COGNITIVE WORKLOAD AND THE DRIVER

Understanding the Effects of Cognitive Workload on Driving from a Human Information Processing Perspective

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ABSTRACT

This doctoral dissertation in psychology focuses on present day transport research issues. Society is affected by the way that our transport system works. In one way or another, the use of the transport system involves different levels of human involvement and control.

The main focus of this dissertation is to understand some important effects of cognitive workload on driving. The driver’s cognitive workload is related to human information processing capacity and the use and allocation of the driver’s attention. In-vehicle technologies are of particular interest in the context of driver workload and human information processing.

The rationale of this thesis starts with the need to explore and develop a sensitive and objective measure of cognitive workload using the peripheral detection task (PDT) method. The next step continues to study the effects of cognitive workload on the human information processing stages (HIPS) framework and the way in which human information processing can be affected by performance shaping factors (PSFs). One of the PSFs had a beneficial effect on performance (experience) and one had a detrimental effect on performance (distraction).

In summary, it is clear that the human driver is limited in the number and the complexity of the tasks he or she can perform at any given time. Moreover, making mistakes, to err, is part of being human; we are fallible. It is impossible to eliminate all driver error so it is therefore important to create an environment for the driver so that his or her slips, lapses and mistakes can be detected and recovered.

Keywords: Cognitive workload, human information processing, driver distraction, human error, performance shaping factors (PSF), intelligent transport systems (ITS), peripheral detection task (PDT).
To Anette, Hannah, Emma and Jonathan
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LIST OF PAPERS

This thesis is based on the following papers which will be referred to in the text by their Roman numerals:


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This doctