident analysis, working memory load, driver distraction

List of papers

Paper I: Engström, J., Johansson, E. & Östlund, J. 2005. Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research, Part F,* 8, 97-120.

Contribution: *The experimental design and planning was worked out jointly with other partners in the HASTE project. Engström conducted the statistical analysis of the driving performance and eye movement data from the fixed-base simulator study and wrote the paper.*

Paper II: Engström, J., Ljung Aust, M. & Viström, M. 2010. Effects of working memory load and repeated scenario exposure on emergency braking performance. *Human Factors,* 52(5), 551-559.

Contribution: *The study was designed and planned by Engström, Ljung Aust and Viström. Engström conducted all quantitative data reduction and statistical analysis and wrote the paper*

Paper III: Engström, J., Ljung Aust, M., Viström, M. & Malta, L. submitted. Effects of working memory load on automatic and controlled performance. Submitted to *Journal of Experimental Psychology: Applied.*

Contribution: *The study was designed and planned by Engström, Ljung Aust and Viström. Engström carried out part of the quantitative data reduction, conducted all statistical analysis and wrote the paper.*

Paper IV: Engström, J., & Ljung Aust, M. 2011. Adaptive behavior in the simulator: Implications for active safety system evaluation. In D. Fisher, M. Rizzo, J. Lee & J. Caird (Eds.) *Handbook of Driving Simulation for Engineering, Medicine and Psychology* . Boca Raton: CRC Press.

Contribution: *The basic ideas behind the proposed theoretical framework were worked out jointly by Engström and Ljung Aust. Engström wrote the chapter.*

Paper V: Engström, J., Victor, T. & Markkula, G. in press. Attention selection and multitasking in everyday driving: A conceptual model. To appear in M.A Regan, T.W. Victor and J.D. Lee (Eds.) *Driver Distraction and Inattention: Advances in Research and Countermeasures*. Ashgate.

Contribution: *Engström worked out the main ideas behind the model and wrote the chapter.*

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1 Introduction

Imagine a truck driver on busy arterial on his way to deliver goods at a grocery store in the city centre, a route that he travels several times every week. He is involved in an intense conversation on the phone and needs to change lane to the right in order to exit the road. He looks in the rear-view mirror to check for potential traffic approaching from behind. Meanwhile, a traffic queue has rapidly built up ahead and when our driver looks back to the road, he finds himself crashing into the queue.

How can we understand the chain of events that led to this crash, and the mechanisms involved? One key issue is why the driver decided to take the eyes off the road at this inopportune moment. Did the fact that he has travelled this route hundreds of times, making the same manoeuvre without any incident contribute? What was the role of the phone conversation? Did it cause a failure to notice the queue ahead in the first place? Did the divided attention between the phone conversation and driving critically delay the braking response when looking back to the road? To what extent were the visual cues from the closing lead vehicle able to attract the driver's attention and gaze?

A further issue concerns the precise meaning of terms such as "attention", "driver inattention" and "driver distraction" and how attention-related factors can be classified in a coherent way in accident and incident analysis. Should we regard our example truck driver as inattentive due to the phone conversation? Should the rear-view glance be regarded as another instance of driver inattention? If so, how do these forms of inattention differ? Should we classify any of these phenomena as driver distraction?

Finally, what are the most effective countermeasures against inadequate attention selection and its consequences, and how can we evaluate the effectiveness of such countermeasures prior to introduction? These are some of the key theoretical and practical questions addressed by the present thesis.

1.1 The need to understand attention selection in driving

Road crashes is one of the world's major societal problems. Every year, about 1.2 million people are killed and 20-50 million injured in road crashes worldwide (Peden et al, 2004). Accident studies have consistently cited driver inattention as the most prevalent specific factor behind road crashes (Treat et al., 1979; Wang, Knipling and Goodman, 1996). More recently, this has been further supported by naturalistic driving studies. In the recent 100-car study, driver inattention was assigned as a contributing factor in 78% of the crashes and 65% of the near-crashes investigated (Dingus et al., 2006). Similar results were found by two naturalistic driving studies that investigated driver distraction in commercial vehicle operations (Olson et al., 2009; Hickman, Hanowski and Bocanegra, 2010).

However, despite major research efforts in the past decades, including in-depth accident analysis, naturalistic driving and experimental studies conducted on-road, on test tracks or in simulators, many of the questions asked above remain unresolved and are subject to hot current scientific and political debate. For example, while a large number of experimental studies have demonstrated significant impairments in driving performance due to mobile phone conversation (see e.g., Horrey and Wickens, 2006), recent naturalistic driving studies have found hands-free phone conversation to have a protective effect on crash risk (Olson et al., 2009; Hickman et al., 2010). Thus, while we know that inattention is a key factor in crash causation, we don't have a clear picture of *how* different forms of inattention lead to crashes. A better understanding of the relation between attention, driving performance and crash causation is needed to identify the most critical aspects of driver inattention and to develop efficient countermeasures.

Part of the reason for this knowledge gap has been a lack of data from the pre-crash phase that are sufficiency detailed to identify specific attention-related factors. However, today this situation is changing rapidly with the advent of large-scale naturalistic collection of crashes and near crashes captured on video along with onboard sensor data. For example, the naturalistic database analysed by Hickman et al. (2010) comprised over 2000 crashes, which is comparable in size with major existing in-depth accident databases. However, a further problem is the lack of a clear conceptualisation of attention applicable in the driving domain. The concept of attention spans a broad range of phenomena and existing research on attention is generally fragmented and tends to deal with specific aspects of attention not always applicable to attention selection in natural tasks such as driving (Trick and Enns, 2009). Thus, there is a need for a general theoretical framework for addressing attention selection in natural driving situations which, together with more specific models of attentional mechanisms, can be used to guide the interpretation of naturalistic and experimental data as well as the development of effective inattention countermeasures and evaluation methods.

1.2 General aim and scope

The general aim of the present thesis is to obtain an improved understanding of the relation between attention, driving performance and crash risk. To this end, the present thesis includes theoretical as well as empirical work. The theoretical developments include a general framework for understanding adaptive driver behaviour (Paper IV) as well as a more specific model of attention selection mechanisms based on this framework (Paper V). The empirical studies (Paper I-III) address a number of outstanding empirical issues in order to support the model development. The specific aims of the thesis are stated in Chapter 4 based on the literature reviews in Chapter 2 and 3.

Key intended applications of the empirical and theoretical results developed in the thesis include more precise and coherent definitions of attention-related mechanisms in accident and incident analysis, the development of inattention countermeasures and methods for evaluating such countermeasures.

In order to keep the scope within reasonable limits, the present thesis focuses mainly on aspects related to visual attention, working memory load [1] and expectancy. Hence, mechanisms behind physiological impairments that may lead to inattention, such as drowsiness, fatigue and intoxication will not be addressed in detail. Moreover, issues specific to attention in non-visual modalities, such as auditory attention, are touched upon but are outside the main scope of the current thesis.

[1] "Cognitive load" is the term most commonly used in the literature to refer to the demands imposed of non-visual tasks such as phone conversation. In most cases this refers specifically to load on working memory. Since "working memory load" has a more precise meaning, it will be used throughout this thesis (one exception, however, is Paper I which was written as part of a larger set of studies that used the more traditional terminology).

1.3 Outline

The thesis is organised as follows: The following chapter provides a review of empirical studies on attention in driving, with the aim to identify key gaps in our current understanding of the relation between attention, performance and crashes. Chapter 3 then provides a critical review of existing theoretical frameworks and models for understanding attention, with a particular focus on their potential application in natural driving situations. Based on Chapter 2 and 3, Chapter 4 defines the specific aims of the thesis.

Chapter 5 provides summaries of the papers included in the thesis, while Chapter 6 discusses the key theoretical and empirical contributions of the thesis with respect to its specific aims. Chapter 6 also discusses the application of these contributions to the three main areas identified above: Accident and incident analysis, countermeasures and evaluation methods.

2 Empirical studies on attention in driving

This chapter provides a review of existing empirical work on the relation between attention, performance and crash risk in the driving context, with the purpose to identify the most important specific research gaps. The review covers accident and incident analysis as well as experimental studies conducted in driving simulators, on test tracks or in real traffic.

2.1 Accident and incident analysis

Various forms of inattention have been frequently been cited as major factors contributing to accidents. The next section reviews results from traditional accident analysis while Section 2.1.2 addresses naturalistic observation and driving studies.

2.1.1 Traditional accident analysis

National accident statistical databases, largely based on police reports, mainly contain information on the outcome of crashes (e.g., in terms of injuries and fatalities) and general circumstances (e.g., road type, time of day and weather conditions) but generally include little information on specific pre-crash factors such as those related to inattention. However, some countries, most notably the US, do report general statistics on inattention-related factors. For example, based on the analysis of several existing national databases, the National Highway Traffic Safety Administration (NHTSA) estimates that 16% of fatal crashes and 20% of injury crashes during 2009 involved distracted driving (NHTSA, 2010). However, such figures are naturally subject to great uncertainty, given the difficulties for police officers to identify inattention-related factors when arriving at the accident site. Moreover, even if such factors are reported by victims or witnesses, it is uncertain to what degree they actually contributed to the crash, let alone *how* they contributed.

Other studies have used epidemiological techniques to study the impact of, in particular, mobile phone use on crash risk. Such studies typically use billing records to establish when cell phone calls began and ended and compare this to the estimated time of the crash. For example, Redelmeier and Tibshirani (1997) and McEvoy et al. (2005) both found a fourfold increase in crash risk due to mobile phone conversation. However, Young and Schreiner (2009), who compared automatic notifications of airbag deployment with billing records for hands-free conversations using the OnStar onboard system, found no significantly increased crash risk. Hence, results from epidemiological studies remain rather controversial and the debate has mainly focused on limitations of the statistical techniques used to calculate crash risk. However, these types of studies do say little, if anything, about the mechanisms behind crashes, which is the main topic of the present thesis.

Some more detailed information on the role of inattention in crash causation may be gained from in-depth accident studies, which refer to more thorough "on-the-spot" analysis of a smaller set of accidents, often carried out by a multidisciplinary team of researchers. Identification of driver-related pre-crash factors such as inattention is generally based on in-depth interviews of victims and witnesses (Sandin, 2007). Such studies have consistently identified inattention as the most prevalent single factor contributing to accidents. The classical Indiana Tri-level study (Treat et al., 1977) involved in- on-site investigations at three levels of depth in the state of Indiana, US. This study identified "human-factors" (in addition to vehicle- and environment factors) as definite or probable cause in 93% of accidents. Of these "human direct causes", *recognition errors* was identified as the largest factor, contributing to 56% of all the crashes investigated. Furthermore, four principal forms of recognition errors were identified: *Improver lookout* (23%), *inattention*[2] (15%), *external distraction* (4%) and *drowsiness/fatigue* (2%). More recently, Wang et al. (1996) performed an analysis of 1995 entries the US National Accident Sampling System (NASS) Crashworthiness Data System, with the specific goal to investigate the role of driver inattention. The results showed that, in total, 25.5% of tow-away crashes involved inattention as a contributing factor. The main sub-categories were *distracted* (13.2%), *looked by did not see* (9.7%) and *sleepy/fell asleep* (2.6%). In addition, in 45.7% of the crashes the contributing factors were classified as "unknown", which indicates a significant degree of underreporting. However, as pointed out by Rumar (1990), the incoherency and lack of scientific basis behind the classification schemes used makes the data from in-depth accident analysis difficult to interpret.

Both Treat et al. (1977) and Wang et al. (1995) identified *looked-but-failed-to-see* as a major factor contributing to crashes. This refers to cases where the driver has looked in the direction of the hazard but failed to react to it. Brown (2005) reviewed in-depth accident analysis and police report data from UK and the US from the 1970's and onwards. The results indicate that LBFTS has consistently been attributed as a major accident cause and has even been proposed as the main attentional/perceptual contributory factor during daylight. However, as pointed out by Brown (2005), these figures are essentially based on subjective data which makes it difficult to draw any strong conclusions. For example, "I did not see" may be used as an excuse to hide traffic rule violations or carelessness.

While existing in-depth accident analyses, mainly based on police reports and interview data, strongly indicate a key role of inattention in crash causation, they do not say much about the mechanisms behind the different types of attention failures or how they lead to crashes. Thus, until recently, very little was known about the relation between attention failures and crashes. However, this has changed radically in the past few years, as reviewed in the following section.

2.1.2 Naturalistic observation

Naturalistic observation generally refers to unintrusive observation of driver behaviour in naturalistic settings. One approach to naturalistic driving observation is represented by the work of Summala and colleagues, who investigated potential causes for car-bicycle collisions at T-junctions and roundabouts which featured an intersecting two-way bicycle lane. Summala, Pasanen et al. (1996) observed drivers' visual search patterns at left and right turns in such intersections by means of cameras located at the roadway. The results showed that, when turning left, drivers tended to look both left and right since, in this case, potential hazards (oncoming cars) were expected from both directions. However, when turning right, glances to the right were far less common since no real hazards were expected from this direction (in right-hand traffic). A further in-depth study on car-bicycle accidents in these types of intersections confirmed that such accidents were more common at right turns with the bicycle approaching from the right than in other scenario configurations (Räsänen and Summala, 1998). The authors concluded that these car-bicycle crashes occurred due to the erroneous expectation that cars approaching from the left were the only relevant hazards, which led to insufficient scanning to the right. As a result, bicyclists coming from the right,

[2] Inattention was here defined rather narrowly as "pre-occupation with competing thoughts"

who had right of way and believed that the driver saw them, appeared outside the drivers' field of view and thus failed to capture the drivers' attention. (Summala and Räsänen, 2000)

More recently, several *naturalistic driving studies* have collected in-vehicle data over longer time periods in naturalistic settings. This data generally includes video recordings from multiple hidden cameras (directed, e.g., at the driver's face and the road ahead) as well as data from onboard sensors. The first major naturalistic driving study was the US 100-car study, which was finalised in 2005 (Dingus et al., 2006; Klauer et al., 2006). This was followed up by a study by Olson et al. (2009) which focused specifically on driver distraction in commercial vehicle operation (CVO)[3]. Finally, Hickman et al. (2010) analysed commercial vehicle (truck and bus) data collected from the DriveCam[4] onboard safety monitoring system. The DriveCam database analysed comprises video and kinematic data from a very large number of safety-critical events, including over 2000 crashes. An overview of the number of safety relevant events analysed in these studies is given in Table 1.

Table 1 Number of safety relevant events in three naturalistic driving studies reviewed

Study	**Crashes**	**Near-crashes**	**Incidents/crash relevant conflicts**	**Unintentional lane deviations**
100-car (Dingus et al., 2006; Klauer et al., 2006)	69	761	8295	
CVO (Olson et al., 2009)	21	197	3019	1215
DriveCam (Hickman et al., 2010)[5]	2421	24 239	204 252	

In the 100-car study, driver inattention was categorised into four main sub-classes: (1) secondary task engagement, (2) fatigue, (3) non-specific eye glance and (4) driving-related inattention to the forward roadway. It was found that 78% of the crashes and 65% of the near-crashes had at least one of these inattention categories assigned as a contributing factor, where secondary task engagement was the most frequent (Dingus et al., 2006). Another important general finding was that the frequency of inattention related factors increased strongly with the severity of the event. As shown in Figure 1, the proportion of inattentive drivers was much higher for crashes than for near crashes and incidents. This indicates that inattention is often what makes a critical incident develop into a crash (Dingus et al., 2006).

[3] This study combined data from two naturalistic data collection efforts, the Drowsy Driver Warning System Field Operational Test (Hanowski et al., 2008) and the Naturalistic Truck Driving Study (Blanco et al., in press) and involved only truck drivers.
[4] This is an aftermarket device equipped with cameras recording the driver and the forward road scene, as well as some kinematic sensors. See www.drivecam.com
[5] While the total data set contained over 2000 crashes, baseline data, which is needed to calculate odds ratios, was only available for a subset of the data containing 1085 crashes, 8375 near crashes and 30 661 crash-relevant conflicts. The definitions of these severity categories were regarded as proprietary information by DriveCam thus not reported in Hickman et al. (2010).

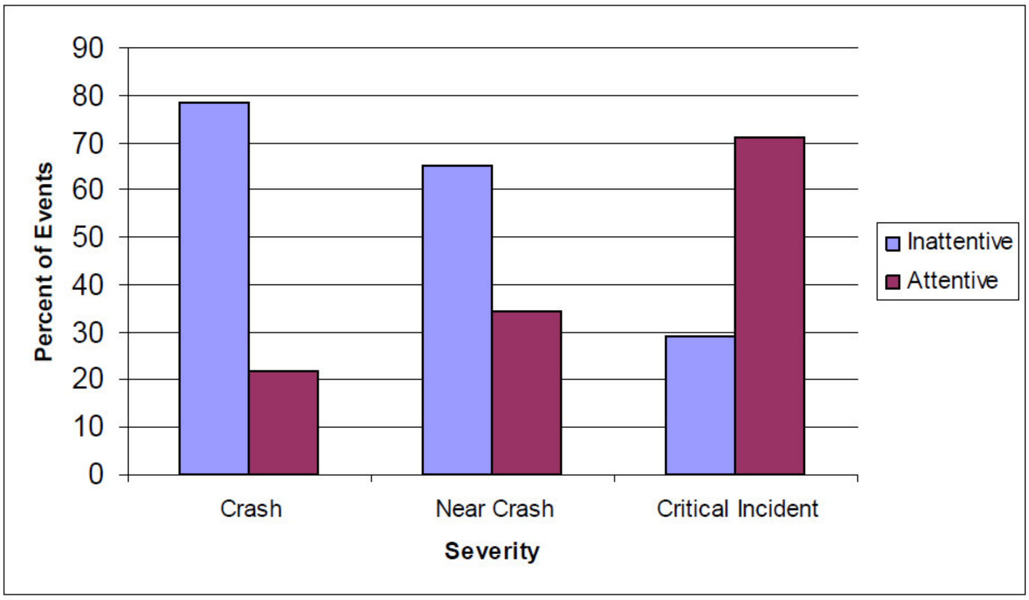

Figure 1 Proportions of inattentive drivers for the three levels of criticality in the 100-car study (from Dingus et al., 2006)

A more detailed analysis was conducted on rear-end scenarios in the 100-car study where it was found that 13/14 of the lead vehicle crashes (93%) and 68% of the near lead-vehicle crashes involved inattention to the forward roadway as a contributing factor. Hence, the results from the 100-car study indicate that inattention is an even more common factor than previously suggested by in-depth accident analyses, in particular for certain types of accidents. Further analysis of kinematic data suggested that a key mechanism behind these rear-end crashes was the *co-occurrence* of attention directed off-road and an unexpected event, for example, a lead vehicle suddenly braking (Dingus et al., 2006). In line with this, Lee et al (2007), in a more detailed follow up-study on the rear-end events, found that eyes-off-road, but not kinematic parameters (such as time-to-collision), distinguished crashes from near crashes for this type of event. By contrast to the in-depth analyses reviewed above, the 100-car study did not find looked-but-failed-to-see (LBFTS) to be a major factor[6]. LBFTS was not coded for any crash, for only two near-crashes and only ten incidents.

A key advantage of naturalistic driving data is the possibility to calculate the risk associated with various activities and factors such as secondary tasks and the time that the eyes are taken off the road prior to the crash. This is done by comparing safety relevant events to baseline (non-event) data, randomly sampled from the whole data set, with respect to the prevalence of the specific factor. The risk is normally calculated in terms of *odds ratios*, which represents the relative risk for a safety critical event when the factor is present, and *population attributable risk* which also takes into account the exposure to the factor. We will focus here on odds ratios, where a significant difference from one represents significantly lower or higher relative risk for being involved in a safety-critical event.

All three studies included in Table 1 calculated odds ratios for various secondary task activities. While Klauer et. al (2006) only included crashes and near crashes in the analysis,

[6] LBFTS was, somewhat oddly, categorised under "daydreaming" together with the sub-categories "lost in thought" and "other".

Olson et al. (2009) and Hickman et al. (2010) based their calculation on all the types of safety critical events listed in Table 1. Some examples of obtained odds ratios are given in Table 2. It should be noted that the types of secondary tasks differ between the studies mainly because the 100-car study only involved private car drivers while and the other two studies involved commercial vehicle drivers.

Table 2 Examples of odds ratios for different secondary task activities found in the three naturalistic driving studies. Entries in bold were significantly different from one.

Activity	**100-car (Klauer et al., 2006)**	**CVO (Olson et al., 2009)**	**DriveCam (Hickman et al., 2010)**
Looking at external object	**3.70**		
Reading	**3.38**	**3.97**	
Applying makeup	**3.13**		
Dial cell phone	**2.79**	**5.93**	**3.5**
Talking/listening to a hands-held phone	1.29	1.04	0.90
Talking/listening to a hands-free phone		**0.44**	**0.65**
Text messaging on a cell phone		**23.2**	**163.6**
Interact with/look at a dispatching device		**9.93**	
Write on pad/note book etc.		**8.98**	
Use calculator		**8.21**	
Talk or listen to citizens band (CB) radio		**0.55**	

The results summarised in Table 2 were generally consistent between studies and strongly indicate that secondary tasks requiring visual interaction are the ones most associated with risk. In particular, extreme values were found for text messaging in the two commercial vehicle studies (text messaging was not available in the US at the time the 100-car study). A further analysis by Olson et al. (2009) also revealed a strong correlation between the relative risk associated with a task and degree to which the task led the driver to glance off-road. Tasks with the highest odds ratios were also associated with the largest proportion of eyes off the forward roadway (see Hanowski et al., in review, for a more detailed discussion on this finding). Furthermore, purely working memory-loading, non-visual, tasks such as mobile phone conversation did not significantly increase risk in any of the studies. By contrast, both Olson et al. (2009) and Hickman et al. (2010) found significantly *reduced* risk during conversation on a hand-held phone and Olson et al. (2009) found the same effect for the use of a CB radio.

Klauer et al (2006) and Olson et al. (2009) also estimated the odds ratios for being involved in a crash or near crash (Klauer et al., 2006) or safety critical event (Olson et al., 2009) as a function of the duration that the eyes were directed off-road within a time window of 5 seconds before and 1 second after the onset of the critical event. The results from both studies are plotted in Figure 2.

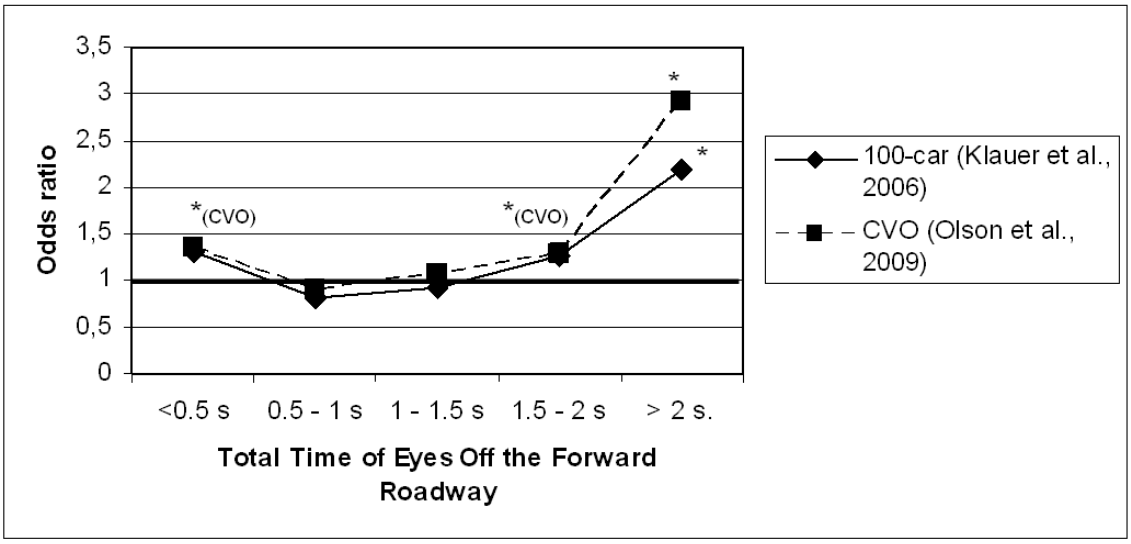

Figure 2 Odds ratios as a function of the total time of eyes off the forward roadway (graph constructed from data in Klauer et al. (2006) and Olson et al. (2009). Asterisks indicate odds ratios significantly different from one.

As shown by the Figure, the results from the two studies were strongly consistent, with the main elevated risk for total off-road glance times longer than 2 seconds. However, perhaps less intuitively, also short glance times (<0.5s) also seems to increase risk somewhat, although the difference was only significant in Olson et al. (2009). Olson et al. (2009) also demonstrated that eyes-off-road time was related to the severity of the event, with longest eyes-off-road times for crashes (mean 2.1 s), followed by near crashes (mean 1.7 s), crash-relevant conflict (mean 1.6 s.) and baseline (mean 1.2 s). This finding is also generally consistent with the findings from the 100-car study (Klauer et al., 2006; Lee et al., 2007).

To summarise, existing naturalistic driving studies have consistently demonstrated an elevated risk of being involved in safety-critical events for tasks requiring visual interaction, with a particularly high risk for text messaging. Moreover, the eyes-off-road time just prior to the event is strongly related to the risk of being involved in a safety-critical event and is also correlated to the severity of the event. This indicates that a key mechanism whereby inattention causes crashes is the simultaneous occurrence of an off-road glance and an unexpected critical event, such as a lead vehicle braking. However, existing naturalistic driving studies do not say much about *why* people decide to look away at inopportune moments. By contrast, the studies by Summala and colleagues on car-bicycle accidents described above offer a more comprehensive analysis on how erroneous expectancies may lead to inadequate visual scanning which eventually lead to crashes. Primarily working memory loading tasks have not been found to increase risk in naturalistic driving studies. For some tasks (talking/listening to hands-free phone and CB radio) the relative risk for a safety-critical event was even found to be significantly reduced.

2.2 Experimental studies on attention in driving

Experimental studies, conducted in driving simulators, test tracks or in real traffic offer the possibility to manipulate specific aspects of attention selection in order to reveal underlying causal relations between attention and driving performance. They may thus be viewed as an important complement to the analysis of real-world accidents and incidents reviewed in the previous section. However, a critical issue is to what extent the effects obtained in controlled experiments generalise to real world driving.

The vast majority of existing experimental studies on attention in driving have focused on how the operation of different types of secondary tasks affects driving performance. These studies have generally employed a *dual task* paradigm where subjects are instructed to perform secondary tasks while driving. Such tasks have included conversing on the phone or entering a destination into a navigation system, as well as artificial tasks such as counting backwards or rehearsing a list of items in working memory. A general distinction can be made between tasks that require the driver to shift gaze between the road and the task, what is commonly referred to as *visual time sharing*, and tasks that only impose cognitive, or more precisely, working memory demands. The next section reviews effects of visual time sharing while section 2.2.2 deals with effects of working memory load.

While dual task studies dominate the experimental literature on attention in driving, there has also been an increasing interest in the relation between expectancy and attention selection, how attention is dynamically scheduled in natural driving situations and the self-regulatory of deployment of attention. Studies addressing these aspects are reviewed in Section 2.2.3.

2.2.1 Effects of visual time sharing

The effect of visual time sharing between driving and a secondary task (typically the operation of some in-vehicle information system) on vehicle control has been addressed in numerous studies. The results from such studies have rather consistently found an increase in lateral control variability (e.g. Zwahlen, Adams, & de Bald, 1988; Greenberg et al., 2003; Östlund et al., 2004; Horrey, Wickens and Consalus, 2006; Merat and Jamson, 2008) accompanied by a reduction in speed (e.g. Curry, et al., 1975; Antin et al., 1990; Merat and Jamson, 2008). Studies employing a car following scenario have also found that drivers tend to increase headway during visual time sharing (e.g., Merat and Jamson, 2008).

Several studies have also found that visual time sharing impairs object and event detection. For example, Lee et al. (2002) found a large effect of visual distraction on responses in a lead vehicle braking scenario. For instance, 38% of the visually distracted participants collided with the lead vehicle compared to 14% of the non-distracted participants. Similar results were obtained by Horrey et al. (2006). Other studies have shown that visual time sharing also degrades detection of less urgent events such as severe lane keeping violations by other vehicles (Greenberg et al., 2003), slowing lead vehicles, brake light onsets, and turn signals of a following vehicle (Angell et al., 2006).

An important issue is to what extent the driving performance impairments induced by visual time sharing are due to visual eccentricity (e.g., driving related stimuli appearing in the visual periphery, or entirely outside the field of view, during off-road glances) or due to attentional interference in the brain. In general, existing studies have not isolated these factors. One exception is a series of studies by Summala and colleagues who used the *forced peripheral vision paradigm*, where subjects are required to maintain gaze at a fixed point inside the vehicle without performing any attention-demanding task. Summala, Nieminen and Punto (1996) found that drivers were relatively good at maintaining lane position using their peripheral field of view. However, Lamble, Laakso and Summala (1999), found that the response times to a slowing lead vehicle increased strongly with visual eccentricity. This indicates a dissociation between the effects of visual eccentricity on lane keeping and event detection.

Other studies have indicated that also the attentional load imposed by visual tasks may affect response performance, independently of visual eccentricity. For example, Merat and Jamson (2008) compared the effect of secondary task on the detection of artificial stimuli presented in different modalities (visually, tactile, and auditory). One of the secondary tasks was manual phone dialling which required visual time sharing. It was found that the dialling task had the same effect on detection performance regardless of the modality of the stimulus to be detected. This indicates that a significant portion of the effect of visual time sharing on event detection is related to an attentional impairment independent of visual eccentricity and even sensory modality.

In general, dual task studies on visual time sharing have yielded relatively consistent results which are also in line with the results from the naturalistic observation studies reviewed in Section 2.1.2. More specifically, experimental studies provide strong evidence that detection of critical on-road hazards is strongly impaired when gaze is directed off-road and detection has to rely on peripheral vision. This is consistent with the strong relation between eyes-off-road and crash risk found in naturalistic driving studies.

2.2.2 Effects of working memory load

While the effects of visual time sharing on driving performance are rather consistent across studies, dual task studies that have investigated the effects of working memory load have yielded strongly inconsistent results. In general, working memory load does not seem to impair lateral control in normal driving conditions. Rather, numerous studies have found *reduced* lane keeping variability under conditions of working memory load (Brookhuis et al., 1991; Östlund et al., 2004; Törnros and Bolling, 2005; Mazzae et al., 2005; Mattes, Föhl and Schindhelm, 2007; Horrey and Simons, 2007; Merat and Jamson, 2008; Mehler et al., 2009; Reimer, 2009). However, a contradictory result was obtained by Salvucci and Beltowska, (2008) who found that working memory load increased deviations from the lane centre during normal lane keeping. Moreover, several studies have found that working memory load degrades performance on artificial tracking tasks (Briem and Hedman, 1995; Strayer and Johnston, 2001; Creem and Profitt, 2001) or non-standard driving task such as steering with a track ball or a computer mouse while lying in a brain scanner (Just, Keller and Cynkar, 2008). Possible reasons for these inconsistent results have not, to the knowledge of the author, been addressed in the literature.

Working memory load has also been found to induce a concentration of gaze towards the road centre (Recarte and Nunes, 2003; Harbluk et al., 2007; Reimer, 2009) and increased steering activity (Rakauskas, Gugerty and Ward, 2004). Other studies have quantified the effect of steering performance in terms of steering entropy (a measure of the disorder in steering wheel movement) and generally found increased steering entropy due to working memory load (Boer, 2000; Boer et al., 2005).

Effects of working memory load on longitudinal control variables such as speed and headway are generally inconsistent between as well as within studies. For example, Patten et al. (2003) found a speed reduction during hand-held phone conversation but not for conversation on a hands-free phone. Horrey and Simons (2007) found increased headway in car following situations due to working memory load but no increase in safety margins during overtaking and merging. A set of parallel studies conducted in the HASTE EU-funded project found small effects of working memory load in both directions for speed and headway measures (Östlund et al., 2004).

Working memory load has also been found to impair object and event detection. Several studies have investigated the effect of working memory load on responses to artificial stimuli in the Peripheral Detection Task (PDT) paradigm (e.g., Törnros and Bolling, 2005; Patten et al. 2003; Merat and Jamson, 2008). In this paradigm, visual stimuli are presented in the peripheral field of view with some temporal (and sometimes spatial) variation with an average inter-stimulus interval of about 4 seconds. These studies have consistently found increased response time due to working memory load.

Other studies have investigated the effects of working memory load on braking responses in lead vehicle braking scenarios (e.g., Brookhuis, et. al.1991; Alm & Nilsson, 1995; Lee et al., 2001; Strayer, Drews and Johnston. 2003; Strayer and Drews, 2004; Strayer, Drews and Crouch, 2006; Levy, Pashler and Boer, 2006; Salvucci and Beltowska, 2008). These studies have generally found delayed responses due to working memory load. However, one puzzling aspect of these studies is that the magnitude of the observed response delay differs strongly between studies, from 50 ms in the study by Salvucci and Beltowska (2008) to about 1500 ms for older drivers in the study by Alm and Nilsson (1995).

Another finding that casts some doubt of the generality of the effects of working memory load on responses to critical events was obtained by Muttart et al. (2007) who had the brake lights of the lead vehicle turned off. By contrast to the studies cited above, which all involved brake light onsets, no effect of working memory load was found when the lead vehicle was just braking unexpectedly (with brake lights turned off). However, working memory load impaired responses in scenarios where the lead vehicle braking event was cued by downstream traffic events. Similarly, Baumann et al. (2008) conducted a simulator study investigating the effect of working memory load on the ability to use a predictive cue (a warning sign) to guide responses to obstacles hidden behind curves. It was found that working memory load only delayed response performance in the cued condition. These studies indicate that working memory load mainly affects responses to cued events (where brake light onsets may be regarded as a predictive cue) while leaving responses to non-cued events, triggered solely by looming (optical expansion), unaffected. If this is true, working memory load may have little effect on responses to critical hazards in many real-world situations, contrary to what is generally assumed. These apparently contradictory results have not been further addressed in the literature.

Working memory load has also been found to impair the semantic encoding of information into long-term memory. For example, Strayer et al., (2003) found that working memory load severely impaired the ability to recall roadside billboards in a post-drive recognition memory test. This effect occurred even if the billboard signs were fixated, indicating that the result was not due to the gaze concentration effect mentioned above.

Finally, working memory load has been found to induce physiological arousal. For example, Mehler et al. (2010) found a systematic increase in heart rate and skin conductance with incremental increases in working memory load.

To summarise, while working memory load has been found to influence several aspects of driving performance, the results of existing studies are often inconsistent or directly in conflict. This holds for effects on lateral control, longitudinal control as well as responses to critical events. Thus, it seems like that working memory load selectively affects certain aspects of driving performance while leaving others unaffected, and sometimes even enhances performance. However, no general explanation for these divergent findings is offered in the literature. Moreover, the (sometimes very large, see Alm and Nilsson, 1995) response delays found in many dual task studies, both for responses to artificial stimuli and braking lead vehicles, appear to contradict the findings from several naturalistic driving studies (Olson et al., 2009; Hickman et al., 2010) that working memory load reduced the risk for being involved in safety critical events.

2.2.3 Expectancy, proactive attention scheduling and self-regulation of attentional effort

Task goals as well as specific expectations on how upcoming traffic situations will develop, critically determine attention selection, perception and decision making, and may play a critical role in crash causation, as demonstrated, for example, by the work of Summala and colleagues (e.g., Summala and Räsänen, 2000) reviewed in section 2.1.2. The key role of expectancy in driving has been acknowledged for a long time by traffic psychologists and road engineers. For example Hills (1980) stated that expectancies "…can profoundly affect the driver's interpretation of the various visual features and signals in a scene and also the various visual judgements he has to make. It is believed that these could partly explain why, anecdotally, a driver can look straight at a cyclist or a motorcyclist and then drive straight out into him. It is thought that the driver is looking for cars and/or larger vehicles since there is a high probability that any potential conflict is going to be with that type of vehicle…" (p. 193). However, these phenomena have not, until recently, been systematically addressed in experimental research, at least not in the driving domain.

A meta-analysis by Green (2000) identified expectancy as the most important factor determining braking response times to critical events. Theeuwes (1996) examined the effect of expectancy on visual search patterns of subjects watching video recordings of intersection approaches. The subjects were instructed to search for a traffic sign indicating a left or right turn and press a left or right button accordingly. Both response times and the time to fixate the sign were strongly increased when the sign was located in an unexpected location.

Recent studies have also explored the dynamic allocation of visual attention in natural environments and tasks. Hayhoe (2000) and Hayhoe and Ballard (2005) review research in this area. Examination of eye movements in natural tasks such as making a sandwich, playing table tennis and driving, have demonstrated that fixations are seldom made to objects that are irrelevant to the task at hand. This shows that the moment-to-moment allocation of visual attention critically depends on the specific task context and the operator's current task goals. Moreover, the information acquired during a single glance is strongly task specific. Hayhoe (2000) suggests that specialised *visual routines* are applied to extract the immediately relevant information (e.g., a red traffic light) from a scene. Furthermore, Hayhoe (2000) introduced the *scheduling problem* which concerns how individual visual routines are dynamically composed into attention allocation patterns matched to the task context. Shinoda, Hayhoe and Shrivastava (2001) investigated attention scheduling in the driving context. In a driving simulator study, subjects were either asked to adhere to traffic rules or just follow a lead vehicle. A no parking sign was replaced by a stop sign for a limited period of time (0.5-1 s.). The change was masked by a white frame in order to eliminate visual transients. The sign was either placed in an unexpected location along the road or at an expected location in an intersection. Analysis of eye movements, braking responses and verbal reports revealed that detection of the stop sign was strongly influenced by both task instruction and sign location, with the highest detection probabilities for subjects instructed to follow traffic rules and when the sign was located at the intersection. This shows that the allocation of visual attention in driving is strongly proactive and driven top-down by the current task goals and driving context.

Related phenomena were studied by Martens (2007). In these studies, subjects drove the same simulated route a large number of times over several consecutive days. In the last session, a traffic rule (e.g. priority rule at an intersection) was changed, as indicated, for example, by a new sign and painted road markings. The majority of the subjects did not exhibit any response to the change, even if they, in many cases, visually fixated the new road sign. In one study, these effects were even found without the repeated exposure to the route (Martens, 2007, Ch. 11) which, indicates that strong expectations, and resulting blindness to important information, can be invoked by the road design itself regardless of repeated exposure.

These effects are related to the phenomena known as *change-* and *inattention blindness*. The former refers to the inability to detect a change in a visual scene if the visual transient associated with the change is masked (Rensink, 2007). By contrast, inattention blindness refers to the inability to detect salient stimuli appearing in the field of view if attention is allocated elsewhere (e.g., Mack and Rock, 1998). Change- and inattentional blindness may also be related to the looked-but-failed-to-see phenomenon that, as reviewed above, has been suggested as a common crash contributing factor in in-depth accident analysis (Brown, 2005). These phenomena have recently also been demonstrated in driving simulator studies (Lee, Lee and Boyle, 2005; White and Caird, 2010). However, beyond verbal reports in in-depth accident studies, there is yet little concrete evidence that links change- or inattention blindness to real-world crashes. For example, as mentioned in section 2.1.2, looked-but-failed-to-see did not appear as a major crash contributing factor in the 100-car study (Dingus et al., 2006).

Evidence for the self-regulatory nature of attention deployment is offered by a study by van der Hulst, Rothengatter and Meijman (1998) who investigated the effect of lack of preview and time pressure on the adoption of safety margins and responses to lead vehicle deceleration events. Preview was manipulated by the presence of fog and time pressure was imposed by the requirement to complete the route according to a fixed time schedule. Drivers not under time pressure increased safety margins while driving in fog while time-pressured drivers did not. However, time pressured drivers reacted more accurately to the lead car decelerations than non-time pressured drivers and thus avoided critical situations. The authors suggested that a key factor behind this result was that time pressured drivers compensated for the smaller adopted safety margins by increasing the degree of attention allocated to driving. This illustrates the intimate relation between attention and adaptive behaviour. If the driver is motivated by a certain goal, for example to reach a destination in time, perceived uncertainty due to reduced safety margins may be compensated for by allocating more attention to the driving task. However, since this generally requires effort, drivers with no such specific motives preferably compensate for the increased uncertainty by increasing safety margins (e.g., slowing down or increasing headway).

In summary, existing studies have demonstrated that attention and scheduling, as well as the extraction of information from the driving scene, is strongly driven top-down by the current task goals and context. This may lead to failures in detecting unexpected, potentially safety-relevant, events that are not relevant to the current task and/or occur in unexpected locations.

Drivers also self-regulate the deployment of attention based on motivation and perceived risk. However, these phenomena have been relatively little studied and, as also noted by Hayhoe (2000) and Shinoda et al. (2001), the basic mechanisms behind attention scheduling in natural tasks are still largely unknown. For example, *how* does perception of task context influence proactive attention scheduling in driving? Moreover, to what extent is top-down selection in driving associated with voluntary, conscious control and to what extent can it occur automatically and effortless. These issues have not been addressed experimentally.

2.3 Summary and key empirical research gaps

Although some national statistical crash databases include information on inattention-related factors, these statistics are subject to great uncertainty and reveals little about the specific role of different inattention-related factors in crashes. In-depth accident analyses, where the analysis of inattention-related factors is largely based on subjective reports, have consistently identified inattention as a major factor involved in crash causation. However, due to incoherent classification schemes the results are somewhat difficult to interpret. Moreover, these types of studies reveal little about the specific mechanisms underlying attention failures and how they lead to crashes. The same can be said about epidemiological studies.

Naturalistic observation and driving studies have greatly enhanced our understanding of such mechanisms and will continue to do so as more and more data are collected. One key finding of existing studies is that the prevalence of attention failures increases with event severity, which indicates that inattention is often what makes critical events develop into crashes. Naturalistic driving studies have consistently demonstrated a strong relation between eyes-off-road time and crash risk. However, purely working memory loading tasks have not been found to elevate risk and, in some cases, even had a protective effect.

A large number of experimental dual task studies have demonstrated decrements in driving performance both due to visual time sharing and working memory load. Effects of visual time sharing are relatively well understood and typically involve increased variability in lane position, a compensatory increase in safety margins in terms of speed reduction and/or increased headway and, most importantly, severely delayed responses to critical events.

However, effects of working memory load are often inconsistent between studies. While several studies have found that working memory load leads to delayed event detection, other studies indicate that this effect mainly occurs for events that are cued (e.g., by brake light onsets, downstream traffic events or traffic signs). Moreover, many studies have found that working memory load induces a reduction in lateral control variability, often accompanied by increased steering activity and gaze concentration towards the road. However, other studies found that working memory load impaired lateral control. Unlike visual tasks, working memory load does not consistently lead to safety margin compensation in terms of reduced speed or increased headway. Finally, there is an apparent discrepancy between experimental dual task studies and naturalistic driving studies regarding the effects of working memory loading tasks. In particular, delayed responses to critical events often found in experimental studies contrast sharply to the protective effects of working memory load that have been found by several recent naturalistic driving studies.

Thus, in general, the mechanisms behind the effects of working memory load on driving performance are still not well understood and the degree to which the results from experimental studies generalise to the real world driving remains an open issue.

Compared to the vast literature on dual task interference, studies that have investigated the role of expectancy, proactive attention scheduling and self-regulation of attention are relatively scarce. Existing work in this area, in particular the car-bicycle accident analysis by Summala and colleagues (Summala and Räsänen, 2000) clearly show that these are key aspects that must be considered in order to understand the relation between attention selection and crashes.

Based on this review, it may be concluded that the key gaps in our knowledge on the relation between attention, driving performance and crash risk concern (a) the effects of working memory load and (b) the mechanisms behind expectancy, proactive attention scheduling and self-regulation of attention. Moreover, the extent to which results from experimental studies generalise to the real world remains an open question, especially with respect to working memory load. Finally, due to these knowledge gaps, we do not yet have a clear understanding of the ultimate question that motivated the present thesis: *How do attention selection failures cause road crashes?*

The following chapter provides a critical review of existing theoretical frameworks of attention and their potential applicability to the understanding of attention selection in natural driving situations.

3 Theories of attention and their applicability to natural driving

So far, we have not been very precise about the meaning of "attention", but rather used the term in its general common-sense meaning, expressed, for example by William James (1890):

"Everybody knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought"

In this view, attention thus refers to the selection of certain environmental features or mental operations over others and is also strongly associated with conscious experience. As we shall see, this general view of attention is still widely held in contemporary attention research. However, the concept of attention has been notoriously hard to pin down scientifically and is used to refer to a broad range of phenomena. As noted by Allport (1993) and Trick and Enns, (2009), applied as well as basic research on attention is still strongly fragmented with a wide variety of models and approaches that are often specific to the particular attentional phenomenon studied.

One tradition, which still dominates applied human factors research, views attention selection as the consequence of limited information processing capacity. Such capacity limitations have been conceptualised as filters (Broadbent, 1958), attentional bottlenecks (Welford, 1952; Pashler and Johnston, 1998) or scarce resources (Kahneman, 1973; Navon and Gopher, 1979; Wickens, 1984). Traditionally, a distinction is often made between *selective* and *divided* attention. The former has been defined as the ability to select tasks, stimuli, or aspects of stimuli, over others (Kahneman, 1973; Wickens and McCarley, 2008). By contrast, divided attention refers to the parallel processing of tasks or stimuli rather than switching between them (Wickens and McCarley, 2008). Another type of attention is *sustained attention*, or *vigilance*, which refers to the effortful mobilisation of mental activity over a prolonged period of time (Wickens and McCarley, 2008). The link between attention, the mobilisation of effort and physiological arousal is emphasised by some authors, in particular Kahneman (1973). While most traditional models focus on the selection of information, some authors have emphasised the role of attention in the selection of action (Norman and Shallice, 1986; Allport, 1987; Neumann, 1987). In the past decades, great progress has also been made on understanding the neural basis of attention (e.g., Desimone and Duncan, 1995; Corbetta and Shulman, 2002; Cohen, Aston-Jones and Gilzenrat, 2004).

This chapter provides a critical review of existing theoretical perspectives on attention with the main purpose to identify theories that can be used as a basis for understanding attention selection in natural driving situations

3.1 Limited capacity models

Since the cognitive revolution in the 1950's and 60's (see Gardner, 1985), information processing (IP) has been the dominating paradigm in cognitive science, especially in the field of applied human factors. IP models generally propose that cognition proceeds in a sequence of information processing *stages*, including sensation, perception, cognition (decision and response selection) and action (response execution). A dominating theme in attention research in this tradition has been the view of attention as a *limited capacity* in human information processing and selective attention as the consequence of such limitations. A key concern is how this limited capacity becomes overloaded by information, resulting in breakdowns in performance, especially during concurrent performance of multiple tasks. Limited capacity models are thus intimately linked to the dual task experimental paradigm.

There is substantial debate over the nature of the limited capacity, however. One aspect of this debate concerns whether selection occurs early (Broadbent, 1958; Handy, Soltani and Mangun, 2001) or late (Moray, 1969) in an assumed information processing sequence from stimulus to response. Another concerns whether the limitations are best conceptualised as due to processing bottlenecks (Welford, 1952; Pashler and Johnston, 1998) or competition for shared resources (Kahneman, 1973; Navon and Gopher, 1979; Wickens, 1984, 2002). Yet another issue of dispute is whether capacity is limited by a single resource/bottleneck (Welford, 1958; Kahneman, 1973; Pashler and Johnston, 1998) or whether there are multiple resources, each with its own capacity limitations (Navon and Gopher, 1979; Wickens, 1984, 2002).

We will focus here on two general accounts of limited capacity that both are commonly applied to the understanding of attention in driving: Resource theory and central bottleneck models.

3.1.1 Resource theory

Resource theory is based on the idea that the limited capacity of the human information processing system can be viewed in terms of *resources* that may be allocated in gradual way to different tasks that demand them. Resources are intended as an abstraction relating to concepts such as attention, effort and capacity (Navon and Gopher, 1979). Since resources are scarce, there will be performance tradeoffs when two or more tasks demand the same resource. In dual task studies, such tradeoffs may reveal the degree of interference between two tasks. Kahneman (1973) proposed an influential resource-based attention model postulating a single, undifferentiated, resource pool, as well as more specific satellite structures. In Kahneman's view, attentional resources are intimately linked to effort and physiological arousal, manifested, for example, in terms of pupil dilation and increased heart rate and skin conductance. A concept closely related to resource theory is *mental workload*, which represents the relation between the demand for resources imposed by a task and the ability of the operator to supply them (Wickens, 2002).

Another concept that traditionally relates to the notion of resources is *automaticity*. Automatic processing relates to the everyday observation that, with practice, we are often able to perform tasks without effort and conscious awareness. Automatic processing has been characterised as a "…a fast, parallel, fairly effortless process that is not limited by short-term memory (STM) capacity, is not under direct subject control, and is responsible for the development of well-developed skilled behaviors" (Schneider, Dumais and Schiffrin , 1984, p.1). By contrast, *controlled (or control) processing* can be characterised as "…a slow, generally serial, effortful, capacity-limited, subject-regulated processing mode that must be used to deal with novel or inconsistent information" (Schneider et al., 1983, p.1). According to resource theory, automaticity can be understood in terms of the amount of resources demanded by a task. Thus, in this view, controlled processes are those that require attentional resources while automatic processes do not require such resources.

Single resource theory, in its strongest form, predicts that dual task interference is solely determined by the degree to which the added demands of the tasks exceed available resources supplied by a single resource pool. However, a large number of dual tasks studies have yielded results inconsistent with this prediction. In particular, it has been demonstrated that interference is often stronger between structurally similar tasks, for example tasks demanding the same sensory modality, than for dissimilar tasks. Moreover, some tasks could be performed with little or no interference at all (see e.g. Wickens, 1984, for a review). Navon and Gopher (1979) and Wickens (1984) suggested that such results are better accounted for by the postulation of *multiple resources*.

Today, *Multiple Resource Theory* (MRT; Wickens, 1984, 2002; Wickens and McCarley, 2008) has become the dominating approach to applied attention research in the human factors community. MRT originally proposed a set of multiple resources that can be described along three dimensions: (1) processing stages (perception, cognition, responding), (2) codes (spatial, verbal) and (3) modalities (visual, auditory). More recently, a fourth dimension, visual processing (focal, ambient), nested within the visual modality, has been added (Wickens, 2002). The model makes the general prediction that dual task interference will be strongest when two tasks demand overlapping resources. For tasks demanding separate resources, little or no interference is predicted.

3.1.2 Central bottleneck models

As just described, resource theory suggests a general conceptualisation of how task performance depends on limited capacity. However, it does not address in detail *how* capacity is limited, for example, whether dual tasks are performed in parallel or switched between in a serial manner. The central bottleneck hypothesis (Welford (1952; Pashler and Johnston, 1998) suggests a more specific account of limited capacity. As most IP models, central bottleneck models assumes that human information processing proceeds in distinct stages. Pashler and Johnson (1998) suggest three main stages: stimulus processing, central processing and response-related processing. In this view, “attention” refers to voluntary processes and “attentional limitations” to “central” limitations, excluding peripheral limitations such as the impossibility to fixate two spatially separated objects at the same time (Pashler and Johnston, 1998). By contrast to resource theory, capacity limitations are viewed in terms of a *central bottleneck* that cannot be shared. Hence, dual task performance necessarily requires serial operation characterised by switching and buffering, similar to the central processing unit of a digital computer. However, it is also assumed that stimulus processing and response execution may, at least to some extent, be performed in parallel. Hence, according to this account, attentional limitations should mainly occur at the central, response selection, stage. The central bottleneck model has been applied in the driving domain by Levy, Pashler and Boer (2006) who applied the classical *psychological refractory period* (PRP) paradigm in a lead vehicle braking scenario. The findings generally replicated PRP effects typically found in laboratory tasks (see Pashler and Johnston, 1998).

The central bottleneck idea is also central in the more general account of multitasking proposed by Salvucci and Taatgen (2008), known as the *threaded cognition* model, which has been applied in the driving context by Salvucci and Beltowska (2008). This computational model was developed within the general ACT-R (Adaptive Control of Thought-Rational) framework which models cognition and behaviour in terms of production rules that implement empirically known psychological constrains (Anderson et al., 2004). While the threaded cognition model assumes a variety of perceptual, cognitive and motor processing resources (this aspect of the model is thus in line with multiple resource theory, Wickens, 1984, 2002), it also postulates the existence of a central processing bottleneck, a central *procedural resource*, which maps between sensory and motor processes and can only be deployed serially. The model also accounts for visual time sharing in terms of a visual resource that controls eye movements, recruited by the procedural resource. Simulations based on the model have yielded detailed predictions of performance impairments for different task combinations. For example, Salvucci and Taatgen (2008) demonstrated that the model accurately predicted effects of phone dialling on lane keeping performance. The model also predicts that working memory loading tasks, due to competition for the procedural resource, should lead to delayed braking responses, less frequent steering updates and, as a result, less accurate lane keeping (Salvucci and Taatgen, 2008). These predictions were tested in a simulator study by Salvucci and Beltowska (2008) who, as reviewed in Section 2.2.2, indeed found that working memory load lead to delayed responses and impaired lane keeping performance. However, at least for lane keeping, both the prediction and the empirical result contradicts a large number of other studies that rather found reduced lane keeping variability and increased steering activity due to working memory load.

Thus, although limited capacity models have been successfully demonstrated to account for certain aspects of dual task performance, some predictions seem to be contradicted by existing empirical results. However, more importantly, limited capacity models are mainly applicable to experimental dual task settings and have little to say about key aspects in real world driving such as the role of expectancy, self-regulation of attention and proactive attention scheduling reviewed in Section 2.2.3.. Hence, limited capacity models seem insufficient for a full account of attention selection in natural driving.

3.2 Beyond limited capacity: Expectancy, proactive attention scheduling and self-regulation

This section reviews models in the basic attention literature that potentially accounts for aspects of attention selection in driving not confined to dual task settings, in particular the phenomena reviewed in Section 2.2.3 relating to expectancy, proactive attention scheduling and self-regulation of attention and in natural driving situations.

3.2.1 Top-down and bottom-up selection

As demonstrated, for example, by the analysis of car-bicycle accidents by Summala and colleagues, reviewed in section 2.1.2, attention selection in natural driving situations is driven top-down by task goals and expectations as well as bottom-up by stimulus input. In the past decade, the distinction between top-down and bottom-up selection has become a cornerstone in basic attention research. Related terms include *endogenous* versus *exogenous* orienting (Posner, 1980) and *goal-directed* versus *stimulus-driven* selection (Corbetta and Shulman, 2002). In the following, we will consistently use the top-down/bottom-up terminology to avoid confusion.

Laboratory studies using the *cueing paradigm* (Posner, 1980) have clearly demonstrated the distinct roles of top-down and bottom-up attention orienting. Jonides (1981) demonstrated that working memory load mainly affected central (top-down) cueing but leaving peripheral (bottom-up) cueing largely unaffected. Such results have led to the influential idea that top-down attention orienting is voluntary, effortful, and thus controlled, while bottom-up attention orienting is reflexive and automatic.

During the past decades, the understanding of the neural mechanisms underlying top-down and bottom-up attention selection has also been greatly enhanced. One particularly influential account is the *biased competition hypothesis* which views attention as an emergent property of multiple neural mechanisms, which resolve neural competition based on bottom-up and top-down biases (Desimone and Duncan, 1995). According to the biased competition hypothesis, top-down and bottom-up biases will have the effect of enhancing the certain neural representations while suppressing competing representations. This idea has been strongly supported by neurophysiological and neuroimaging studies in monkeys and humans (e.g., Chelazzi et al., 1993; Kastner et al., 1998, 1999).

Recent studies have also demonstrated the strong role of emotion in biasing attention selection (see reviews in Pessoa, 2008; Phelps, 2006; Vuilleumier, 2005). Evidence suggests that this biasing mechanism works according to similar principles as "normal" biased competition (Vuilleumier, 2005).

In the original formulation if the biased competition hypothesis (Desimone and Duncan, 1995), it was suggested that the top-down bias originated from the pre-frontal cortex (PFC). However, the detailed function of the PFC in generating this bias was left unspecified. An extension of the model, featuring a more detailed account of PFC function, is offered by Miller and Cohen (2001), called *Guided Activation Theory*. According this model, the PFC serves to maintain activity of neural patterns representing goals and the means to achieve them. The key role of PFC bias is to "provide bias signals to other brain structures with the net effect to guide the flow of activity along neural pathways that establish the proper mappings between inputs, internal states, and outputs needed to perform a given task" (Miller and Cohen, 2001, p 167). More specifically, the bias is needed to select a task relevant, but weak, *neural pathway* over an inherently stronger one. Repeated selection of a pathway strengthens it so that it eventually does not require bias from the PFC to be activated, which leads to increasingly automatic performance. The model thus suggests that automaticity may be considered in terms of the *strength of neural pathways* (an idea originally formulated by Cohen, Dunbar and McClelland, 1990). In terms of this model, dual task interference could be understood in terms of the degree of overlap between these pathways. Miller and Cohen refer to the attentional biasing function of the PFC as *cognitive control*. Cognitive control thus enables behavioural flexibility in non-routine situations by the selection of weak, but task relevant, pathways over stronger pathways representing automatic, habitual, behaviours.

There is also a general consensus that working memory is closely associated with top-down attention selection (Desimone and Duncan, 1995; Corbetta and Shulman, 2002), and, more specifically, with cognitive control (Miller and Cohen, 2001). Cognitive control implements working memory by maintaining activation of task, or goal, relevant representations in the absence of stimulus input (Miller and Cohen, 2001)

The distinction between top-down and bottom-up selection is clearly of key importance for understanding attention selection in driving, especially for conceptualising the roles of expectancy and stimulus driven reactions to critical hazards (e.g., Summala and Räsänen, 2000; Theeuwes, 1996). Moreover, the biased competition hypothesis and the guided activation theory offer models of the neurobiological principles of attention selection and automaticity which may be useful as the basis for more applied models of attention in driving.

However, these models are still mainly concerned with specific laboratory tasks and fail to account for many of the key phenomena reviewed in Section 2.2.3, in particular the self-regulation of attention and dynamic attention scheduling in natural driving situations.

Moreover, as mentioned above, a common implicit assumption in these models is that that top-down selection is always controlled while bottom-up selection is always automatic. However, intuitively, selection of information and actions selection in driving and other everyday activities is often habitual and unconscious, yet top-down driven by expectations and task goals. Thus, a model of attention selection in driving should account for this type of habitual top-down selection. This topic is further addressed in the following section.

3.2.2 Trick and Enns' 2-dimensional framework

Trick and Enns (2009; see also Trick et al., 2004) have proposed a conceptual framework specifically intended to account for attention selection in driving. As just mentioned, many existing attention models tend to associate top-down selection with controlled performance and bottom-up selection with automatic performance. Trick and Enns rather suggest that controlled/automatic and top-down/bottom-up[7] dichotomies should be treated as separate dimensions.

Tricks and Enns suggest two general modes of automatic processing, *reflex* and *habit* which relate to bottom-up and top-down selection respectively. The former refers to automatic responses such as visual orienting to sudden luminance onsets or looming, while habit relates to goal-directed behaviours that, through practice, have become effortless and unconscious. This includes basic driving skills that distinguish experienced from novice drivers, such as allocating attention in advance towards the most relevant aspects of a road scene. However, Trick and Enns (2009) also suggest that habits may be detrimental for road safety when they are imported into new situations that require different behaviours.

The authors further suggest two forms of controlled processing: *deliberation* (top-down) and *exploration* (bottom-up). In driving, deliberation occurs when "(a) conditions are challenging (low visibility, heavy traffic, unexpected events, unfamiliar environments) (b) when individuals perform unfamiliar activities or combinations of activities (dual tasks) that require an action plan to be constructed on-line using moment-to-moment feedback from the environment; (c) when individuals are acting strategically, and not simply reacting to events in the immediate environment; (d) when individuals react to symbolic information that must be interpreted to be acted upon; and (e) when maladaptive habits and reflexes must be monitored and overcome." (Trick and Enns, 2009, p. 70). Deliberation hence corresponds to the traditional notion of top-down attention selection.

The remaining category, *exploration* refers to conscious exploration of the environment which is not driven by specific goals. This includes, for example, drivers in non-demanding conditions scanning the environment to explore roadside objects such as advertisement, trees etc. (Hills, 1980). These four modes of attention selection are illustrated in Figure 3.

[7] Trick and Enns use the terms endogenous/exogenous terminology rather than top-down/ bottom-up and argue that these two concepts have a slightly different meaning (see Trick et al., 2004). However, for simplicity, we retain the top-down/bottom-up terminology here.

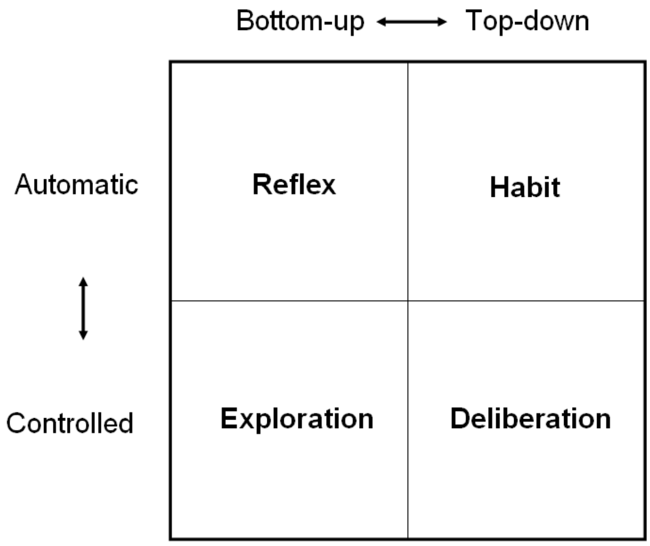

Figure 3 Trick and Enns' 2-dimensional framework for attention selection in driving (adopted from Trick and Enns, 2009)

This framework provides a useful starting point for approaching many of the empirical phenomena reviewed in Chapter 2. In particular, it accounts for the notion of skilled, habitual, yet top-down driven, attention selection which is not captured by standard models of top-down and bottom-up selection (or by limited capacity models). However, as a general conceptual framework, rather than a specific model, it does not yield specific testable predictions. Moreover, the framework does not specifically address aspects related to dynamic attention scheduling in natural tasks or the self-regulation of attention. These topics are addressed in the following two sections.

3.2.3 Self-regulation of attentional effort

As illustrated, for example, by the study by van der Hulst et al. (1998) reviewed in Section 2.2.3, drivers manage attention in a self-regulatory fashion, driven, on the one hand, by the desire to accomplish task goals and, on the other, by the need to maintain acceptable safety margins. Thus, from this perspective, attention selection may be viewed as a form of adaptive behaviour. Several recent models in the general driver behaviour literature suggest that adaptive behaviour occurs as the result of a balance between excitatory and inhibitory forces. Excitatory forces may involve task goals such as the desire to arrive to a destination in time (as in van der Hulst et al., 1998) or to enter a destination into the navigation system. However, such goals need to be balanced against the need to maintain safe driving and respect traffic rules, which represent inhibitory forces. The zero-risk theory, originally developed by Näätänen & Summala (1976), suggested that drivers normally regulate their behaviour to maintain the subjectively perceived *risk* at a zero level. In a more recent development of this model, partly based on Gibson and Crooks (1938), Summala (2007) proposed the concept of a *safety zone*, the boundary of which represents when a crash becomes inevitable, for example, the speed at which a vehicle starts to skid or roll over in a curve, or the minimum time-to-collision for which it is possible to avoid a crash by braking. Furthermore, Summala (2007) suggested that concept of risk in the zero-risk theory may be substituted for *discomfort*. Thus, according to this model, the driver strives to maintain a state of zero discomfort. The difference between this comfort zone boundary and the safety zone boundary represents the *safety margin* selected by the driver. Discomfort includes *feelings* of immediate risk or threat (e.g., in a critical traffic situation), but is also associated with the mobilization of *effort* to cope with excessive task demands (Hockey, 1997). Thus, in this view, adaptive driver behaviour occurs as the result of the desire to accomplish task goals while remaining in the comfort zone. When the driver perceives a feeling of discomfort, for example due to reduced perception of surrounding traffic when engaged in visual time sharing, she will compensate by slowing down and/or increasing headway in order to remain in the comfort zone. However, if strongly motivated to accomplish the task, she may also invest addition attentional effort to cope with the increased demand. The general idea that adaptive behaviour is governed by emotions and feelings has also been developed by Fuller (2007) and Vaa (2007).

However, these general driver behaviour models have not addressed the role of attention specifically. Lee, Regan and Young (2009) outlined a control-theoretic view on driver distraction which builds on similar principles. The authors suggest that drivers actively control their attention allocation strategies at three levels: operational, tactical and strategic (these general levels of driving control were originally proposed by Michon, 1985). Furthermore, at each level, control may be reactive (based on feedback), proactive (based on anticipation) or adaptive (involving adjustments of the general goal state). At the operational level drivers control the basic resource investments for driving and secondary tasks. At the tactical level, they control task timing, while control at the strategic level concerns the general exposure to potentially demanding situations. They further suggest that driver distraction can be understood as a breakdown in control at any of these levels and that a failure at one level may propagate to other levels. For example, a failure at the strategic level to control the general task demand may cause problems in the temporal scheduling between driving and a secondary task which, in turn, may lead to excessive demands for visual resources and a breakdown in operational control.

Another control theoretic model of the self-regulation of attention and effort has been developed by Hockey (e.g., 1997). The basic idea behind this model is that maintenance of performance stability under demanding conditions is a self-regulatory process that manages the mobilisation of mental effort. The mobilisation of effort is aversive and thus associated with a cost. In the face of increasing task demand, an operator may choose to protect task performance by investing effort (with an increase in cost) or accept a reduction in performance (at no cost). Hence, according to the model, the self-regulation of attentional effort is based on continuous cost-benefit decisions.

A more neurobiologically based model along the same lines is offered by Botvinick et al. (2001; see also Botvinick, 2007), which represents an extention of the guided activation theory reviewed above (Miller and Cohen, 2001). Botvinick et al. suggest that the recruitment of cognitive control is driven by the monitoring of conflicts between neural pathways in a self-regulating fashion, governed mainly by the anterior cingulated cortex (ACC). Thus, when the ACC detects a conflict between ongoing tasks, it signals to the pre-frontal cortex that cognitive control is needed to resolve it. A related account is offered by Aston-Jones and Cohen (2005), who further suggest a key role of global arousal modulation, originating in the brainstem, in the self-regulatory recruitment of cognitive control. A general synthesis of the attention models developed by Cohen and colleagues can be found in Cohen et al. (2004).

The models reviewed in this Section offer a strong theoretical basis for understanding the self-regulatory aspects of attention deployment in natural driving situations. These models may also explain compensatory behaviours observed in dual task studies, such as slowing down while visually time sharing with a secondary task, phenomena which are seldom addressed by limited capacity models. However, they do not specifically account for the type of dynamic scheduling of attention in natural driving situations exemplified by Shinoda et al. (2001; see Section 2.2.3). This topic is addressed in the following section.

3.2.4 Attention scheduling in natural tasks

In naturalistic driving situations, driving itself may be viewed as a multitasking activity where the driver continuously has to select the right information at the right time. As reviewed in Section 2.2.3, the extraction of information from a scene is strongly task specific and may be understood as the application of specific visual routines (Hayhoe, 2000). The top-down driven scheduling of such visual routines, generally involving eye movements, was termed the *scheduling problem* by Hayhoe (2000). From a more general perspective, the scheduling problem also applies to action and, in natural tasks, perception and action are intimately linked (e.g., Allport, 1987; Neumann, 1987). Indeed, the movement of the eyes towards an object in order to apply a visual routine could itself be considered an action.

A model of visual routines, applied to the automatic control of a simulated vehicle, was developed by Salgian and Ballard (1998). In this model, visual routines (for traffic light detection, vehicle detection, looming detection etc.) were linked to more general *behaviours* such as car following, traffic light behaviours, obstacle avoidance etc.). However, this model did not implement a realistic solution to the scheduling problem (Hayhoe, 2000).

A more elaborated computational model of context-driven visual allocation and action selection, based on similar ideas, was developed by Sprague and Ballard (2003) and implemented to control a virtual human with the task to collect litter in a simulated urban environment. Basic sensory-motor primitives were conceptualised in terms of a set of *microbehaviours* such as *pick up object* or *look for crosswalk*. These were arbitrated by means of value functions that represented the outcome value (reward) or loss of different microbehaviours in a specific situation. Thus, at each time step, the behaviour with the greatest expected value (or the least expected loss) was selected. These value functions were learned through experience by means of a reinforcement learning algorithm. Finally, the set of behaviours applicable in a certain situation was determined by a general representation of task context.

A conceptual model of the role of attention in action scheduling was proposed by Norman and Shallice (1986), and later implemented computationally by Cooper and Shallice, (2000) (see also Cooper et al., 2005). This model proposes two complementary mechanisms for selection and control of attention for action. The first mechanism, which deals with routine selection, is termed *contention scheduling* and acts through mutual lateral competition between *schemata* which implement routine actions at different levels of abstraction. Schemata can be activated bottom-up by triggers, which receive input from the perceptual system. The second mechanism, called the *supervisory attentional system (SAS),* controls contention scheduling according to current goals and task demand by means of top-down biasing of schemata representing willed acts. The deployment of the SAS is assumed to require effort and is accessible to conscious awareness. The Norman and Shallice (1986) model is in many respects similar to the guided activation model of Miller and Cohen (2001) described above, where the SAS plays a similar role as cognitive control in the model of Miller and Cohen (2001). These models also converge on the view that basic actions are governed by parallel sensory-motor control structures (schemata or neural pathways) that may interfere through lateral inhibition, or "cross-talk" (see also Allport, 1993).

A common feature in the models reviewed so far in this section is the notion of functional units for perception and/or action control, such as "visual routines", "behaviours" or "schemata", which compete for being selected. Selection is influenced bottom-up by stimulus input and top-down by a representation of the task context (Salgian and Ballard, 1998; Sprague and Ballard, 2003) or by an "executive" system initiating willed acts (Norman and Shallice, 1986). It should be noted that the precise definition of "schemata" or "behaviours" differs somewhat between authors. However, in general these can be viewed as a functional units of action control (Pezzulo, 2007) which may refer to basic motor actions such as "pick-up", routine action sequences such as "add milk from carton" or more general tasks such as "prepare instant coffee" (see Cooper and Shallice, 2000). As suggested by Arbib (1991), the schema concept offers an intermediate level of action representation that can be related to brain theory as well as cognitive modelling and robotics.

Finally, largely in parallel to the models reviewed above, Wickens and colleagues (e.g., Wickens and McCarley, 2008; Wickens and Horrey, 2009) have proposed a computational model of visual scanning known as SEEV. The model computes the probability that foveal vision is allocated to a particular area of interest in terms of the weighted sum of four key factors: *S*aliency, *E*ffort, *E*xpectancy and *V*alue. Here, salience refers mainly to physical stimulus properties such as contrast and visual transients and effort refers to the energetic costs of allocating attention to a certain target area. These are viewed as bottom-up influences on visual scanning. By contrast, expectancy and value are viewed as top-down factors. Expectancy is defined in terms of the expected information content associated with an area of interest, as determined by event frequency (bandwidth) and contextual cues. Finally, value refers to the subjective value, or utility, in sampling an area of interest (or the loss of ignoring it). The probability of fixating an area is thus given by a trade-off between the positive influence of saliency, expectancy and value and the negative influence of effort. Horrey, et al. (2006) applied a simplified version of the model (with only the top-down components, expectancy and value, included) to the prediction of visual time sharing patterns in a driving simulator study, and found good model fits to human data.

The models reviewed in this section are all useful starting points for conceptualising attention scheduling in natural tasks such as driving, although they differ somewhat in scope. SEEV is essentially a model of visual scanning and does not account for other attentional phenomena. By contrast, Norman and Shallice's (1986) model is broader in scope and, in addition to action scheduling, addresses other key aspects of attention discussed in this chapter such as automaticity and top-down/bottom-up selection as well as dual task interference. It is also largely compatible with the more neurobiologically based guided activation theory reviewed above (Miller and Cohen, 2001), but described on a more abstract level. Sprague and Ballard (2003) and the SEEV model both incorporate the notion of *value* as a key factor determining the allocation of visual attention. However, none of these models account for the self-regulatory aspects of attention reviewed in the previous section.

Rather surprisingly, with the exception of SEEV, and the more engineering-oriented model of Salgian and Ballard (1998), the models reviewed in this section have not, to the knowledge of the author, been applied in the driving domain.

3.3 Summary

This Chapter reviewed existing models of attention and discussed to what extent they are applicable to the understanding the relation between attention, performance and crash risk in natural driving. The review shows, as previously noted by Allport (1993) and Trick and Enns (2009), that the field of attention research is strongly fragmented and that no comprehensive model of attention exists today.

Most existing attention models that have been applied in the driving domain are based on the concept of limited capacity. However, as argued above, limited capacity models are severely limited in their scope and mainly apply in experimental dual task situations. In particular, they do not account for key issues in real-world driving such as expectancy, dynamic attention scheduling and the self-regulation of attention.

Contemporary basic research on attention offers detailed, often neurobiologically based, models of specific laboratory phenomena. A key focus of this research has been to elucidate basic mechanisms behind top-down and bottom-up selection, cognitive control and automaticity. While these models are strongly relevant to the understanding of attention selection in driving, they are generally too specific to be directly applicable in the driving domain. In particular, as pointed out by Trick and Enns (2009), these models often conflate the top-down/bottom-up and controlled/automatic dimensions. While top-down selection in laboratory tasks is probably most often controlled, everyday experience suggests that habitual top-down selection is ubiquitous in driving and thus need to be accounted for by driver attention models.

In general, the framework by Trick and Enns (2009), originally outlined in Trick et al. (2004), offers a very useful starting point for the study of attention in driving. However, the framework does not specifically address dynamic aspects of attention such as self-regulation and dynamic attention scheduling. Relatively few existing models have addressed these aspects. With respect to self-regulation of attention, models of adaptive behaviour in the general driver behaviour literature, as well as the control-theoretic accounts of Lee et al. (2009) and Hockey (1997), may serve as starting points. Botvinick et al. (2001) and Aston-Jones and Cohen (2005) offer neurobiological accounts of attentional self-regulation. A rare example of a high-level synthesis of neurobiological models of attention, including selection mechanisms, cognitive control, automaticity and attentional self-regulation can be found in Cohen et al. (2004).

Finally, models of attention scheduling include the SEEV model, which, however, only accounts for visual scanning. Other approaches, in particular the attention-to-action model proposed by Norman and Shallice (1986), account for attention and action scheduling in terms of the selection of mutually competing schemata, or related concepts such as “behaviours” or “routines” (Salgian and Ballard, 1998; Sprague and Ballard, 2003). Such models may also account for other key phenomena, including dual task interference. Still, they have so far not been applied in the driving domain. Nevertheless, they seem to be a good starting point for the development of a general model of attention selection in natural driving.

4 Specific aims

As stated in Section 1.2, the general aim of the present thesis is to obtain an improved understanding of the relation between attention, performance and crash risk in driving. Chapter 2 reviewed related empirical work and identified a number of outstanding research gaps, in particular regarding the effects of working memory load on driving and the basic mechanisms underlying expectancy, proactive attention scheduling and self-regulation of attention. Chapter 3 reviewed existing theories of attention and discussed their applicability in the driving domain and concluded that traditional limited capacity models fail to account for key aspects relevant for attention selection in natural driving situations. While some contemporary attention models developed in basic research do address such aspects but are often too specific to be directly applicable in the driving domain.

Based on these reviews, the following specific aims of the present thesis have been defined.

1. Develop a general conceptual model of attention selection in driving able to account for expectancy, dynamic attention scheduling and attentional self-regulation in natural driving, but also dual task interference (Paper IV, V)
2. Obtain a better understanding of the effects of working memory load on driving performance (Paper I, II, III).
3. Obtain a better understanding of the key mechanisms behind expectancy and dynamic attention scheduling (Paper II, III)
4. Clarify to what extent results from experimental studies generalise to the real world (Paper II, III, IV)
5. Define a general conceptualisation of how attention selection failures cause road crashes (Paper V)

5 Summary of papers

This chapter provides summaries of the papers included in this thesis. Paper I represents a broad investigation of the effects of visual time sharing and working memory load on driving performance. Paper II focuses more specifically on the effects of working memory load and repeated event exposure on braking responses in a lead vehicle braking scenario. A key goal of this study was to investigate how working memory load affected top-down attention selection driven by expectancies to the repeated events. Paper III follows up on the results from Paper I and Paper II with the general goal to investigate possible reasons for existing inconsistencies regarding the effect of working memory load on driving performance. A further specific objective was to examine more in detail how top-down attention scheduling is affected by working memory load.

Paper IV outlines a general framework for understanding adaptive driver behaviour which served as the starting point for the more specific model of attention selection in driving developed in Paper V.

5.1 Paper I: Effects of visual and cognitive load in real and simulated motorway driving

This paper reports from three parallel, but closely coordinated, studies, two of which were conducted in driving simulators and one in the field using an instrumented vehicle. The general objective was to investigate systematically the effects of visual time sharing and working memory load[8] on driving performance, behaviour and physiological state. The experiments were conducted as part of a more general set of coordinated studies within EU-funded HASTE project, reported in Östlund et al. (2004).

5.1.1 Method

Data were collected from three experimental settings: (1) a fixed base simulator, (2) an advanced moving base simulator and (3) an instrumented vehicle driven in real traffic. A common experimental methodology was applied and, as far as possible, the same scenarios and dependent measures were included in all three experiments. In total, 120 subjects participated, 48 in each of the simulator studies and 24 in the field study.

Two secondary tasks were used in all three sub-studies, one visual and one auditory/cognitive (working memory loading) task. The visual task involved visual search for a target arrow among distractor arrows on a LCD touch display positioned over the centre console. The difficulty was varied at three levels by altering the orientation of the non-target arrows and the size of the array The working memory task required the subject to keep an updated count of a number of target sounds, presented in sequence among non-target sounds. The difficulty was manipulated at three levels by varying the number of target sounds.

The effects of performing the visual and the working memory task were assessed in terms of a variety of dependent variables which can grouped into the following general categories: (1)

[8] In Paper I the term cognitive load, rather than working memory load, is used, as this was the common terminology used in the HASTE project. However, in order to be consistent with the rest of the thesis, the latter term is used in this summary.

longitudinal vehicle control, (2) lateral vehicle control, (3) physiological signals, (4) eye movements and (5) self-reported driving performance measures. In addition, secondary task performance was assessed in non-driving (static) as well as driving (dynamic) conditions.

5.1.2 Results

Effects of the visual task

The effects of the visual task were generally in line with previous studies (reviewed in Section 2.2.1). Visual time sharing led to significantly increased lane keeping variability (in terms of increased standard deviation of lane position), but only in the fixed-base simulator. However, a strong tendency in the same direction was also obtained in the moving-base simulator. No effect on lane keeping was found in the field. Also, visual time sharing led to significantly increased frequency of steering wheel reversals increased in all three sub-studies. The speed was significantly reduced in all three settings while mean skin conductance and heart rate increased as a result of the visual task.

Effects of the working memory task

The effects of the working memory task contrasted strongly to the effects of the visual task. Both simulator studies found that the working memory load induced significantly reduced lane keeping variability. The results from the fixed-based simulator for standard deviation of lane position are shown in Figure 4. A tendency for reduced lane keeping variability was also present in the field, but the effect was not statistically significant. In general, this effect was very robust and replicated in most of the parallel HASTE experiments (see Östlund et al., 2004). Steering wheel reversal rate increased significantly in the field but not in the simulators. The working memory task also induced a significant reduction in standard deviation of gaze angle, indicating a concentration of gaze to the road centre. An effect on physiological measures (increased heart rate) was only found in the field. No effects on speed were found for the working memory task in any of the settings.

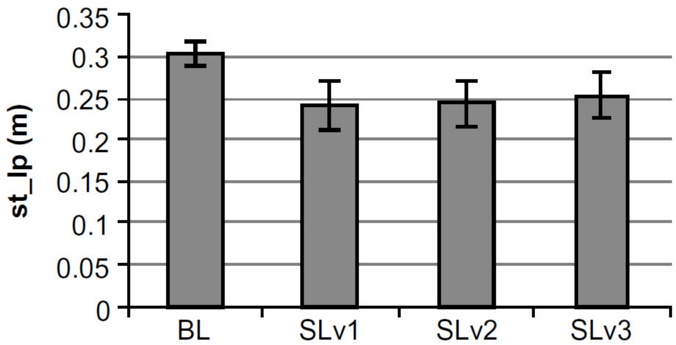

Figure 4 Reduction of lane keeping variability, measured in terms of standard deviation of lane position (st_lp), due to working memory load in the fixed base simulator (BL=baseline, SLv1-3=the three difficulty levels of the cognitive task. Error bars represent 95% confidence intervals.)

5.1.3 Discussion

The key finding of this study was the markedly different effects of the visual and the working memory task. Visual time sharing induces an intermittent control strategy, where the driver strives to maintain acceptable lane keeping performance by means of more frequent steering corrections and a compensatory reduction of speed. By contrast, working memory load leads to a gaze concentration towards the road centre, reduced lane keeping variability but no speed reduction. Both tasks led to increased steering activity, but probably for different reasons. In the case of visual time sharing, the steering manoeuvres are performed in order to correct for heading errors while for the working memory task, it was suggested that the increased steering frequency occurred either as a side effect of gaze concentration or due to an effort to increase lateral safety margins. In general, these results showed that dual task interference in driving is a multi-faceted phenomenon and cannot be captured by single constructs such as, for instance, "workload".

5.2 Paper II: Effects of working memory load and repeated scenario exposure on emergency braking performance

While Paper I addressed a broad range of effects of visual time sharing and working memory load, it did not examine responses to critical events. The general objective of this study was to investigate the role of top-down and bottom-up attention selection mechanisms in responses to critical events, and how these are affected by working memory load A further objective was to address the generalisability of the results from experimental studies to real-world settings.

Several experimental studies have found delayed braking responses to lead vehicle braking events during concurrent performance of working memory (WM) loading tasks, such as hands-free phone conversation (see Section 2.2.2). However, one potential issue with these studies is the use of repeated, and hence somewhat expected, braking events.

Responses to expected events could be regarded as largely top-down driven, while responses to unexpected events should be driven bottom-up. Laboratory studies have found that working memory load affects impairs top-down selection more than bottom-up selection (e.g., Jonides, 1981). In line with this, driving studies have found that working memory load specifically affected responses to cued events (which should be top-down driven) but had no effect when the cues were removed (in which case selection should be driven bottom-up; Muttart et al., 2007; Baumann et al., 2008). Based on the assumption that working memory load only affects top-down selection, one would expect a working memory loading task to interfere more with responses to expected, top-down driven, than with unexpected, bottom-up driven, events. It follows that responses to repeated, expected, events in experimental studies may not be representative of responses to critical events in naturalistic settings, which are generally unexpected.

Thus, when the critical events are repeated, one would expect an interaction between working memory and repeated exposure such that the *effect* of working memory load increases with repeated exposure. The specific objective of this study was to test this hypothesis.

5.2.1 Method

Forty participants, 20 women and 20 men, participated in the study. A critical lead vehicle braking scenario was implemented in a fixed-based simulator and repeated six times, intermingled with catch trials. Care was taken to ensure that the first event was truly unexpected to the subjects. The working memory task was to count down in decrements of 7 from a given, randomly selected, three-digit number. The independent variables were working memory load (varied between groups) and repeated scenario exposure (varied within groups). The dependent variables were accelerator release time and accelerator-to-brake movement time.

5.2.2 Results and discussion

Accelerator pedal release times were strongly reduced with repeated scenario exposure. The main reduction occurred between the first and the second exposure with a difference of 374 ms. Working memory load delayed responses with a small but significant amount (178 ms). However, contrary to our hypothesis, the two factors did not interact. There were no effects on accelerator-to-brake pedal movement time. The results are shown in Figure 5.

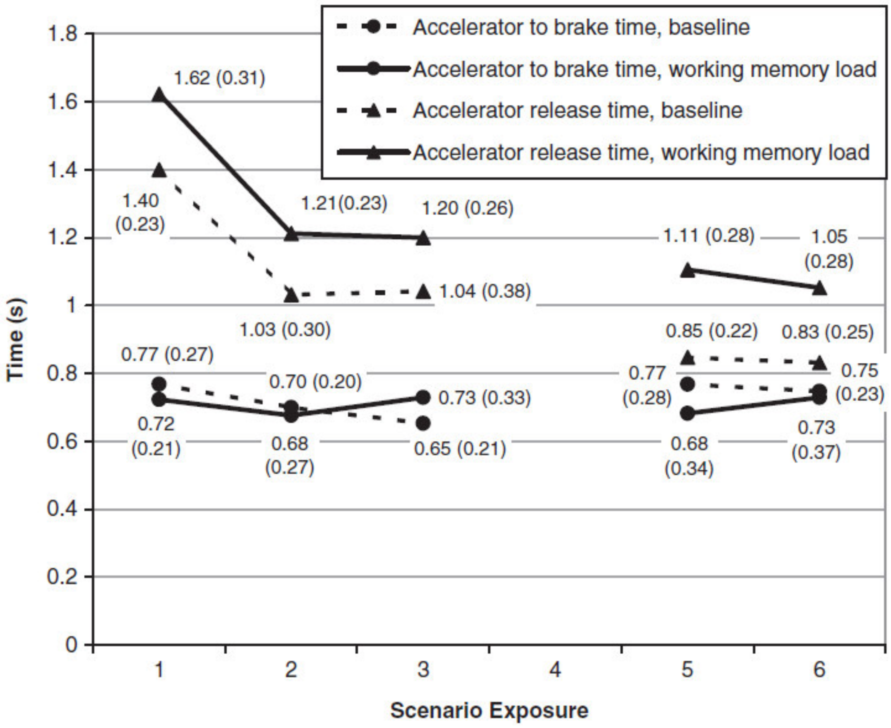

Figure 5 Effects of working memory load on accelerator release time and accelerator-to-brake movement time across exposures (standard deviation within parentheses). Data from exposure 4 were missing due to a technical error.

The results showed (a) that that working memory loaded participants responded slower than the baseline (non-loaded) group also for the first, unexpected event and (b) that the loaded participants were no more impaired than the baseline participants in developing faster responses with repeated exposure.

The first observation implies that working memory load may also affect bottom-up selection. In reconsidering the original hypothesis, it was suggested that this may be due to the fact that subjects in this study responded mainly to the brake light onset rather than to looming cues. In the real world, brake light onsets mainly function as predictive cues rather than triggering braking responses directly. By contrast, strong looming cues invariably trigger avoidance responses. Hence, speeded responses to brake lights may require some cognitive mechanism that is shared with working memory load and thus affects responses also in surprising situations, which may explain the observed delay due to working memory load for the first exposure to the event. This implies that working memory load should not affect responses to looming cues in unexpected situations, an issue addressed in Paper III.

The second observation implies that at least some forms of top-down selection seem to be unaffected by working memory load. It was suggested that this mechanism may be related to the *contextual cueing* phenomenon studied by Chun and Jiang (1998; 1999). These authors found that that implicit learning of co-varying static or dynamic contextual patterns in visual scenes may implicitly (unconsciously) guide top-down responses to subsequent events.

These results strongly question the traditional assumption that top-down selection is always a voluntary, effortful, process associated with working memory while bottom-up selection is always automatic. Rather, at least some forms of top-down selection may occur more automatically while bottom-up selection may sometimes rely on cognitive mechanisms that are also involved in working memory. These results thus yielded important constraints for the development of the attention selection model presented in Paper V and led to an alternative hypothesis examined in Paper III.

5.3 Paper III: Effects of working memory load on controlled and automatic driving performance

Existing studies on the effects of working memory load on driving performance have yielded apparently inconsistent results. This holds for event detection, lateral control as well as longitudinal control measures (see section 2.2.2). The basic reasons for these inconsistencies are not well understood. The general objective of this paper was to examine a possible resolution to this dilemma: that working memory load mainly affects controlled but not automatic aspects of driving performance.

Controlled performance is associated with effort and conscious awareness while automatic performance is effortless and unconscious. As discussed above, a commonly held view is that top-down selection is generally controlled while bottom-up selection is automatic. This was the basis for the hypothesis tested in Paper II: Loading working memory, which is generally believed to rely on controlled performance, should mainly affect top-down selection but leave bottom-up selection unaffected. However, the results from Paper II, contrary to this hypothesis, rather suggested that top-down selection may sometimes run automatically while bottom-up selection may sometimes be controlled. Hence, top-down versus bottom-up selection and controlled versus automatic performance are best viewed as separate dimensions, as suggested by Trick and Enns (2009; see Section 3.2.2).

Based on Trick and Enns' framework, it was hypothesised that working memory load should selectively affect exploration and deliberation (controlled performance) while leaving reflex and habit (automatic performance) unaffected. This hypothesis was tested for a variety of driving performance and behaviour indicators including braking avoidance, the development of anticipatory braking and attention scheduling strategies with repeated exposure, lane keeping, visual exploration of billboards and the semantic encoding of billboard content into long-term memory.

5.3.1 Method

48 subjects participated in the study. A simulated route was implemented which contained a rural and an urban section. The route was repeated 12 times with some variation in layout between repetitions. The working memory task was to count down with seven from a randomly selected 3-digit number.

Half of the subjects performed the working memory task while the other half performed no secondary task. In addition, half of the group was instructed to minimise deviations to the lane centre on the rural road while the other group received no such instructions.

In the urban environment, a critical braking scenario was implemented at a signalised intersection where an oncoming vehicle unexpectedly turned left and crossed the path of the subject vehicle. The braking scenario occurred six times, randomly distributed over the twelve repetitions. Employing a similar experimental design as in Paper II, it was examined how working memory load and increased expectancy (induced by the repeated exposure) affected brake onset time, gaze response time, and anticipatory visual attention scheduling (measured in terms of visual scanning).

On the rural road, we investigated effects of working memory load on lane keeping performance, steering wheel reversals, visual exploration of roadside billboards and semantic encoding of billboard content. In addition, we examined how the instruction to optimise lane keeping interacted with the effect of working memory load. The key hypothesis here was that such deliberate optimising should require controlled performance and hence be impaired by working memory load. Thus the independent variables were working memory load and lane keeping instruction, both varied between groups.

Visual behaviour was measured by means of a head-mounted eye tracking system and was analysed manually. Semantic encoding of billboard content into long-term memory was assessed by means of a post-drive recognition memory test.

5.3.2 Results and discussion

In general the results supported the hypothesis that working memory load selectively affects controlled performance (deliberation and exploration) but leaves automatic performance (reflex and habit) unaffected.

In the critical braking scenario, working memory load had no impact on brake onset time. In particular, for the first, unexpected event, brake onset times, as well as the gaze response time (the time from the moment when the oncoming vehicle initiated the turn until the subjects' gaze landed on the vehicle) were very similar (and even somewhat faster for the working memory loaded group), which is in line with the hypothesis given that initial responses to the present event were reflexively triggered by looming cues. With repeated exposure, both loaded and non-loaded subjects responded faster and also glanced more frequently towards the oncoming vehicle in anticipation of the event, which indicates, in line with Paper II, the presence of an automatic top-down selection mechanism not affected by working memory load. However, a subset of the non-loaded subjects developed specific strategies not exhibited by the loaded subjects. Specifically, many non-loaded subjects, after repeated exposure, began to brake before the onset of the event and exhibited very long single glances towards the oncoming vehicle, thus actively ignoring other relevant information. This was manifested in terms of a significantly larger proportion anticipatory braking responses and significantly longer mean single glance duration for non-loaded subjects. This suggests, in line with the hypothesis, that the development of deliberate (controlled, top-down), flexible, attention selection strategies is impaired by working memory load.

On the rural road, working memory load led to reduced lane keeping variability for non-instructed subjects, which is in line with several previous studies (e.g., Paper I). This effect vanished for instructed subjects. However, the predicted lane keeping impairment for instructed subjects was not found (by contrast to the previous study by Salvucci and Beltwoska, 2008). It was suggested that this may have been due to differences in road curvature and the subjects' driving experience between the two studies. In any case, the lack of lane keeping impairment for non-instructed subjects was in line with the present hypothesis, given that normal lane keeping is strongly automatised (habitual).

Working memory load strongly reduced the visual exploration of billboards (controlled, bottom-up) and the semantic encoding of billboard content, which could be regarded as requiring deliberation (controlled, top-down).

An overview of the present findings, mapped onto Trick and Enns' 2-dimensional framework is given in Figure 6. Taken together, these results suggest that the key effect of working memory on driving performance is to induce a resort to reflexive and habitual behaviour, impairing more flexible, effortful strategies that rely on controlled performance.

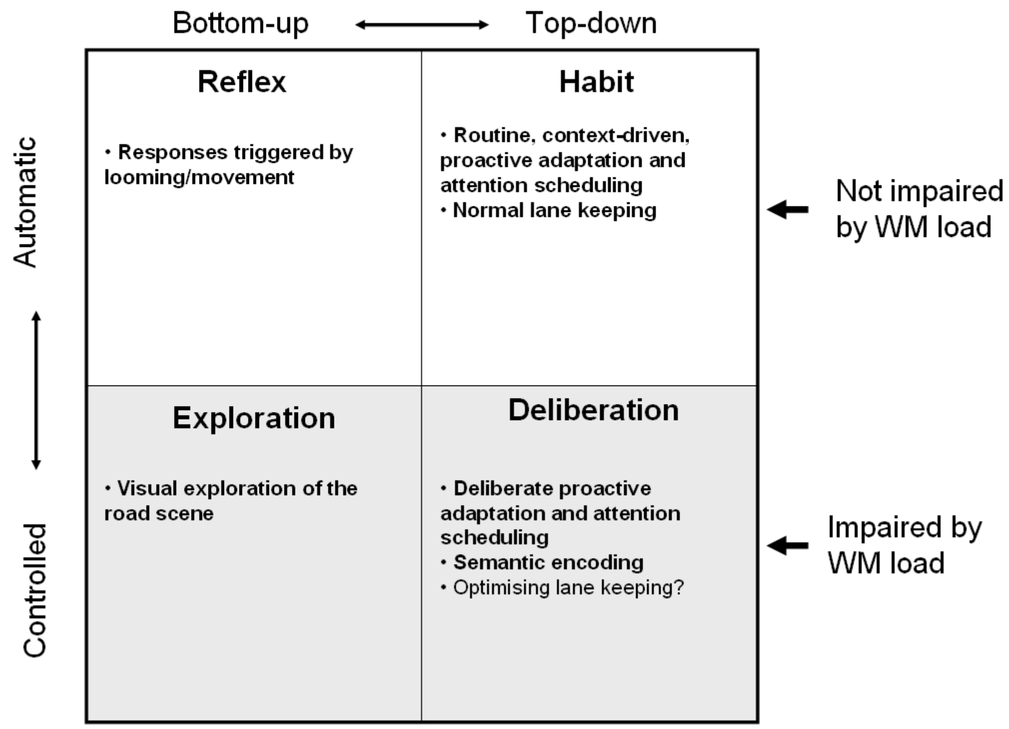

Figure 6 Overview of the findings of Paper III in terms of Trick and Enns' (2009) framework.

5.4 Paper IV: Adaptive behaviour in the simulator: Implications for active safety system design

This book chapter outlines a general conceptual framework for understanding adaptive behaviour in driving and applies it to the problem of active safety system evaluation in driving simulators. A similar framework, applied to the more general problem of active safety system requirement specification and evaluation, is outlined in Ljung Aust and Engström (2011).

The framework starts from a general conceptualisation of adaptivity in biological systems, which can be viewed as a consequence of the need of an organism to sustain itself over longer periods of time in a continuously-changing environment (Pfeifer & Scheier, 2000). The state of an organism and its environment can be described in terms of a space defined by variables relevant for its survival (for example, blood sugar and body fluid). Within this space there is a *viable zone* that the organism must stay within to function properly and, ultimately, to survive. Adaptive behaviour is the result of, on the one hand, the active exploitation of opportunities for actions afforded by the environment, and/or created by the system, to satisfy goals and motives and, on the other hand, the need to remain safely within the viability zone.

In the driving domain, the viability zone may be considered as a *safety zone* in Driver-Vehicle-Environment state space that defines the objective opportunities for action (Summala, 2007; Gibson and Crooks, 1938). The safety zone boundary separates situations in two classes: those that result in successful outcomes and those that do not. In most conditions, drivers seek to maintain a feeling of zero discomfort. This may be conceptualized as a *comfort zone* which should lie within the safety zone to ensure safe driving. The comfort zone is subjectively defined and governed by emotional signals experienced in terms of feelings (Damasio, 1994; Summala, 2007; Fuller, 2007; Vaa, 2007). The difference between the comfort and safety zones is the *safety margin* chosen by the driver, which can be operationalized, for example, in terms of time-to-contact. The maintenance of safety margins relies on perception of relevant information, such as optically-specified expansion rates or road surface textures. However, it can also be based on more general knowledge, obtained, for example, through traffic messages warning for slippery roads or animals on the road ahead. These concepts are illustrated in Figure 7.

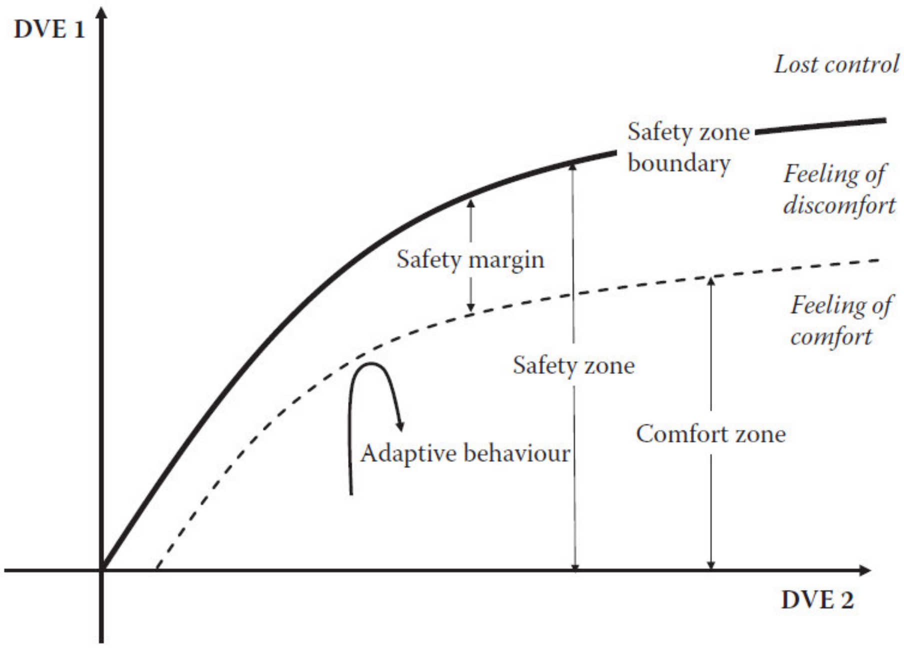

Figure 7 Illustration of the (objective) safety zone, the (subjective) comfort zone and the resulting safety margin between them in a space defined by two Driver-Vehicle Environment (DVE) parameters

Adaptive strategies employed by drivers to maintain their safety margins are generally proactive and driven top-down by expectations on how driving scenarios will unfold. Examples include the self-regulation of driving demand by, for example, by slowing down and increasing headway, or altering attention and task allocation strategies (e.g., focusing attention on the road ahead when a critical event is expected).

In normal driving conditions, drivers generally operate in a *satisficing* mode, only investing as much effort that is needed to remain in the comfort zone. Excitatory forces, related to specific goals and motives, push the driver towards the comfort zone boundary. If these excitatory forces are strong, or the situation is forced-paced, operation shifts to an *optimising* control mode. The mobilisation of strong effort itself induces discomfort in terms of strain or fatigue and is thus generally avoided unless there is strong motivation for it or if the task is forced paced.

Failures in this adaptation process are the key mechanisms behind real-world accidents. This may occur due to an unexpected event or a failure to correctly perceive the safety zone boundary, thus leading to the adoption of inappropriate safety margins (where, in the worst case, the comfort zone exceeds the safety zone). Drivers may also adopt insufficient safety margins due to overestimation of their own capacity. Hence, it is these types of situations that need to be re-created in simulator-based active safety evaluation.

Based on this conceptual framework, the chapter discusses various problems associated with implementing critical situations in driving simulators, including how to recreate kinematic conditions, how to trick drivers out of their comfort zones, the consequences of using repeated scenarios and motivational differences between driving simulators and the real world.

5.5 Paper V: Attention selection and multitasking in everyday driving: A conceptual model

This book chapter, which constitutes the core of the present thesis, outlines a conceptual model of attention selection and multitasking in everyday driving, with the intention to account for the empirical results obtained in Paper I-III as well as other existing findings in the driver attention literature (reviewed in Chapter 2). The model represents a further development of earlier models presented in Victor (2005), Engström (2008), Engström, Markkula and Victor (2009) and Engström (2010b).

The model is based on the view of attention selection as a form of adaptive behaviour, rather than a consequence of limited capacity. A key starting point was thus the conceptualisation of adaptive behaviour outlined in Paper IV. Other main sources of inspiration were the general framework attention selection in driving proposed by Trick and Enns (2009) and Trick et al. (2004), the attention-to-action model by Norman and Shallice (1986) and the more neurobiologically detailed attention models developed by Cohen and colleagues (Cohen et. al., 2004), reviewed in Chapter 3.

5.5.1 The model

Everyday driving can be viewed as a multitasking activity where drivers have to strike a balance between the achievement of goals and the discomfort associated with perceived risk and other undesired outcomes. Attention plays a key role in this process. Safety-relevant information and actions need to be proactively selected in order to maintain acceptable safety margins. In demanding situations, or when the driver is strongly motivated towards a specific goal, additional attentional effort could be invested to deal with the situation. Thus the key *function* of attention selection in everyday driving is to enable an appropriate balance between goal achievement and the maintenance of acceptable safety margins.

Central to the proposed model is the concept of *schemata* which represent functional units of action control at different levels of abstraction. In the model, to two general schema levels are proposed: (a) *Basic schemata* and (b) *task context schemata*. Basic schemata may be further subdivided into (i) *sensory-motor schemata* and (ii) *semantic schemata*. The former are directly linked to sensation and actuation and implement real-time sensory-motor acts or activities such as “keep in lane”, “avoid front obstacle” and “press button”. Sensory-motor schemata also include active sensing, for example, “look left”. Semantic schemata, by contrast, represent perceptual acts such as “recognise traffic light”. Finally, task context schemata represent more general tasks such as “follow the car ahead” or “turn right at T-junction”.

In terms of the model, attention selection may be conceptualised as the selection of schemata. Thus, *attention* represents the outcome of this process, i.e., a set of active schemata. In the model, schemata are selected by virtue of their level of activation and the selection process involves collaboration and competition between schemata which may be biased by sensory input as well as various internal sources of activation. This is largely based on the *contention scheduling* mechanism proposed by Norman and Shallice (1986). Collaboration between schemata results in *schema coalitions*. For example a “turn-right at T-junction” task context schemata may be associated with lower-level, basic, schemata such as “look left”, “recognise car“, “slow down”, “turn right” etc. Thus, an active schema coalition will determine how attention and actions are proactively selected in a certain task context. Schemata may also compete. Thus, schemata involved in a winning coalition will inhibit related schemata which are not members of that coalition.

The excitability of a schema depends on its *strength*, which determines the degree to which it is *automatised*, an idea derived from Cohen et al, (1990). Strong schemata may thus be triggered and run with little effort. By contrast, weak schemata require top-down *cognitive control* bias to become active and/or override competing stronger schemata. Automaticity, and hence schema strength, develops with experience, in particular through repeated exposure to *consistent*, as opposed to *variable*, perception-action mappings (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; Schneider, Dumais and Shiffrin, 1983).

Based on these ideas, specific mechanisms for Trick and Enns' (2009) four selection modes could be outlined. In terms of the model, *reflexive* (bottom-up, automatic) selection occurs though stimulus-driven activation of strong (i.e., automatised) schemata. This may also involve the activation of context schemata, which corresponds to *gist perception*, that is, the rapid and effortless holistic perception of a scene (Potter, 1975). *Habitual* (top-down, automatic) selection of strong basic schemata is driven by associated task context schemata, which, as just described, are initially triggered reflexively by familiar scenes. Thus, basic schemata relevant in a certain context (such as "look left" in the "turn-right at T-junction" context) may be triggered automatically in advance, thus representing implicit (non-conscious) *expectations* on what information and actions are relevant in the upcoming scenario. This is strongly related to the phenomenon known as *contextual cueing* studied by Chun and Jiang (1998, 1999).

Deliberate (top-down, controlled) selection is driven by *cognitive control* and involves the specific biasing of weak (non-automatised) schemata in situations when they are needed to accomplish task goals. This may also involve overriding stronger schemata selected reflexively or habitually. Deliberate selection is thus, for example, deployed in new or challenging conditions such when entering a novel complex intersection, or when motivated towards a specific goal which requires optimising driving performance (e.g., driving faster than usual to keep a fixed time schedule). It is also needed to inhibit habitual tendencies such as the strong tendency of a Swedish driver (used to right-hand traffic) to look left when about to turn right at a T-junction in the UK. Deliberate selection also implements the basis for working memory, which corresponds to the active maintenance of schemata in the absence of stimulus input.

Finally, *exploration* (bottom-up, controlled) also involves cognitive control. However, by contrast to the specific, goal-directed, biasing involved in deliberation, exploration, in terms of the model, involves a global increase in schema activation, which facilitates bottom-up selection of weaker schemata. This typically occurs in non-demanding driving situations where drivers scan the environment for potentially interesting information (Hills, 1980). Both deliberation and exploration requires effort and is generally associated with increased arousal.

Moreover, all forms of selection may be biased by a *value system* with links to the individual schemata. Hence, a schema associated with value will have a competitive advantage in the competition with other schemata. The value system is also involved in the self-regulatory recruitment of cognitive control, where cognitive control is recruited when schemata are in conflict or the currently selected schema yields low value (an idea based on Botvinick et al., 2001). Finally, the value system plays a key role in directing schema learning. The proposed model is schematically illustrated in Figure 8.

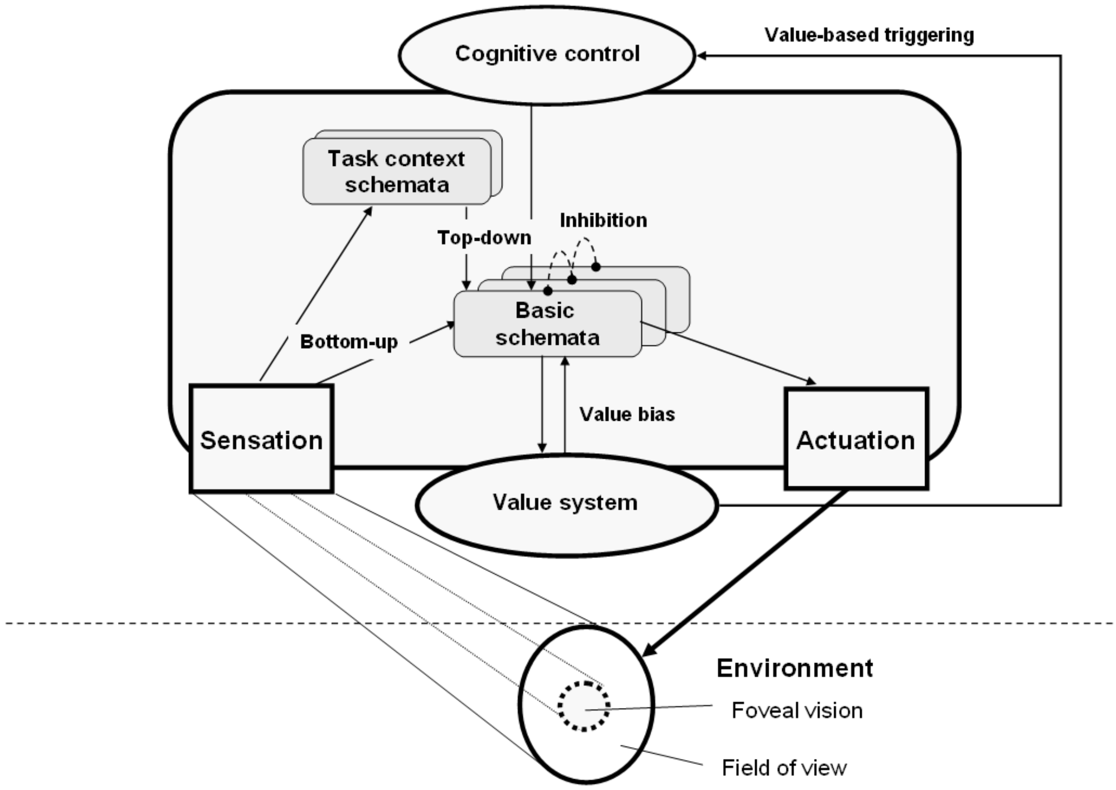

Figure 8 General illustration of the proposed attention selection model. Arrows represent excitatory and dots inhibitory links.

5.5.2 Model application

It was demonstrated by a concrete working example how the model may account for attention selection in the type of intersection scenario studied by Summala and colleagues (Summala and Räsänen, 2000; se Section 2.1.2). It was also discussed how the model suggests a novel way to conceptualise the relation between attention and crashes and how this may be used to guide analysis of accidents and incidents in naturalistic driving data. Moreover, based on the model, a taxonomy of dual task interference mechanisms was outlined, involving three main types of interference: (a) *Peripheral interference* (the basic competition for sensory and actuator systems such as the eyes and the hands) (b) *structural (cross-talk) interference* (competition between schemata) and (c) *control interference* (competition for cognitive control). Moreover, based on the model, precise definitions of driver inattention and driver distraction were proposed, based on the more general definitions suggested by Regan, Hallet and Gordon (in press). It was further suggested how value biasing, a key feature of the model, may influence the willingness to engage in secondary tasks while driving and how this may explain the extreme risks found for certain secondary task activities such as text messaging.

Finally, it was discussed how the proposed model relates to existing attention selection models, and some further practical implications were outlined. Some directions for future work were also suggested, including the possibility to implement the model computationally.

6 Discussion

This chapter discusses and summarises the main theoretical and empirical contributions of the present thesis with respect to the specific aims stated in Chapter 4. The following section discusses the first aim, the development of a novel theoretical framework for understanding attention selection in driving (Paper IV and V), and relates the proposed framework to the existing theories of attention reviewed in Chapter 3. Section 6.2 discusses the empirical results obtained in Paper I, II and III, focusing on the effects of working memory load on driving performance and mechanisms behind expectancy and proactive attention scheduling. Section 6.3 discusses the implications of the present findings regarding the generalisability of experimental studies to the real world (Aim 4). Section 6.4 addresses how attention may relate to crash risk (Aim 5), and discusses how the present model may be used to guide accident and incident analysis. Section 6.5 discusses applications of the present findings in the areas of countermeasure development and evaluation method development. Finally, Section 6.6 provides some general conclusions.

6.1 A novel theoretical perspective on attention selection in driving

This section places the conceptual framework, and the specific attention selection model, developed in the present thesis (Paper IV and V) into the theoretical context reviewed in Chapter 3. The following section discusses the key principles of the attention selection model in relation to the existing models on which it was based. Section 6.1.2 then discusses how the present model relates to existing limited capacity model that still dominate applied research on attention in driving. Section 6.1.3 addresses how the key concepts attention, expectancy, inattention and distraction may be conceptualised and precisely defined in terms of the present model. Finally, Section 6.1.4 discusses limitations and suggests some directions for future development of the model.

6.1.1 Accounting for attention selection in everyday driving

The first specific aim of the present thesis was to develop a conceptual model of attention selection as it occurs in natural driving situations as opposed to constrained laboratory conditions. A key starting point for the model development was that attention selection could be viewed as a form of adaptive behaviour. As suggested in Paper IV, adaptive behaviour in driving results from balance between multiple excitatory and inhibitory goals/drives and can be generally conceptualised in terms of the maintenance of a subjective *comfort zone* which defines the safety margin to an objective, physically definable, *safety zone* boundary where a crash becomes unavoidable. The comfort zone is individually determined by a value system and value is represented in the brain/body by emotional signals perceived in terms of feelings (Damasio, 1994). *Adaptive driver behaviour* may thus be defined as a continuous regulation of behaviour, based on anticipation and perceptual feedback, with the purpose to obtain goals while remaining safely within the comfort zone. These concepts are based on converging ideas in the general driver behaviour literature (Summala, 2007; Fuller, 2007; Vaa, 2007), which partly originate in the classical model of automobile driving by Gibson and Crooks (1938). However, there have been few links between these types of models and research on driver attention. One exception is the control-theoretic model of driver distraction proposed by Lee et al. (2009). The present framework makes the link more explicit by proposing that attention selection can be regarded as a form of adaptive behaviour. More specifically, according to the present framework, the key *function* of attention in natural driving is thus to select the right action at the right time in order to achieve goals while at the same time maintaining acceptable safety margins (that is, remaining within the comfort zone).

While basic attention research tends to view top-down selection as always controlled and bottom-up selection as an automatic process, Trick and Enns' (2009) suggested that this may lead to ignorance of key aspects of attention selection in driving. Their 2-dimensional framework has been adopted in the present thesis and a key objective of the present model development was to outline specific selection mechanisms for Trick and Enns' four general attention selection modes: reflex, habit, deliberation and exploration.

Moreover, while basic research on attention tends to focus on the role of attention in perception (for example in laboratory visual search tasks), attention in natural tasks is strongly linked to *action*. The schema representation used in the present model is well suited to capture this intimate relation link between attention and action in natural tasks and also accounts for the role of task context in influencing habitual selection in routine situations. The schema concept was largely adopted from Norman and Shallice (1986) although it has been used by numerous other authors (see Arbib, 1992 and Pezzulo, 2007 for reviews). Other concepts such as *behaviours* (Brooks, 1991), *microbehaviours* (Sprague and Ballard, 1993) or *visual routines* (Hayhoe, 2000; Salgian and Ballard, 1998) are essentially similar to schemata as conceived in the present model, that is, as functional units of action control.

The presently proposed attention selection mechanism was largely based on Norman and Shallice's (1986) contention scheduling principle, which involves a set of parallel, potentially competing, schemata, selected by virtue of their level of activation. The selection could then be biased top-down or bottom-up by various sources. In the present model these sources include sensory input, task context schemata, cognitive control and the value system. This general idea is also largely in line with the biased competition hypothesis of the neural basis for attention selection (Desimone and Duncan, 1995) but conceptualised here on a more abstract level, with a stronger focus on action selection.

However, Norman and Shallice (1986) did not suggest any specific mechanism behind automaticity but merely suggested that those processes that can be implemented by contention scheduling alone, and thus do not require bias from the supervisory attention system (SAS), are automatic. This is hence similar to the classical, somewhat circular (Navon, 1984; Neumann, 1987), view that automatic processes are those that do not require attentional resources. By contrast, the present model suggests a more specific conceptualisation of automaticity in terms of *schema strength*, which develops with repeated exposure to consistent stimulus-action contingencies in the real world (Shiffrin and Schneider, 1977; Schneider et al., 1983). This idea was mainly adopted from the model of Cohen et al. (1990), further developed in Miller and Cohen (2001) who proposed that automaticity can be understood in terms of neural pathway strength. Thus, in terms of the present model, strong schemata implement automatic (reflexive and habitual) selection.

In the present model, weak schemata need to be biased by *cognitive control* to become active or to override strong, competing, schemata. This concept was adopted from Miller and Cohen (2001) and is essentially similar to the SAS proposed by Norman and Shallice (1986). Hence cognitive control is needed for controlled selection (deliberation and exploration). Moreover, *working memory* may be viewed as deliberate selection (active maintenance), of schemata in the absence of sensory input. This provides a strong basis for interpreting the present empirical results (Paper I-III) on the effects of working memory load on driving performance, as further discussed in Section 6.2.2).

However, neither Miller and Cohen (2001), nor Norman and Shallice (1986), address how cognitive control is recruited. An account of this in needed to avoid the homunculus problem (who controls cognitive control?) and but also to understand how attention is self-regulated in natural driving conditions. The present model suggests that such self-regulation is based on continuous feedback from the *value system*, which monitors the performance of the schema system in terms of whether the current task yields sufficiently valuable outcome and/or whether schemata are in conflict. If the value system indicates that current performance is insufficient to meet task demands or there is a conflict between schemata, cognitive control is recruited to resolve the problem by means of deliberate selection. This idea is largely based on the neurobiologically based model by Botvinick et al., (2001), but also generally in line with the control-theoretic accounts of Lee et al. (2009) and Hockey (1997).

Schema selection is also strongly biased by associations with a value system which may be innate or established through experience. This idea, which was not considered by Norman and Shallice (1986), was mainly inspired by the computational models developed by Sporns et al., (2000) and Sprague and Ballard (2003). In line with Vuilleumier (2005), the value biasing mechanism is assumed to work according to the same principles as other top-down and bottom-up biases in the model.

The present model is also generally compatible with the SEEV model developed by Wickens and colleagues (e.g., Wickens and McCarley 2008; Wickens and Horrey 2009), which incorporates many of the key aspects attention selection in natural driving addressed in the present thesis. However, SEEV is still essentially a model of visual scanning and does not provide any specific account of attention selection mechanisms.

The present model thus represents a synthesis of several converging themes in the basic attention literature, applied here for the first time in driving domain. The model also provides a link between these attention models and the general driver behaviour literature. While the present model is most strongly related to the model by Norman and Shallice (1986), it incorporates several additional aspects of strong relevance to everyday driving such as a more specific account of automaticity, the self-regulatory deployment of cognitive control and value biasing. The following section addresses how the present model relates to models in the limited capacity tradition.

6.1.2 Limited capacity and dual task interference

While the main focus of the present model was to account for aspects traditionally not accounted for by limited capacity models, such as those discussed in the previous section, it does not deny the existence of limited capacity and dual task interference. On the contrary, the model offers a precise taxonomy of different forms of dual task interference, based on the distinction between peripheral, structural and control interference (see Paper V). Many limited capacity models are less specific in this respect. For example, multiple resource theory (Wickens, 1984, 2002) is rather vague on the actual mechanisms underlying the different resources. On the one hand, resources are sometimes described as the “fuel” of attention (Wickens and McCarley, 2008), a characterisation which, in terms of the present model, best fits the role of cognitive control. However, at the same time, specific sensory functions such as focal vision are also considered as resources (Wickens, 2002). Peripheral interference, such as the competition for the eyes by spatially separated stimuli, was originally considered outside the scope of resource theory (Wickens, 1984) but now seems to be included in the visual perceptual resource (Wickens, 2002; Wickens and McCarley, 2008). Based on the present model, this conflates the distinction between of peripheral and structural interference, which is of crucial importance in natural driving.

Similarly, the present model does account for "bottlenecks", but denies the strong claim by some authors that a single central bottleneck is sufficient to explain dual task interference (Pashler and Johnston, 1998; Levy et al., 2006). Rather, according to the present model, bottlenecks may occur at all three levels of interference: due to peripheral interference (since the eyes can only be directed towards one location at a time), structural interference (due to inhibitory cross-talk between similar schemata) as well as control interference (due to concurrent demands for cognitive control).

With respect to limited capacity models, the present model is probably most closely related to the model by Kahneman (1973) who proposed a general attentional resource related to the effortful deployment of attention, similar to cognitive control in the present model, and multiple satellite structures, similar to the basic schemata in the present model.

In general, the present model is not fundamentally incompatible with limited capacity models. Rather, it represents a *shift in focus* from attentional limitations to the role of attention selection in adaptive driver behaviour. A key claim of the present thesis is that the latter is the key to understand of the relation between attention, performance and crashes in natural driving, although capacity limitations do exist and must be accounted for as well.

6.1.3 Defining attention, expectancy, inattention and distraction

As discussed in Chapter 3, the concept of attention has been notoriously hard to pin down scientifically. In its common-sense meaning (represented, e.g., by the quote from James in Chapter 3), attention generally refers to the conscious, effortful selection of some perceptual inputs over others. This view is still prevalent in contemporary attention research, where "attentive" processes generally refers to those that are conscious and effortful (i.e., controlled) while "pre-attentive" processes are unconscious and effortless (i.e., automatic). Moreover, top-down selection is generally viewed as controlled while bottom-up selection is considered automatic.

However, this view of attention is difficult to apply in the driving domain where many key aspects of performance are strongly overlearned and automatised and thus, in this view, does not involve attention at all. The present thesis suggests a different conceptualisation of attention selection which includes all four selection modes suggested by Trick and Enns (2009; reflex, habit, deliberation and exploration). As described above, the model defines *attention selection* as the selection of schemata, and *attention* as the outcome of this processes, that is, a set of active schemata. Trick and Enns' four modes of selection then relate to *how* the schemata are selected, that is, whether selection is driven bottom-up or top-down and whether it involves cognitive control. Hence, in this view, attention selection may be both controlled and automatic. From this perspective, the traditional notion of attention refers mainly to deliberation while the other three selection modes fall outside the traditional scope of attention. While such a view may be sufficient to account for many laboratory phenomena, it clearly leaves out aspects of key relevance for understanding selection of information and action in natural driving situations.

Traditionally, a distinction is also often made between various forms of attention, such as selective, divided, switched, focused and sustained attention, however, often without precise definitions of the mechanisms involved (e.g., Wickens and McCarley, 2008). The present model offers a clearer conceptualisation of such varieties of attention. For example, to the extent that certain schemata are selected over others, attention is selective. If several schemata are selected in parallel (while, for example, competing for cognitive control) attention is divided. Sustained attention involves the deployment of cognitive control over a longer time period to sustain activation of weak schemata. However, the presently proposed general term "attention selection" applies to all these variants and also emphasises the active nature of attention.

Furthermore, *expectancy* may be defined as the anticipatory top-down biasing of specific schemata. Thus, expectancy and attention can essentially be viewed as two sides of the same coin. Like attention, expectancy may be controlled and accessible to conscious awareness (deliberate) as well as automatic and unconscious (habitual).

Paper V also discusses how *driver inattention* and *driver distraction* may be more precisely understood in terms of the present model. If one accepts the general definition proposed by Regan et al. (in press) of driver inattention as *"Insufficient, or no attention, to activities critical for safe driving"*, this can be understood in terms of the present model as cases where certain schemata critical for "safe driving" are not sufficiently active (for whatever reason). Regan et al (in press) further define *driver distraction* as: *"The diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving."*

In terms of the present model, distraction can be understood as the selection of non-safety-critical schemata that compete with those considered safety critical, with the consequence that the activation of safety-critical schemata is reduced. According to the present model, this may occur due to any of the three proposed types of dual task interference (see Paper V):

a. *Peripheral interference:* If gaze is directed off-road, safety-critical schemata may to become deactivated (or fail to be triggered) due to reduced visual input;
b. *Structural interference:* If, for example, the secondary task is strongly perceptually loading, safety-critical schemata may be inhibited due to structural cross-talk interference between schemata.
c. *Control interference:* If the competing task demands cognitive control, weak (non-automatised) safety-critical schemata may become deactivated due to a lack of cognitive control.

However, the model does not resolve this more philosophical problem of how to define a "safety critical activity" (see Regan et al., in press, and Rasmussen, 1990, for a further discussion of this issue).

6.1.4 Limitations and directions for future model development

One issue somewhat left open in the present version of the model concerns the precise role of arousal. It is generally accepted that the effortful deployment of attention (cognitive control) is associated with an increased in arousal (Kahneman, 1973; Aston-Jones and Cohen, 2005). Arousal is manifested in the brain as a global modulation of neural activity originating from the reticular activation system in the brainstem and this modulation is generally believed to play a key role in attention (Coull, 1998). In particular, the influential cue utilisation hypothesis proposed by Easterbrook (1959) suggests that an increase in arousal, or "emotional drive", leads to increased attentional selectivity resulting in a narrowing of attention. This constitutes an explanation for the classical Yerkes-Dodson law (Yerkes and Dodson, 1908) which states that performance depends on arousal according to an inverted U-shaped function. However, the physiological mechanisms behind effort and arousal and its link to attention are still only partially known and to keep the present model as simple as possible, these aspects were not explicitly included in the model but rather conceptualised as an implicit effect of cognitive control. However, future developments of the model could incorporate more specific mechanisms for how arousal modulates schema selectivity. Here, the work by Aston Jones and Cohen (2005) and Gilzenrat et al. (2010) is a good starting point.

A related issue concerns the mechanisms behind the self-regulatory recruitment of cognitive control. In the present version of the model, these mechanisms were rather vaguely defined in terms of monitoring of schema conflicts and outcome by the value system. This idea was based on the much more detailed neurobiological model by Botvinick et al. (2001; Botvinick, 2007) and future development of the model could incorporate more detailed accounts of these mechanisms, which may also be linked to the arousal modulation just discussed (as suggested by Aston-Jones and Cohen, 2005).

In the future, it would also be interesting to explore the possibilities to implement the present model computationally. As illustrated, for example, in the "conceptual" simulation in Paper V (Figure 4 and 5 in Paper V), the context-driven interactions between top-down and bottom-up factors in natural tasks may be rather complex and, thus, a computational model may yield novel predictions not readily accessible by conceptual analysis. Existing work in this area, that may serve as potential starting points, include the computational implementation of the conceptual Norman-Shallice model by Cooper and Shallice (2000) and the work of Ballard and colleagues (Salgian and Ballard, 1998; Sprague and Ballard, 2003). Also, Botvinick (2008) provides a useful review of computational hierarchical action/attention selection models that should be applicable also to the modelling of drivers' attention selection in naturalistic driving situations.

6.2 Understanding the relation between attention and driving performance

This section summarises these empirical results obtained in Paper I-III, relates them to the existing literature reviewed in Chapter 2 and suggest how they may be interpreted in terms of the present theoretical framework (outlined in Paper IV and V and discussed in the previous section). The discussion focuses on the key open empirical research questions identified in Chapter 2, relating to the specific aims 2 and 3 of this thesis: How working memory load affects driving performance and the key mechanisms behind expectancy and dynamic attention scheduling. However, effects of visual time sharing, partly addressed in Paper I, are briefly addressed as well

6.2.1 Effects of visual time sharing

As concluded in Chapter 2, effects of visual time sharing on driving performance are relatively well understood. Paper I found, in line with existing studies (Zwahlen, Adams, & de

Bald, 1988; Greenberg et al., 2003; Horrey et al., 2006; Merat and Jamson, 2008), that visual time sharing led to increased standard deviation of lane position (SDLP) compared to baseline driving (no task). However, this effect was only statistically significant in one of the three sub-studies, the fixed base simulator. A strong tendency was also observed in the moving-base simulator but no effect was observed in the field study. There was no increase in the number of lane exits in any of the sub-studies. The visual task also led to a relatively strong increase in steering wheel reversal rate. In a subsequent more detailed analysis of this data, which also included data from a rural road scenario not reported in Paper I, Markkula and Engström (2006) found a typical pattern where lane deviation builds up during glances away from the road which is intermittently corrected by a relatively large steering wheel correction when the driver looks back. An example of this pattern is shown in Figure 9.

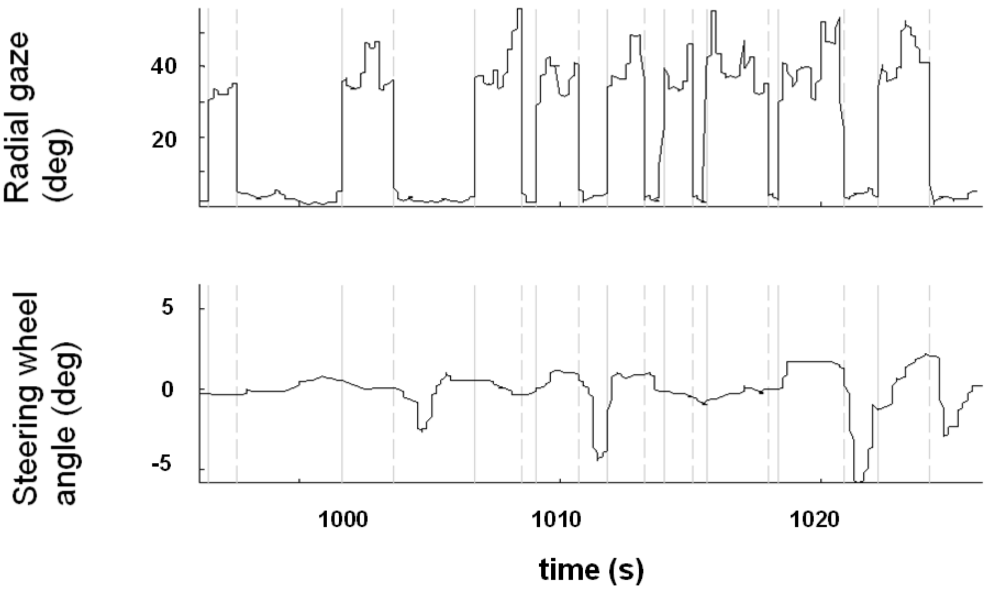

Figure 9 Synchronised gaze and steering wheel angle signals during visual time sharing illustrating the typical large, intermittent, steering correction when the driver looks back to the road. Radial gaze represents the combined vertical and horizontal gaze angle (from Markkula and Engström, 2006)

Also in line with existing studies (Curry, et al., 1975; Antin et al., 1990; Merat and Jamson, 2008), the results from Paper I showed that visual time sharing resulted in a reduction of speed. There was also a significant increase in heart rate and skin conductance which indicates increased arousal. Finally, as reported in a companion paper providing a more detailed analysis of visual behaviour (Victor et al., 2005), glance durations to the IVIS display were consistently shorter in the field than in the simulator.

Effects of visual time sharing on object and event detection were not empirically investigated in the present thesis. However, as reviewed in Chapter 2, other studies have found that visual time sharing leads to significant response delays, both to slowing lead vehicles (Lamble et al., 1996; Horrey et al., 2006) and artificial stimuli (Merat and Jamson, 2008). This is consistent with naturalistic driving studies (Klauer et al., 2006; Olson et al., 2009; Hickman et al., 2010) which have found a strong relation between visual diversion from the forward roadway and the risk for being involved in safety critical events.

Interpretation

In terms of the taxonomy of interference mechanisms outlined in Paper V, effects of visual time sharing on event detection are partly due to peripheral interference related to competition for the eyes and partly due to structural (cross-talk) interference between competing schemata and/or control interference (competition for cognitive control). It seems like the latter type of interference dominates for artificial detection tasks such as the Peripheral Detection Task (PDT), as indicated by the results of Merat and Jamson (2008) who found the same effect of a phone dialling task regardless of the stimulus modality of the detection task stimuli. This may be explained by the fact that these stimuli are relatively predictable and the subject is able to schedule the visual time sharing to reduce effects of peripheral interference. However, peripheral interference seems to play a stronger role in affecting responses to critical events, such as a braking lead vehicle (Lee et al., 2002; Horrey et al., 2006). This makes sense given that these events are less predictable and thus may more often coincide with off-road glances. As indicated by recent naturalistic observation and driving studies (reviewed in Section 2.1.2), peripheral interference in responding to critical events (due to eyes off road) is probably the most important single factor contributing to road crashes.

It seems likely that the increased lane deviation due to visual time sharing observed in Paper I occurred mainly due to peripheral interference related to the competition for the eyes. Even if lane keeping may be guided by peripheral vision (Summala, Nieminen et al., 1996), it may be assumed that the quality of visual input required for lane keeping is reduced during off-road glances. This leads to the intermittent lateral control strategy illustrated in Figure 9 resulting in increased lane keeping variability.

As demonstrated in particular by Salvucci and Taatgen (2008), a single bottleneck model may at least partly account for such peripheral interference during visual time sharing and its effect on lateral control. This is not surprising, given that the eye itself can be viewed as a strong bottleneck that must be deployed serially (although, as noted by Wickens, 2002, ambient vision may to a large extent function in parallel to focal vision).

However, limited capacity models fail to account for other aspects of the results obtained in Paper I, in particular the compensatory speed reduction and the fact that lane keeping performance was not adversely affected in the field. The present model offers an alternative interpretation of these results, based on the general view of attention selection as a form of adaptive behaviour. In terms of the model, the results reported in Paper I can generally be understood as a mobilisation of attentional effort (deliberate selection) to keep the variability in lane position within acceptable boundaries, representing the driver's individual comfort zone. More specifically, when instructed to perform the visual task, the subjects mobilised cognitive control to manage the dual task situation. This resulted in increased arousal, as indicated by increased heart rate and galvanic skin response. In order to compensate for the degraded visual input from the forward roadway subjects reduced their speed. In the simulator sub-studies, the participants allowed rather long glances to the secondary task display which resulted in increased keeping variability. However, this variability may still be regarded to be within their comfort zones. In the field, however, the comfort zone could be expected to be smaller (and safety margins larger) due to the actual risk involved; hence glances to the S-IVIS display were shorter and lane keeping was not allowed to deteriorate.

A general implication of this interpretation is that effects of time sharing on driving cannot be predicted solely based on dual task interference due to limited capacity, but also strongly depends on adaptive attention allocation strategies. The degree to which the driver is willing to take the eyes off the road and let lane keeping deteriorate is determined, on the one hand, by the motivation to accomplish the secondary task and, on the other, by the driver's individual comfort zone. If the comfort zone is large (e.g. when driving on a wide motorway in sparse traffic or in the simulator at no real risk), drivers may allow for relatively large performance decrements which will not be predicted solely based on the difficulty of the secondary task. Thus, adaptive behaviour may be very prevalent, not only in real world driving situations, but also in classical dual task settings, at least as long as attention allocation is self-paced and the driver is allowed to operate in satisficing mode. The present thesis offers a theoretical framework for understanding such effects which are not well accounted for by traditional limited capacity models.

6.2.2 Effects of working memory load

As reviewed in Chapter 2, effects of working memory load on driving performance are poorly understood and existing studies have often yielded apparently inconsistent results. Hence, one of the key aims of the present thesis was to obtain a better understanding of how working memory load affects driving performance and identify possible reasons for the existing inconsistencies. Below the main present findings with respect to event detection/response, semantic encoding and vehicle control are discussed separately, followed by a general discussion on how these results may be reconciled based on the present theoretical framework.

Working memory load and event detection-response

Paper II found that working memory load led to a small but significant response delay to a braking lead vehicle with brake lights turned on. The effect was independent of repeated exposure and occurred also for the first, entirely unexpected, braking event. This is generally in line with existing similar studies that investigated the effect of working memory load on responses to lead vehicle braking events cued by brake light onsets (e.g., Brookhuis, et. al.1991; Alm & Nilsson, 1995; Lee et al., 2001; Strayer, et al., 2003; Strayer and Drews, 2004; Strayer et al., 2006; Levy et al., 2006; Salvucci and Beltowska, 2008). However, Paper III used a different type of scenario, a suddenly turning incoming vehicle, which did not involve any predictive cues. Rather, responses in this scenario were triggered solely by looming and movement cues, at least for the first, unexpected, event. In this study, no response delay due to working memory load was found. This was the case for brake onset time as well as gaze response time. This result is consistent with other studies that included non-cued events (Muttart et al., 2007; Baumann et al., 2008) and supports the idea that working memory load mainly affects responses to cued events.

Moreover, in a follow-up on Paper II, Engström (2010a) conducted a meta-analysis of existing lead vehicle braking studies on working memory load which strongly indicated the response delay attributed to working memory load in these studies depended strongly on scenario criticality. More specifically, studies that have employed non-critical lead vehicle braking scenarios with large initial headways have typically found large effects, whereas studies that used more critical scenarios (small initial headways) found smaller effects.

Working memory load and semantic interpretation/encoding

Paper III found, in line with Strayer et al (2003), that working memory load strongly impaired subsequent recognition of roadside billboard signs, suggesting that working memory load affects semantic encoding into long-term memory. In another study conducted within the scope of the present thesis, Engström and Markkula (2007) further demonstrated that working memory load impairs semantic *interpretation* of information. The study employed the Lane

Change Test (LCT; Mattes, 2003) methodology, where subjects are required to change to a specified lane when commanded by pop-up roadside signs. It was found that working memory load led to a significantly increased number of erroneous lane selections. The most common error was that the driver did not perform any lane change at all. However, there were also several cases where a lane-change was made, but to the wrong lane. This indicates that the sign was detected but incorrectly interpreted.

Working memory load and vehicle control

Paper I, Paper III and several other studies (Brookhuis et al., 1991; Östlund et al., 2004; Horrey and Simons, 2004; Törnros and Bolling, 2005; Mazzae et al., 2005; Mattes et al., 2007; Merat and Jamson, 2008; Mehler et al., 2009; Reimer, 2009) found *reduced* lane keeping variability due to working memory load. However, as reviewed in Chapter 2, these results are inconsistent with other studies that found the opposite effect (i.e., impaired lateral control due to working memory load). However, these studies differed from the present studies (and the others cited above) in several important respects. For example, Salvucci and Belowska (2008) explicitly instructed subjects to minimise lane deviations from the lane centre. Other studies that found this effect employed artificial tracking tasks (Briem and Hedman, 1995; Strayer et al., 2001; Creem and Profitt, 2001) or non-standard driving task such as steering with a track ball or a computer mouse in a brain scanner (Just et al., 2008).

In both Paper I and Paper III, the reduced lane keeping variability was accompanied by an increased frequency in micro steering reversals. However, in Paper I, this effect was rather weak and found only in the field. A more detailed analysis of steering wheel data from the same study (as well as data from the simulated rural road) was conducted by Markkula and Engström (2006). This analysis demonstrated that, by contrast to visual tasks which, as described above, induce relatively large steering reversals (Figure 9), working memory load induce an increase in microscopic steering corrections. This effect is illustrated in Figure 10. Thus, the weak effect on steering wheel reversal rate found in Paper I may be explained by a too large setting of the gap size parameter (1 deg,). This was further supported in Paper III, which, in line with Markkula and Engström (2006), found the strongest effect of working memory load on steering wheel reversals for the smallest gap size (0.1 deg.). Similar effects of working memory load on steering activity have been found in other studies, although these have generally used different metrics such as steering entropy (Boer, 2000; Boer et al., 2005), which is not diagnostic of the amplitude of steering wheel movements.

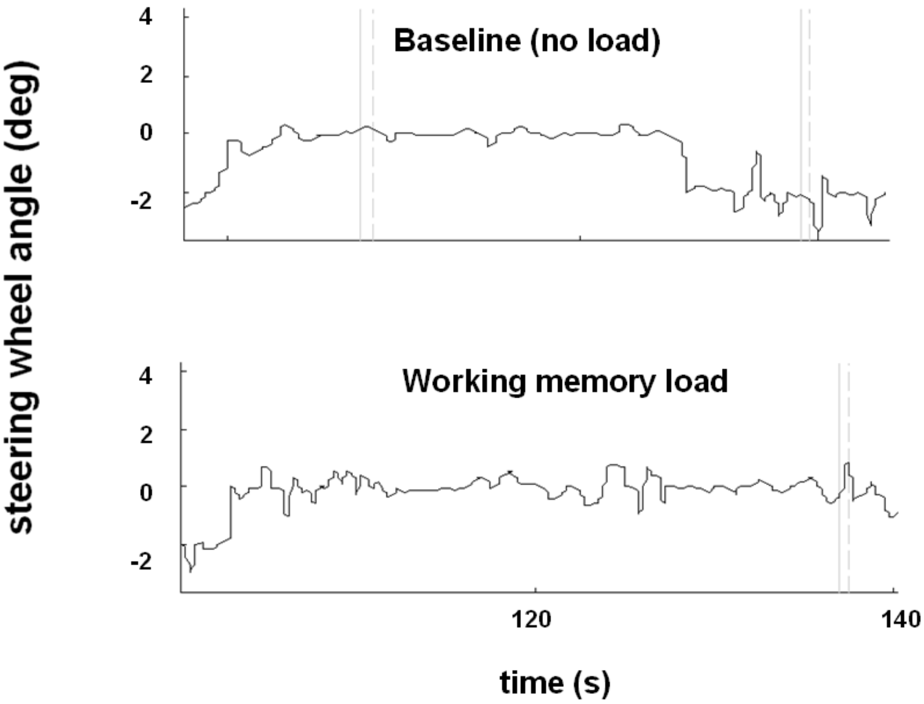

Figure 10 Comparison of the steering wheel angle signal for baseline driving and driving while performing a cognitively (working memory-) loading task (from Markkula and Engström, 2006)

Working memory load had no effects on vehicle speed, neither in Paper I nor in Paper III. This indicates that drivers did not increase longitudinal safety margins to compensate for the reduced attention. As reviewed in Chapter 2, other studies have found inconsistent results with respect the effect of working memory load on safety margin compensation (Patten et al., 2003; Horrey and Simons, 2007; Östlund et al., 2004).

Working memory load, visual behaviour and physiological state

Another key finding in Paper I was that working memory load induces a gaze concentration towards the road centre. This effect is illustrated in Figure 11, adopted from Victor et al., (2005) who conducted a more detailed analysis of the same data. Consistent with this, Paper III found that working memory load significantly reduced the visual exploration of billboards. The gaze concentration effect have also been found in several other studies (Recarte and Nunes, 2003, Harbluk et al. 2007; Reimer, 2009).

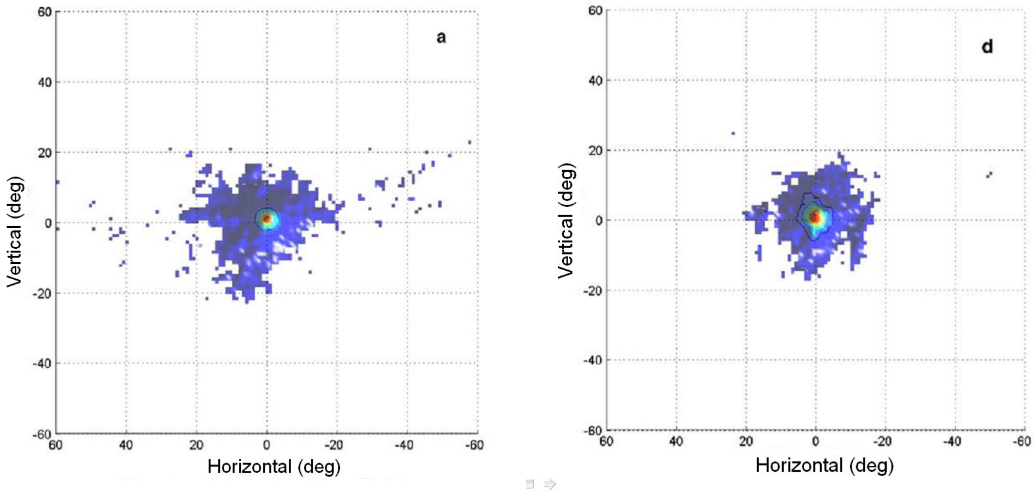

Figure 11. Spatial density plots of gaze angle, demonstrating gaze concentration as a function of working memory load. These data were obtained in the field for motorway driving. Left panel: Baseline driving (no task). Right panel: a cognitively loading working memory task (from Victor et al., 2005).

Paper I also found some indications of increased physiological arousal due to working memory load. However, these effects were rather weak and only statistically significant in the field. Mehler et al. (2009) found a much stronger relationship between working memory load and physiological arousal and it is possible that the present weak effects may have been due to limited sensitivity of the measurement equipment.

Interpretation

Taken together, the present results from Paper I and Paper III indicate that working memory load leads to more focused scanning and steering behaviour, resulting in reduced lateral control variability but, by contrast to visual tasks, no compensation of safety margins. There were also weak indications in Paper I that working memory load led to increased arousal.

These results seem difficult to reconcile with existing limited capacity models. The predictions of multiple resource theory with respect to effects of working memory load are rather vague and have been subject to debate. For example, Moray (1999), advocating a single channel theory, suggested that MRT should not predict any interference between mobile phone conversation and driving since these tasks rely on different resources. However, Wickens (1999) replied that such interference is accounted for by common demands for perceptual and cognitive resources within the stage dichotomy. However, resource models do not offer precise predictions of which aspects of driving that would be susceptible to such interference.

By contrast, single bottleneck models (Pashler and Johnston, 1998; Salvucci and Taatgen, 2008) offer very detailed predictions, suggesting that working memory loading tasks compete with driving tasks for a central bottleneck and, thus, the two tasks have to be performed in a serial manner. This yields the key prediction that working memory load should lead to less frequent steering corrections and, as a result, increased variability in lane position (Salvucci and Taatgen, 2008). Moreover, responses to critical events should always be delayed by a fixed amount during working memory load (Salvucci and Taatgen, 2008). These predictions are in line with some existing findings but contradictory to others. In particular, the predicted impairment in lateral control has been found for artificial tracking tasks, in experimental set-ups that used non-standard input controls and when subjects were instructed to optimise lane keeping performance. However, the present studies (Paper I and III) as well as numerous other studies have found the opposite effect, that is, enhanced lane keeping, accompanied by *increased* steering frequency. These results directly contradict the predictions of single bottleneck models. Single bottleneck models are, however, in line with the finding of Paper II, and several other studies, that working memory load delays responses in lead vehicle braking scenarios. However, they do not explain the finding in Paper III, supported by Muttart et al. (2007) and Baumann (2008) that responses solely triggered by looming appear to be unaffected by working memory load. Neither do they explain the large differences in the response delay observed by different studies which seem to be directly related to scenario criticality (Engström, 2010a).

The present framework offers a possible explanation for these apparently contradictory results, namely that *working memory load mainly affects controlled performance but leave automatised tasks unaffected*. More specifically, in terms of Trick and Enns' (2009) framework, the hypothesis suggests that working memory load should impair deliberation and exploration and induce a resort to reflex and habit. In terms of the present model (Paper V), automaticity is determined by the strength of schemata which is established through repeated exposure to consistent mappings during real world driving. Weak, non-automatised, schemata require cognitive control to be activated. Since working memory loading tasks require cognitive control, top-down activation of weak schemata will be depleted resulting in impaired performance on non-automatised tasks. However, strong, automtatised, schemata which do not rely on cognitive control should not be affected by working memory load.

The empirical results obtained in Paper I-III, as well as other studies, are generally in line with this interpretation. Normal lane keeping is a strongly automatised task and should thus, contrary to the prediction of Salvucci and Taatgen (2008), not be negatively affected by working memory load (Paper I, III). The same holds for responses to unexpected events solely triggered by looming cues, which were not affected in Paper III.

However, speeded braking responses to brake light cues can be regarded as controlled since brake light onsets normally do not require an immediate braking response. In real world driving, there is no consistent mapping between brake light onsets and immediate braking. Thus, these responses have not been automatised and should be slowed by working memory load (as found by Paper II). The same argument also apples to other predictive cues, such as the downstream traffic events studied by Muttart et al. (2007). However, it should be noted that this specific idea was not tested in a single experiment in the present thesis. In a future study, this could be straightforwardly tested by systematically varying the presence of brake lights in an unexpected lead vehicle braking scenario. The key model prediction would be that working memory load only delays responses when brake lights are present.

Semantic interpretation and encoding of information should also be impaired by working memory load (Paper III), given that this directly involves working memory.

This general hypothesis that working memory load mainly affects controlled performance may also explain why some existing studies found that working memory load induced impaired lateral control. As mentioned above, a common denominator of these studies is that they employed non-practiced lateral control task such as artificial tracking or non-standard control inputs. Hence, these tasks should rely on cognitive control and be affected by working memory load.

Still, Salvucci and Beltowska (2008), who used a normal lane keeping task, found impaired lane keeping due to working memory load, thus supporting the prediction of their bottleneck model. However, in this study, participants were instructed to minimise deviations to the lane centre, that is, to optimise performance. In terms of the present model, such optimising relies on cognitive control, which may explain this contradictory result. This idea was directly tested in Paper III, where half of the subjects were given a similar instruction as in Salvucci and Beltowska (2008). However, while the expected lane keeping enhancement was obtained for non-instructed subjects, the predicted impairment was not found for instructed subjects (working memory load had no effect for this group). Thus, the hypothesis that working memory load selectively affects controlled tasks was generally supported but not completely confirmed by the results of Paper III (possible reasons for the inconsistencies with Salvucci and Beltowska, 2008, are discussed in Paper IIII). An alternative way to directly test the hypothesis with respect to lateral control would be to manipulate automaticity in terms of the difficulty of the lateral control task. This could, for example, be done by altering the type of control device used for steering. Thus, a future study could compare the effect of working memory load on lane keeping performed with a normal steering wheel or a joystick. The present model would predict that working memory load induces enhanced lane keeping performance in the former case and impaired performance in the latter.

It should be noted that the suggested hypothesis may in principle be accounted for by limited capacity models. In terms of resource models, one may simply state that tasks not affected by working memory load do not require cognitive resources, that is, they are automatised. For bottleneck models, this would amount to giving up the strict assumption of single serial bottleneck. However, given the usually rather vague conceptualisation of resources or bottlenecks, it seems unclear *a-priori* which tasks that should be regarded as automatised (i.e., demanding no resources or bypassing the bottleneck) and which should be regarded as automatised. This makes such an account somewhat circular (see Neumann, 1987, and Navon, 1984, for similar arguments). The present model offers a more specific account of the mechanisms underlying automaticity (schema strength established through exposure to consistent mappings) which avoids this circularity and enables more specific predictions.

A key finding of the present thesis, as well as several previous studies, not discussed so far, is the enhanced lane keeping effect, accompanied by increased steering frequency and gaze concentration. This finding is clearly very difficult to reconcile with limited capacity models, which provide no plausible explanation why driving performance would be enhanced by cognitively loading tasks. One proposed explanation is that the enhanced lane keeping effect is due to an increase in steering effort to increase lateral safety margins to compensate for the reduced attention to the road (Törnros and Bolling, 2005; Reimer, 2009; Paper I). However, a problem with this hypothesis is that working memory load, unlike visual time sharing, does not consistently result in an adjustment of longitudinal safety margins, such as a reduction of speed (Paper I, Paper III). Given that this would be the least effortful way to increase safety margins, one would expect it to occur before any further effort is invested in lateral control.
The present model offers an alternative explanation, initially suggested in Paper I and further developed in Paper III. When driving in non-demanding conditions, drivers may invest cognitive control to visually explore the environment and allow lane keeping performance to degrade as long as safety margins are not violated. This leads to non-optimal, satisficing, lane keeping performance, which leaves room for improvement (that drivers are indeed satisficing

in the baseline condition was confirmed in Paper III, where performance improved substantially for drivers instructed to opimise lane keeping).

Since, according to the present model, visual exploration relies on cognitive control (Paper V), it should suffer under working memory load, as confirmed by Paper III. This leads to concentration of gaze towards the road centre (as found in Paper I) which yields enhanced visual input for lane keeping. This will enhance the strongly automatised lane keeping schema thus leading to more frequent steering corrections and improved lane keeping compared to the sub-optimal, satisficing, baseline performance. Hence, the effect should not be found for drivers that are optimising, as confirmed by Paper III.

The present framework also suggests a possible explanation for the inconsistent effects of working memory load on longitudinal control (speed and headway). Given that working memory load induces a resort to habit, one would expect loaded drivers to resort to their "default" longitudinal safety margins. Hence, if drivers are instructed to drive at the posted speed limit, the effect of working memory load on speed will depend on the difference between the posted speed and drivers', subjectively defined, default speed. Thus, some loaded drivers may speed-up while others may slow down when loaded by a working memory task. This implies that a key effect of WM load should be an increased between-subject variance compared to baseline, which was indeed found in Paper III (this was also found in the analysis for Paper II but eventually not reported in the paper).

To conclude, the present framework offers a novel interpretation of the effects of working memory load on driving performance that may reconcile apparently inconsistent results in the literature. In particular, the idea that working memory load mainly affects controlled performance, but leaves automatised tasks unaffected, represents a novel contribution of the present thesis that can be further tested in future studies. Further implications of these ideas with respect to the generalisability of results from experimental studies to the real world are discussed in Section 6.3. First, however, we will address how the present framework may account for mechanisms behind attention scheduling in natural tasks.

6.2.3 Expectancy and anticipatory attention scheduling

While both experimental and naturalistic driving studies provide strong evidence that glances in the wrong direction (most often off-road) induce long response delays and cause crashes, little is known about drivers' proactive attention and gaze scheduling. As demonstrated by Summala and colleagues (Summala and Räsänen, 2000) in the field and Shinoda et al. (2000) in the simulator, top-down factors, such as task goals and context-induced expectancy, seem to be of key importance in determining drivers' attention allocation and visual scanning patterns. However, the basic mechanisms behind top-down attention selection and scheduling are largely unknown. A key aim of the present thesis was to address this research gap.

In Paper II and III, expectancy and proactive attention scheduling was studied by means of exposing subjects to repeated critical events. A main goal was to examine to what extent top-down, expectancy-driven, attention selection and scheduling relies on cognitive control (i.e., represents controlled, as opposed to automatic, performance). As reviewed in Section 3.2.1, a widely held view is that top-down selection is controlled while bottom-up selection is automatic (e.g., Jonides, 1981).

In the present studies a critical event was repeated six times for cognitively loaded and non-loaded subjects. A key idea behind this experimental design was that repeated exposure to the events should gradually increase expectancy. Thus, the first, unexpected, scenario should be triggered mainly bottom-up while top-down selection should increase with repeated exposure.

Results

In Paper II, a lead vehicle braking scenario was repeated six times for loaded and non-loaded subjects. The key dependent measure was accelerator release time. There were significant main effects of both working memory load and exposure but no interaction. Working memory load led to a constant small (average 178 ms) response delay across exposures. Repeated exposure led to a strong reduction in response time for both loaded and non-loaded drivers, with the main effect (374 ms) between the first and the second exposure.

In Paper III, a critical scenario was again repeated six times. However, this time the scenario (an oncoming vehicle suddenly turning at a signalised intersection) was designed to be more critical than the lead vehicle braking scenario in Paper III, and automatically triggered by looming/movement cues. In addition to brake response time, eye-glances towards the oncoming vehicle were analysed in order to investigate how increased expectancy and working memory load influenced the participants' anticipatory attention scheduling strategies.

As in Paper II, repeated exposure reduced response time. With repeated exposure, both non-loaded and loaded subjects increased the number of glances towards the oncoming vehicle. However, as discussed above, working memory load did not affect braking responses in this scenario. However, working memory load affected adaptive strategies employed by the subjects. While many non-loaded subjects, with repeated exposure, initiated braking in anticipation of the event, such strategies were rarely adopted by loaded subjects. Moreover, many non-loaded drivers began to focus visual attention strongly on the oncoming vehicle, as indicated by significantly longer mean duration of single glances. This indicates a shift in attention scheduling *strategy* that did not occur for loaded drivers.

Interpretation

The results from Paper II and Paper III question the classical assumption that top-down selection is always controlled and bottom-up selection always automatic. In both Paper II and III, response times were reduced with repeated exposure but this improvement was not significantly affected by working memory load. Similarly, in Paper III, both loaded and non-loaded subjects increased the number of glances towards the oncoming vehicle with repeated exposure. This indicates that at least some forms of top-down selection may proceed automatically (i.e., does not rely on cognitive control). This also provides empirical support for Trick and Enns' (2009) two-dimensional framework where automaticity and top-down/bottom-up selection are treated as separate dimensions. The mechanism behind this automatic top-down selection is probably closely related to the *contextual cueing* phenomenon studied by Chun and Jiang (1998, 1999). These authors found in a series of laboratory experiments that co-varying patterns (that is, consistent mappings) could be learned implicitly (without awareness) and subsequently guide attention top-down in visual search. In terms of the present model, such contextual cueing may be conceptualised in terms of the activation of higher-level task context schemata which subsequently bias associated basic schemata responsible, for example, for braking avoidance and visual orientation towards potential hazards.

However, as indicated by Paper III, certain aspects of top-down selection do seem to rely on cognitive control, as indicated by the difference in single glance duration and braking strategies between loaded and non-loaded subjects. In terms of the present model, a key role of cognitive control is to override strongly automatised schemata in order to enable flexible behaviour when needed. In this scenario, the ability to maintain gaze fixed at the oncoming vehicle for an extended time period requires the overriding of habitual tendencies, for example, checking the traffic light at the intersection. Hence cognitive control is needed to enforce this change in scanning strategy, which explains why this ability is impaired by a working memory task that competes for cognitive control. Thus, the hypothesis proposed in the previous section, that working memory load mainly affects controlled performance, may be extended to the case of top-down attention scheduling: Working memory load leaves habitual (top-down, automatic) attention scheduling strategies unaffected but impairs the deployment of more flexible, deliberate (top-down, controlled), scheduling strategies.

An important aspect of the findings from Paper III was that the between-subject variance, in particular for brake onset time and single glance duration, increased strongly when the critical event was repeated. This effect was strongest for non-loaded subjects but occurred also for the loaded group. In terms of the present model, there are several potential sources of such variance. First, the main reason for the large variance between non-loaded subjects was clearly that only a subset of them adopted flexible strategies such as anticipatory braking or fixating gaze on the oncoming vehicle. In terms of the model, such strategies involve cognitive control, are deployed with effort, and thus depend ultimately on the goals and motivations of the individual subject. In an experimental situation, some subjects may be keen to demonstrate that they are able to avoid crashing into the oncoming vehicle, thus investing effort to perform in a more optimising mode, while others may be more indifferent (due to the lack of real risk), thus operating in a more satisficing mode. A second source of variance is that habitual attention scheduling schemata are strongly individual, as they have been shaped by previous experience and also strongly influenced by subjective value. Thus some subjects may have a stronger habitual tendency to scan the road for pedestrians or checking the traffic light, which will affect how their habitual attention scheduling patterns develop with repeated exposure (for example, a loaded subject with a strong "check traffic light" schema will devote fewer glances to the oncoming vehicle than a subject with a weaker "check traffic light" schema). Such individual differences could indeed be observed during the manual analysis of visual behaviour for Paper III. More generally, drivers also differ with respect to their preferred safety margins (i.e., the size of their comfort zones). As discussed above, this may explain the larger between-subject variance for loaded drivers with respect to mean speed found in Paper III. Whether drivers will increase or reduce speed when resorting to habitual behaviour under working memory load depends on their "default" safety margins. The present model offers a useful conceptualisation of such individual differences.

Paper V discusses how the model may account for the classical finding of Summala and colleagues (e.g., Summala and Räsänen, 2000; see Chapter 2 above) that a familiar context may induce erroneous expectations that do not match the situation at hand. In terms of the model, this occurs due to the initial bottom-up selection of a default, largely automatised, "turn-right at T-junction" context schema, which, in turn activates associated basic schemata such as "look left" and "search for cars" top-down. The model may also explain the finding by Theeuwes (1996) that response times and time to fixate a road sign depended on whether they were placed in an expected location: To the extent that the sign location matches the drivers' context-induced schemata, search should be fast. If there is a mismatch, search is slower. Finally, the model suggests a general explanation for inattentional blindness in terms of top-down application of a mismatching schema. Even if a stimulus manages to attract gaze bottom-up it will not influence behaviour if it fails to override the prevailing schemata. This is more difficult in perceptually loading conditions (Lavie, 2010) where competing schemata are actively suppressed. However, inherently strong schemata, that is, those that are largely automatised, should be relatively immune to inattentional blindness. This is in line with findings by Mack and Rock (1998) that familiar stimuli, such as ones own name, have a stronger chance to "break through" inattentional blindness.

This suggests several interesting directions for future empirical work. In particular, it would be interesting to investigate how attention scheduling strategies are affected by working memory load in less critical, and more naturalistic, situations such as the turn right at T-junction scenario studied by Summala and Räsänen (2000). The model predicts that habitual scanning strategies should be relatively preserved under working memory load but less flexible and more stereotyped compared to strategies adopted by non-loaded drivers. Moreover, loaded drivers should be more susceptible to *capture errors* (Norman and Shallice, 1986), that is, the automatic triggering of an inappropriate schema when cognitive control is unavailable to correct it. Basic research has demonstrated that working memory load, similar to pre-frontal damage (Norman and Shallice, 1986), impairs the inhibition of automatic, reflexive, behaviours (Roberts, Hager and Heron, 1994; Lavie, 2010). To the knowledge of the author, such effects have not been investigated in the driving domain.

6.2.4 Summary

This section summarises the main empirical findings discussed in the previous three sections. The present results clearly demonstrate that visual and purely working memory-loading tasks affect driving performance in very different ways. Paper I demonstrated, in line with previous studies, that visually demanding tasks while driving impairs lane keeping performance and leads to a compensatory reduction in speed. Other studies (experimental as well as naturalistic) have demonstrated that visual diversion from the road strongly impairs the ability to respond to critical events such as a lead vehicle that brakes unexpectedly. However, even in a controlled experimental setting such as in Paper I, the effect of visual time sharing on performance cannot be predicted solely based on dual task interference due to limited capacity. Rather, the effect will be strongly determined by adaptive strategies, such as slowing down and allowing lane keeping performance to deteriorate as long as safety margins are not violated.

The present results further suggest that, by contrast to visual tasks, working memory load selectively affects controlled performance (deliberation and exploration) while leaving automatic performance (reflex and habit) unaffected. This idea resolves several apparent inconsistencies in the driver distraction literature. This leads to very different predictions compared to central bottleneck models which suggest that working memory load will disrupt all aspects of driving due to competition for a single bottleneck.

Finally, Paper II and Paper III specifically addressed mechanisms behind top-down selection and attention scheduling (Aim 4). The results offer empirical support for Trick and Enns' (2009) suggestion that top-down attention selection and scheduling is often automatic (habitual). However, it was also found that working memory load may affect more deliberate, flexible, scheduling strategies, thus leading to more stereotyped, rigid proactive behaviour. This also further supports the general hypothesis that the key effect of working memory load is to induce to a resort to reflex and habit.

6.3 Generalisability of experimental studies

An important aim of the present thesis (Aim 4) was to address the issue of how well experimental results on attention in driving might generalise to the real world. This section discusses this issue based on the present theoretical developments and empirical findings discussed in the previous sections.

In the driver distraction literature, rather strong claims are often made about the implications of driving performance impairments observed in experimental studies for actual road safety. For example, in a paper comparing the effects of alcohol and working memory load on driving performance, Strayer, Drews and Crouch (2004) stated:

"Drivers using a cell phone exhibited a delay in their response to events in the driving scenario and were more likely to be involved in a traffic accident. Drivers in the alcohol condition exhibited a more aggressive driving style, following closer to the vehicle immediately in front of them, necessitating braking with greater force. With respect to traffic safety, the data suggest that the impairments associated with cell phone drivers may be as great as those commonly observed with intoxicated drivers." (p. 381).

With respect to visual tasks, it was suggested in Section 6.2.1, based on the results from Paper I, that effects of time sharing on driving cannot be predicted solely based on dual task interference related to limited capacity, but also strongly depends on adaptive attention allocation and behaviour. In Paper I, visual time sharing impaired lane keeping performance in the simulators but not in the field. Moreover, Victor et al. (2005), analysing the same data set, found shorter off-road glances in the field. It was suggested that this was due to the fact that drivers adopted larger safety margins in the field and, as a consequence, reduced single glance duration and did not allow lateral control to deteriorate. Hence, the effects of a visually demanding task on visual behaviour and driving performance could generally be expected to be exaggerated in simulators compared to the real world. However, the general finding that off-road glances strongly delay responses to critical events seem to apply in experimental settings (Summala, Nieminen and Punto, 1996; Lee et al., 2002.; Horrey et al., 2006) as well as in the field (Klauer et al., 2006; Olson et al., 2009; Hickman, 2010).

For working memory loading tasks, the response delays commonly found in lead vehicle braking scenarios are often suggested to be directly related to increased crash risk, as exemplified, for example, by the quote above (see also the recent white paper by the National Safety Council; NSC, 2010). However, the findings of the present thesis question the generality of such results. Paper II found a response delay due to working memory load to a lead vehicle braking event cued by brake lights. However, no such effect was found in Paper III where the responses to the oncoming lead vehicle were triggered solely by looming/movement cues. This is in line with other studies that found response delays only for cued tasks (Muttart et al., 2007; Baumann et al., 2008). Moreover, the meta-analysis in Engström (2010a) indicated that the magnitude of the response delay depends critically on scenario criticality (initial time headway). As criticality increases (initial headway is reduced), the response delay is strongly reduced.

As discussed in Section, 6.2.2, these findings may be explained by the general hypothesis that working memory load mainly affects controlled performance while leaving automatic performance unaffected. From this perspective, it may be suggested that existing experimental studies have mainly demonstrated impairments of working memory load on controlled performance (e.g., responding to brake lights, visual exploration, encoding semantic information etc.). However, real world driving is to a large extent habitual and reflexive (i.e., automatic), at least for experienced drivers. In particular, responses to hazards could be expected to be mainly reflexively triggered, for example, by looming cues, and should thus, as indicated by the results of Paper III, be minimally affected by working memory load. Hence, response delays found for cued events in experimental studies may not generalise well to real world critical situations. As indicated by Paper III, this should also hold for habitual aspects of driving such as lane keeping and routine proactive attention scheduling. Thus, the present findings suggest that experimental results on the effects of working memory load on driving performance should be interpreted with great caution.

As reviewed in Chapter 2, naturalistic driving studies have generally not found elevated risk due to working memory loading tasks. The idea that working memory load selectively affects controlled performance may partly explain this apparent discrepancy with experimental dual task studies. However, it does not explain why working memory load should have a protective effect, as found by Olson et al., (2009) and Hickman et al., (2010) for commercial heavy vehicle drivers conversing on a hands-free phone or a CB radio. A further possibility is that arousal associated with cognitive control deployment helps to keep the driver alert during monotonous driving, which may help to prevent drowsiness-related critical events (Hanowski, personal communication). Such an effect would naturally be expected to be most prevalent for commercial vehicle drivers who often drive for long hours on monotonous routes, which may explain why the protective effect was not found in the 100-car study. However, it may be further speculated that the gaze concentration effect induced by working memory load (Paper I, Paper III) may reduce the risk of safety critical events due to an increased likelihood that gaze is directed on-road in the case of an unexpected event.

However, that said, it cannot be ruled out that working memory load leads to more "upstream" effects, for example, due to failures to interpret and encode semantic information. This may induce erroneous expectancies and subsequent errors in top-down selection which may lead to critical situations. Such factors may not have been captured in existing naturalistic driving analyses, which typically analysed a time window 5 seconds before the crash. More detailed analysis of naturalistic driving data, focusing more on the *reasons* for schema-situation mismatches may help to resolve these issues. This topic is further addressed in the following section.

6.4 How do attention failures lead to crashes?

The ultimate motivation for the present research was the question how problems in attention selection may lead to crashes. The final aim of the present thesis was to define a general conceptualisation of how attention selection relates to crashes based on the proposed attention selection model (Paper V).

A general conceptualisation of the relation between normal driving, conflicts and crashes of different severity is illustrated in Figure 12 (adopted from Victor et al. 2010, building on the classical Heinrich triangle). Normal driving situations develop relatively often into non-severe conflicts. In most of these cases, the situation is quickly recovered by the driver. According to the present framework, such situations result in a feeling of discomfort (triggered by the value system) and are critical for learning anticipatory avoidance behaviours (Fuller, 1984; Summala and Räsänen, 2000; Fuller, 2007; Summala, 2007; Vaa, 2007; Paper IV; Paper V).

However, sometimes events develop into more severe situations and, very infrequently, into crashes. A key issue for accident analysis is thus to understand the mechanisms whereby normal driving evolves into a critical situations and further into crashes. Of equal importance, however, is to understand the mechanisms that lead to successful recovery from critical situations.

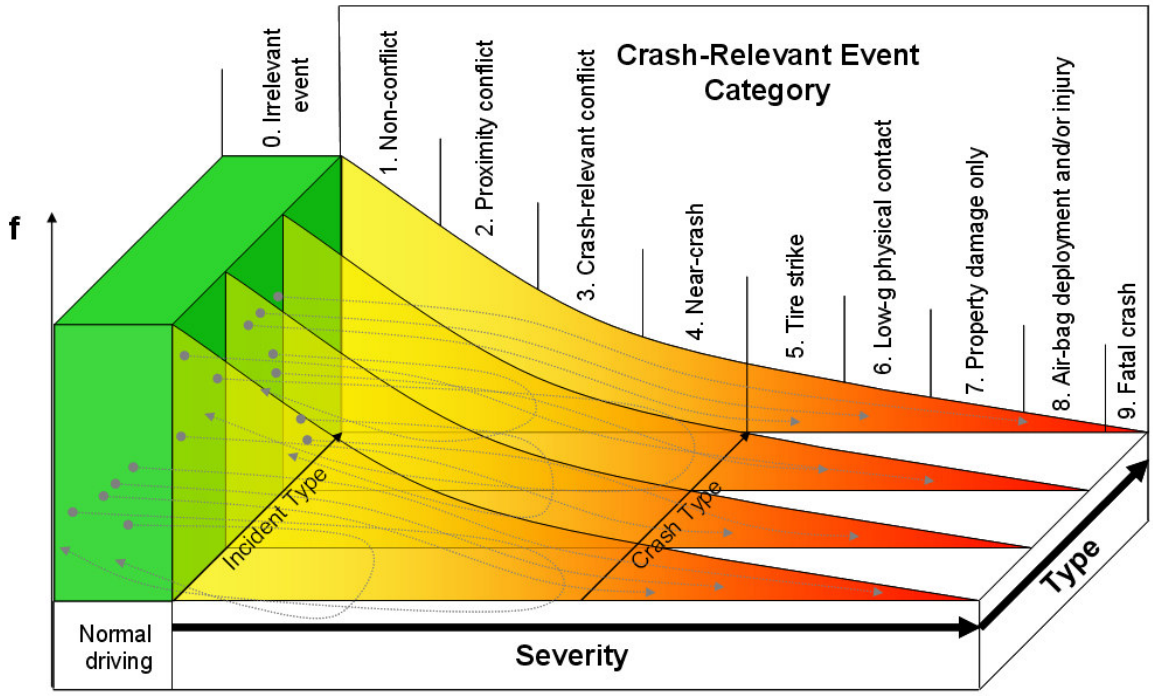

Figure 12 Conceptualisation of the relation between normal driving, incidents and crashes (from Victor et al., 2010; f=frequency)

Until recently, not much was known about how events in the pre-crash phase lead to crashes and even less about the precise role that attention selection may play in this process. However, as reviewed in Section 2.1.2, this situation has now changed with the advent of naturalistic driving studies. However, a conceptual framework for describing how attention failures relate to conflicts and crashes is still lacking. Based on the proposed attention selection model, Paper V suggests an initial step in this direction, briefly described in the following section.

Towards an novel accident model

In Paper V, it was suggested attention selection serves two key functions in preventing crashes, which may be conceptualised as barriers. The first is the *proactive barrier* which prevents drivers to enter into critical situations by means of top-down selection of schemata based on anticipation on how situations will develop. This proactive selection, which develops with driving experience, is often habitual but may also be guided by cognitive control when needed. Critical situations may occur when there is a mismatch between the proactively selected schema and the actual situation. In such cases, the second, *reactive*, barrier may prevent a crash by triggering rapid bottom-up (reflexive) selection of avoidance schemata. The proposed accident model is illustrated in Figure 13.

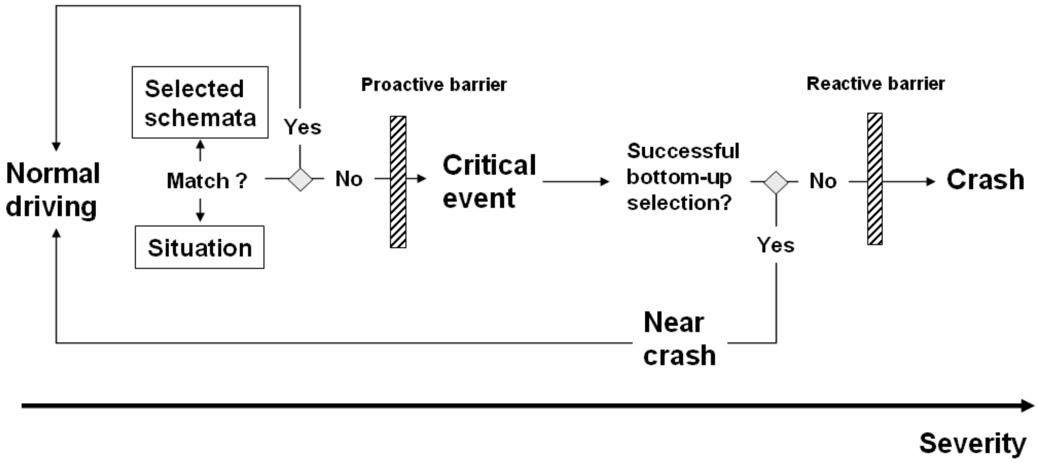

Figure 13 A conceptual model relating attention failures to crashes (from Paper V)

According to this model, a key goal of crash/near crash analysis is thus to identify (1) reasons for why proactive selection resulted in a schema-situation mismatch (breakdowns of the proactive barrier) and (2) why reactive selection failed to trigger a timely avoidance reaction (breakdowns of the reactive barrier). While existing naturalistic driving studies have shed much light on the latter question, reasons why drivers select the wrong schema in the first place have rarely been addressed. Preliminary candidates for reasons of the two types of failures are outlined in Paper V.

A preliminary, yet unpublished, application of these ideas to the analysis of publicly available data from the 100-car study is described in the Addendum.

Application to accident and incident analysis

While the present thesis have not provided a conclusive answer to the question how attention failures lead to crashes, it suggests some potential ways forward in the search for this holy grail of driver attention research. In particular, the novel accident model proposed above may provide guidance on "what to look for" in accident and incident analysis in terms of a set of proactive and reactive selection failures. However, the model, and in particular the attention failure categories suggested in Paper V, should be viewed as preliminary and needs to be validated against real data.

A key feature of the present model is the emphasis on attention failures related to inappropriate actions, in particular taking the eyes off road at the wrong moment, rather than overload of central attentional capacity. At least for the limited set of rear-end crashes and near crashes analysed in the Addendum, it may be observed that the central capacity limitations or information overload appear to be of little relevance for explaining why these rear-end crashes occurred. Rather, the key mechanism was that the driver chose to look away at an inopportune moment. During the off-road glance, the lead vehicle braked and looming cues were unable to trigger an avoidance reaction since the looming cues occurred outside the field of view. In some cases, the narrative written by the video analyst indicated that the driver was misled by contextual cues to look away. However, in most cases, the precise reason for looking away was not possible to infer from the narrative. In any case, there was no evidence that it was due to overload of central attentional capacity.

Naturalistic driving studies have so far mainly been concerned with failures of the reactive barrier, in particular how crashes often occur when off-road glances coincide with unexpected events. However, they have so far provided little information about the reasons for failures of the proactive barrier. In particular, the question why a driver involved in a crash decided to take the eyes off the road in the first place remains largely open. This may be one reason for why factors such as working memory load and inattentional blindness have not been attributed as key contributing factors in naturalistic driving studies, while they have been more commonly identified in in-depth accident analysis and epidemiological studies (Brown, 2005; Redelmeier and Tibshirani, 1997; McEvoy et al., 2005).

How, then, can we get at breakdowns of the proactive barrier? It is possible that such failures are more likely to be found in naturalistic observation if they are explicitly looked for. The work by Summala and colleagues (Summala and Räsänen, 2000) represents a good example. Moreover, subjective interview data from involved drivers would probably be very useful as a complement to naturalistic observation data. However, given that schema selection, according to the present model, often occurs automatically, the driver's memory his/her own attention allocation patterns might be limited. A very interesting topic for further research would be to compare drivers' own statements on their beliefs, intentions and actual scan patterns in the pre-crash phase to video data.

6.5 Application to inattention countermeasure and evaluation method development

As stated in Chapter 1, the present research is mainly intended to be applied in three general areas: (a) Accident and incident analysis, (b) the development of countermeasures for attention failures and (c) the development of methods for evaluating such countermeasures.
The application to accident and incident analysis was discussed in the previous section while this section focuses on the two latter application areas.

6.5.1 Inattention countermeasures

There are several possible ways in which the different types of attention-related failures discussed in this thesis could be counteracted. Below a number of inattention countermeasure are discussed based on the findings of the present thesis.

Safe human-machine interface design

The design of the in-vehicle human-machine interface is naturally of key importance to minimise distraction from secondary tasks. Recent results from naturalistic driving studies (Klauer et al., 2006; Olson et al., 2009; Hickman et al., 2010), provide strong arguments for non-visual means for interaction, such as voice control. However, the working memory demands imposed by such systems should not be neglected. As voice-based interfaces grow in complexity, there is a risk that the operation of such systems (e.g., navigating through complex menus) may place high demands on working memory. As indicated by the present results, in particular Paper III, high working memory load may induce a resort to reflex and habit, resulting in rigid, inflexible, behaviour which may turn out to be critical in situations where behavioural flexibility is required. Moreover, as also found in Paper III, working memory load strongly impairs the semantic encoding of information. This may lead to failures in perceiving safety critical information such as traffic signs, and may thus impair subsequent top-down selection. It should be stressed that, that although crash contributing factors associated with working memory load have not shown up in naturalistic driving studies, it is still unclear to what extent this is due to their actual infrequency or limitations in current naturalistic data analysis methodologies. Thus, while the present framework supports the development of non-visual interfaces, the issue of excessive working memory demands must be carefully addressed in in-vehicle interface design.

The present thesis also emphasises the subjective, emotional, *value* of a task as a key factor that determines its distraction potential. According to the present framework, the decision to engage in a task in a particular situation is due to a balance between the motivation to complete the task and the perceived discomfort when uncertainty builds up and driving performance deteriorates during task engagement. Thus, a driver will be more willing to engage in a demanding secondary task in a potentially risky situation if the task is strongly associated with positive value. This implies that the most hazardous secondary tasks should be those that induce strong (peripheral-, structural- and control-) interference with driving but at the same time are strongly associated with value. As suggested in Paper V, text messaging on a cell phone is a prime example of such a task. This may explain the extreme risk found for text messaging in naturalistic driving studies (Olson et al., 2009; Hickman, 2010; Section 2.1.2). This implies that certain functions that are currently finding their way into modern vehicles, such as social media, may impose very strong crash risks, which are not solely determined by interface design.

Proactive information

With the advent of wireless technologies for vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication, there are increasing possibilities to provide drivers with advance information on upcoming events, such as accidents, traffic queues and slippery road conditions. According the present framework, this type of information may be very useful for supporting the proactive selection of appropriate schemata, thus facilitating correct expectancies and reducing the risk for breakdowns of the proactive barrier. Some studies have already demonstrated such benefits of onboard navigation systems (van der Horst and Martens, 2010).

Distraction mitigation

Camera-based computer vision technology has made it possible to unintrusively monitor drivers' eye and/or head movements. This may be used to alert the driver on inappropriate visual behaviours, such as long off-road glances (see examples in Engström and Victor, 2009). A key issue here is the transparency of the alert, so that the driver knows how to improve visual behaviour based on the feedback. This type of function may also be used in more general safety management programs as further discussed below.

Collision avoidance warnings

A key implication of the present model is that the bottom-up response to a warning signal may be faster, and more likely to "break through", if the signal is associated with emotional value. This suggests potential applications for emotional (value associated) warning signals. In support of this idea, Gray (2011) demonstrated that auditory looming and car horn signals were superior to neutral warnings in speeding up braking responses in a lead vehicle braking scenario. However, the horn signal produced a significantly greater number of responses to false alarms than the veridical looming warnings, thus indicating a significant benefit of the latter. See also Larsson et al. (2009) for related work. Lee (2006) offers a general review of the key role of emotion in human factors engineering.

Behaviour-based safety management

Behaviour-based safety management programs are commonly employed by commercial vehicle fleets to obtain long-term behavioural change among their drivers towards a safer driving style (Hickman et al. 2007). These programs generally involve some form of performance monitoring combined with incentive programs (Barton and Tardif, 2002). Recently, there has been an increased focus on drivers' attention allocation strategies as one of the targets for such programs, enabled by unintrusive attention monitoring technologies (Engström and Victor, 2009). Given that, as suggested in the present thesis, much of attention allocation behaviour is automatic and unconscious, governed by overlearned schemata, such programs could have a strong potential in bringing inappropriate behaviours to the drivers conscious attention and support a long-term improvement in attention allocation strategies. In terms of the present model, such a long-term behavioural change implies the establishment of new habitual schemata which initially requires attentional effort (cognitive control) to override existing dominant habits. This emphasises to the important role of sufficiently motivating incentive schemes. The learning of improved attention scheduling schemata may also be facilitated by computer-based training, for example, using driving simulators (Pradhan et al., 2009)

Infrastructure design

According the present framework, drivers' attention allocation strategies are strongly determined by the environmental context. Hence, the design of infrastructure elements plays a key role in triggering schemata and hence driver expectancies. Thus, as suggested by Theeuwes and Godthelp (1995), "self-explaining roads" that reliably trigger appropriate schemata should have a strong potential for improving road safety.

6.5.2 Evaluation methods

An important issue, which has been the subject of several major research initiatives, is how to evaluate in-vehicle functions with respect to their, positive or negative, effect on attention. This may involve the distraction potential of a new interface design (e.g., Östlund et al., 2004; Angell et al., 2006) or the ability of active safety systems to support crash avoidance by alerting the driver on potential hazards (Ljung Aust and Engström, 2010). These topics are addressed in the following two sections.

Evaluating the distraction potential of human-machine interfaces

Based on the present framework, there are three main aspects of an in-vehicle human-machine interface design that determines is distraction potential and hence are relevant to evaluate in laboratory-based assessment. The first is the degree to which the system requires visual-manual interaction, in particular the degree to which long single glances are needed to extract relevant information. The second is the degree to which the system supports proactive task management. The third is the degree to which the interaction with the system requires the deployment of cognitive control (e.g., by demands on working memory).

The first aspect is possible to capture by means of eye movement analysis (Victor et al., 2008; ISO, 2002). Alternatively, the occlusion technique (Foley, 2008; ISO, 2007) offers a cheaper and less laborious way to assess the need for visual interaction. The occlusion technique also offers a way to measure the second aspect (proactive task management) in terms of *interruptability* (Foley, 2008).

In order to measure the demand for cognitive control, the Detection Response Task (DRT) paradigm (van der Horst and Martens, 2010; Engström, 2010b) seems to be the most promising option available. The method has repeatedly been shown to be sensitive to different levels of working memory load as well as driving demand (van der Horst and Martens, 2010; Engström, 2010b). According to the present model (Paper V), the effect of working memory load on the DRT mainly occurs since responding to these types of artificial stimuli relies on cognitive control, which is depleted by working memory loading tasks (see Engström, 2010b). This explains why effects of secondary tasks on DRT performance are generally independent of visual eccentricity and even the sensory modality of the DRT stimulus (e.g., Merat and Jamson, 2008; see review in Engström, 2010b). However, one open issue concerns the application of the DRT to measure the working memory load of visual manual tasks. In this case, it is possible that the DRT is also sensitive to structural interference effects related to concurrent manual responses (for example providing manual input to a system with one hand while pushing the DRT button with the other). Such effects may thus mask the more global effects related to cognitive control deployment (control interference). This issue clearly needs to be investigated in further development of the DRT method.

To the extent that it is practically feasible, physiological measures of arousal such as heart rate and skin conductance may yield further indices on the degree of cognitive control deployed (Mehler et al., 2010).

However, measures of lateral and longitudinal control (such as standard deviation of lane position and speed) are clearly not well suited for evaluation of secondary task demand. As discussed in Section 6.2.1, for visual tasks such measures mainly reflect adaptive task management strategies rather than the interference caused by the system under evaluation. For working memory loading tasks, the direction of the effect on lane keeping appears to depend on the difficulty of the lane keeping task (as discussed in Section 6.2.2). Moreover, working memory load may affect speed and headway in both directions, possibly depending on the relation between the drivers' "default" speed/headway and the posted speed limit and/or instructions (as discussed in Section 6.2.2). Thus, neither for visual, nor cognitive tasks, do vehicle control measures provide an accurate estimation of secondary task load.

Finally, as already discussed, laboratory based evaluation is not able to capture the motivational factors that determine the willingness to engage in distraction in the in real world, or the adaptive strategies that the driver may employ to manage the dual task situation. In the real world the emotional value of a task will critically determine to what extent drivers will engage in it in potentially critical situations. Hence, while dual-task, laboratory-based, distraction assessment (using e.g., occlusion or the DRT) may be very useful during system development, they would be less suitable as the basis for general consumer testing methodologies (generating star ratings similar to EuroNCAP). Since, according to the present framework, the real world distraction potential of a task is only partly determined by the interface design, such tests may yield misleading indications on which tasks are suitable to perform while driving and which are not. The real-world distraction potential of a secondary task can probably only be captured in naturalistic driving studies.

Evaluating the effectiveness of active safety systems

As discussed in Paper IV, evaluating active safety systems in controlled experiments is notoriously difficult. The goal is generally to create critical scenarios that are sufficiently representative to the real world pre-crash scenarios targeted by the active safety system. However, the key problem is that drivers who anticipate critical scenarios will adopt various adaptive strategies, including shifts in attention allocation strategies to remain inside their comfort zones. The experimenter thus has to invent various means to trick the drivers out of their comfort zones at the right moment in time (see Paper IV). See also Ljung Aust and Engström (2010) for a more general application of the conceptual framework outlined in Paper IV to active safety system requirement specification and evaluation.

A recent study by Ljung Aust, Engström and Viström (in preparation) demonstrated that driver's responses to collision warnings in experimental settings is the result of relatively complex adaptation and attention allocation strategies determined by expectations induced by repeated exposure to events, as well as the scenario criticality. The present thesis offers a conceptual framework for better understanding such effects when designing active safety evaluation studies.

6.6 Conclusions

The general objective of the present thesis was to obtain a better understanding of the relation between attention, performance and crash risk. Based on reviews of relevant empirical and theoretical work, a number of specific aims were defined.

The first aim was to develop a general conceptual model of attention selection in driving able to account for attention selection as it occurs in natural driving situations. The present framework (Paper IV and V) represents a shift in perspective from the traditional notion of attention as a resource or bottleneck with limited capacity to a view of attention selection as a key aspect of adaptive driver behaviour. From this perspective, the key *function* of attention in driving is to select the right information at the right time to support the accomplishment of (driving and non-driving related) task goals while at the same time ensuring the maintenance of acceptable safety margins. Such a view accounts for a range of key phenomena that are difficult to conceptualise in terms of limited capacity such as expectancy, dynamic attention scheduling and attentional self-regulation. Moreover, while traditional models have tended to focus on effortful and conscious (i.e., controlled) aspects of attention, the present model, in line with Trick and Enns (2009), suggests a broader view of attention which also includes reflexive and habitual (i.e., automatic) selection, which are of key importance in natural driving. However, at the same time, the proposed model offers a novel taxonomy of different dual task interference mechanisms which is useful for characterising different forms of driver inattention and distraction.

A further key aim of the present thesis was to obtain a better understanding of the effects of secondary tasks on driving performance. Effects of visual time sharing are relatively well understood. Although visual tasks may induce central attentional interference (structural and control interference according to the present model), it may be concluded that the key effect in driving is related to basic peripheral interference resulting from off-road glances. In particular, off road glances severely delays responses to unexpected critical events (such as a lead vehicle braking) and this could be regarded as the key known attention-related mechanism that gives rise to road crashes. However, the further issue, relating to proactive attention scheduling, *why* drivers sometimes decide to take their eyes off the road at inopportune moments has not been thoroughly addressed.

The effects of working memory load on driving performance are less well understood and, hence, this was a major focus of the empirical work in the present thesis (Aim 2). As reviewed in Chapter 2, studies on working memory load have generated apparently inconsistent results. The results from the present thesis (Paper III) suggest that these inconsistencies may be largely resolved based on the idea that working memory load selectively affects controlled performance (deliberation and exploration) while leaving automatic performance (reflex and habit) unaffected. However, this novel hypothesis clearly needs to be further validated empirically.

The thesis also examined mechanisms behind expectancy and proactive attention scheduling strategies (Aim 3). The present results (Paper II and III) demonstrated, contrary to common belief, that basic top-down, proactive, attention selection and scheduling may operate automatically, without the need for cognitive control. However, more flexible attention allocation strategies require cognitive control and are inhibited by working memory load. This further supports the general idea that the key effect of working memory load is to induce a resort to reflex and habit, which leads to inflexible, stereotyped behaviour.

An important aim of the thesis was to clarify to what extent results from experimental studies, in particular studies on the effects of driver distraction on driving performance, can be generalised to the real world (Aim 4). It may be concluded that the common finding that visual diversion from the road strongly delays responses to unexpected critical events are well in line with the results of naturalistic driving studies. However, the present findings strongly indicate that experimental results on the effect of working memory load should be interpreted with caution. As discussed above, the present results indicate that working memory load selectively affects controlled driving performance. It could thus be suggested that many experimental studies measured impairments in controlled performance while such impairments would not necessarily occur in routine real world situations were performance is largely automatised (reflexive and habitual). This may be one reason for the apparent discrepancies between naturalistic driving and experimental studies with respect to the effects of working memory load. However, it may also be the case that existing naturalistic driving analyses have failed to identify more upstream accident-contributing factors related to working memory load. Further empirical work is needed to resolve these issues.

Finally, although the present thesis does not offer the final answer to the question how attention failures lead to crashes, it suggests a novel way to approach the problem (Aim 6). Specifically, it was suggested that attention related failures may be divided into two general categories: (a) failures of critical stimuli to trigger a last-second avoidance manoeuvre bottom-up and (b) failures that lead to a mismatch between top-down, proactively selected, schemata and the actual situation. In terms of the suggested accident model, the former may be referred to as breakdowns of the reactive barrier and the latter as breakdowns of the proactive barrier. Naturalistic driving studies have forcefully demonstrated that eyes-off-road is the key factor behind breakdowns of the reactive barrier. The most important challenge for future accident and incident research is to identify the key mechanisms behind breakdowns of the proactive barrier, for example, what makes driver take the eyes off road at inopportune moments. The present thesis has provided some initial ideas of potential mechanisms behind such failures (Paper V), but much further research is needed to validate these ideas against empirical data. Such work could involve experimental studies, accident and incident analysis (in particular based on naturalistic driving data) as well as the development of computational simulation models of attention selection mechanisms which could be based on the conceptual model outlined in this thesis.

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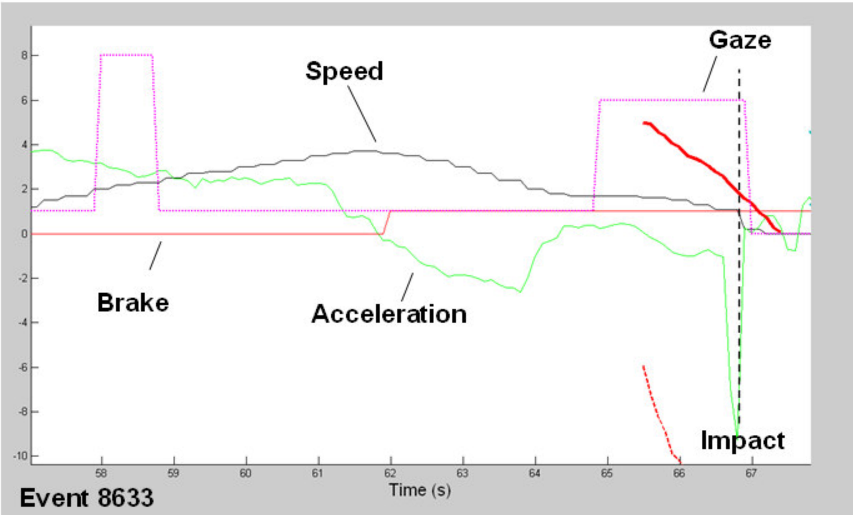
Addendum: Analysis of rear-end crashes and near crashes in the 100-car study

In order to examine the applicability of the accident model outlined in Section 6.4, a preliminary (yet unpublished) analysis was carried out on publicly available naturalistic data from the 100-car study. The analysis focused on rear end crashes and near crashes and used vehicle and manually reduced gaze data which were synchronised and plotted using Matlab. Moreover, narratives from the video analysis were used (however, videos were not directly analysed since these are not publicly available). An example of the data used for the analysis is given in A1.



Narrative: Subject driver is approaching a right turn at an intersection. The lead vehicle briefly stops at stop sign, then moves forward as if completing the turn. As the subject driver looks out his left window to check traffic, the lead vehicle stops again. The subject vehicle hits the lead vehicle in the rear. Inopportune glance.

Figure A1 Example of 100-car data used for the present analysis

The 100-car database was initially searched for all crash events (i.e. events where “Event Severity” was assigned to “Crash”) with the variable “Event Nature” assigned to “Conflict with a lead vehicle”. A further criterion was that the speed, brake, longitudinal acceleration and front radar data should be available. 10 events fulfilled these criteria. Two of these where excluded as they were not representative of typical rear-end conflict situations: In one case (event no. 8856), the subject vehicle hit a spinning vehicle coming from the left lane in the rear and the other case (event no. 8733) occurred during parallel parking. The 8 remaining events were retained for detailed analysis.

In order to also investigate cases of successful avoidance, the database was also searched for near crashes with “Event Nature” assigned to “Conflict with a lead vehicle”, which resulted in a total of 240 events that also satisfied the criteria of complete time series data. From these, 8 events were randomly selected for detailed analysis.

The data were analysed based on the accident model outlined in Section 6.4 (Figure 13). Thus, the goal was to identify (1) mismatches between the proactively selected schema and the how the situation developed and (2) reasons why last-second reactive selection failed (for crashes) and succeeded (for near-crashes). To be able to aggregate the data, a set of preliminary pre-crash factors was defined and each event was analysed in terms of a causation tree similar to that used in the DREAM method for in-depth accident analysis (Sandin, 2008). The aggregated result for the eight near crashes is shown in Figure A2. As can be seen in the Figure, the crash events were very homogenous in terms of causation patterns. In all but one case, the critical event occurred due to selection of a competing schema which coincided with the lead vehicle braking unexpectedly. The competing activity involved both driving-related activities (such as looking for other traffic or checking the mirror) and non-driving activities (e.g., rubbing the eye). This resulted in an, often very long, glance away from the road which was the main reason for the failure of the closing lead vehicle to trigger a timely avoidance reaction. In the one remaining case, the driver fell into sleep just before the lead vehicle braked. Based on the narratives, it was difficult to identify the precise reason why the drivers selected the competing schema. However, in two cases it seemed like drivers were "tricked" to look away by misleading contextual cues induced by the behaviour of the lead vehicle. Thus, for example, in the narrative shown in Figure A1, the lead vehicle moved forward as if to complete the turn, which led the driver to look left to check for traffic.

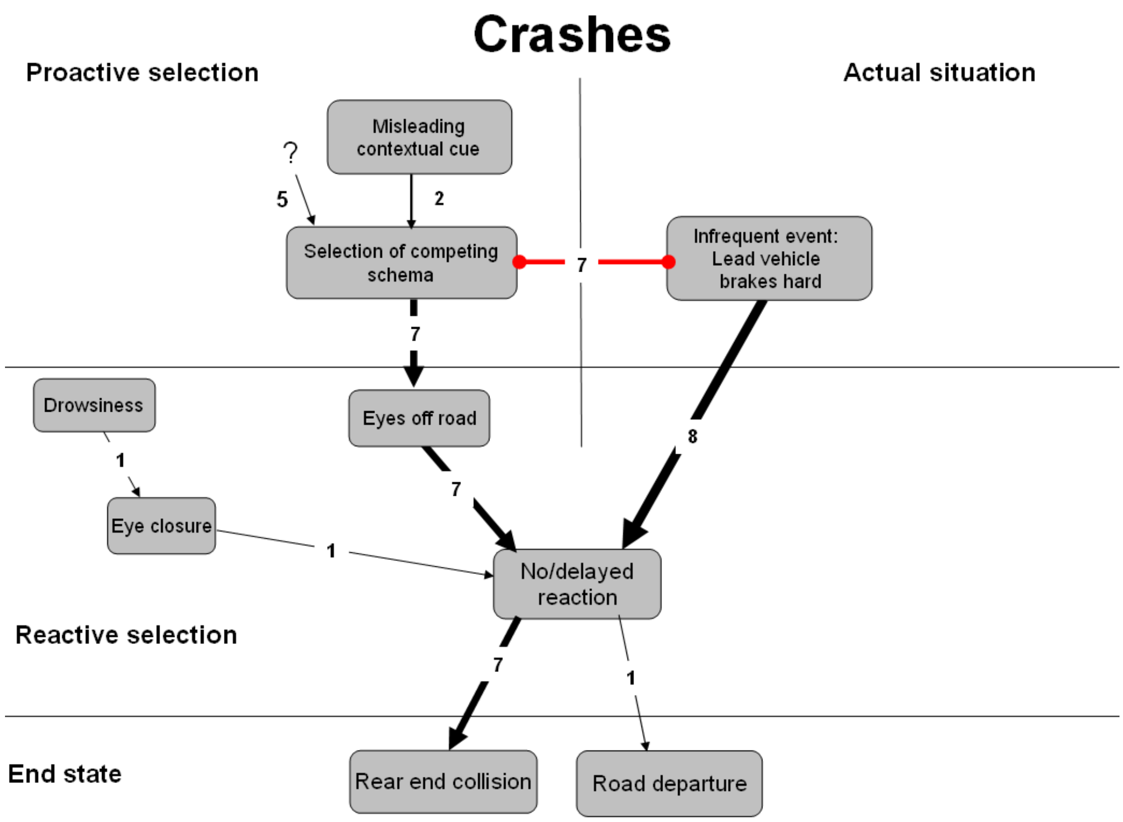


Figure A2 Aggregated causation tree for the eight rear-end crashes. Numbers on the arrows indicate the number of events following this path. The red line indicates the schema situation mismatch.

The corresponding analysis for the randomly selected eight near crashes is shown in A3. As can be seen, the causation patterns were here more heterogeneous. The key causation pattern that was observed for the crashes (eyes-off road due to mismatching proactive selection of a competing schema) was found in four cases. The key reason for the successful escapes was that the drivers looked back to the road early enough for a timely reactive selection to take place. In addition, there were several cases where an unexpected event (e.g. the lead vehicle braking, changing deceleration rate or cutting in) occurred when the driver already had his/her eyes on the road. This enabled a fast bottom-up reaction and a timely avoidance reaction.

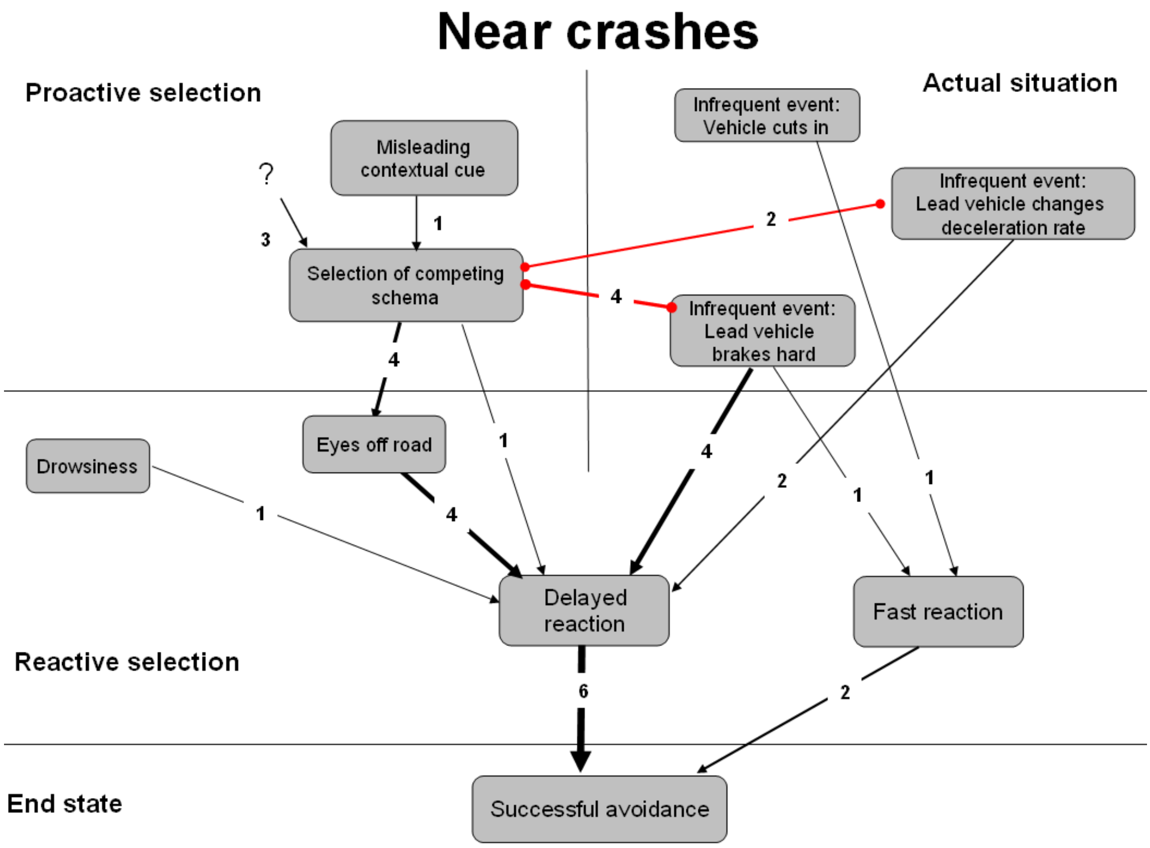


Figure A3 Aggregated causation tree for the eight, randomly selected, rear-end near crashes. Numbers on the arrows indicate the number of events following this path. The red line indicates the schema situation mismatch.

While the present analysis should be viewed as preliminary, it illustrates the potential value of the present attention selection model in guiding the analysis of naturalistic driving data. In particular, the 2-stage accident model provides guidance on "what to look for" in the analysis in terms of a set of proactive and reactive selection failures.

A comparison between the causation patterns for crashes and near crashes shows that the latter are much more heterogeneous. In particular, eyes off-road, disabling the reactive barrier, seems to be the single factor that make rear-end conflicts develop into crashes.

While the present analysis provides a rather detailed picture on mechanisms relating to the second barrier (i.e., reasons for failures in last second reactive selection), it says relatively little about the reasons for why the mismatching schema was selected in the first place (in the present cases, why the driver chose to take the eyes off the road). It is likely that more information on this may be extracted from actual video data (rather than the short narratives used here). Moreover, subjective interview data from involved drivers would probably be very useful as a complement.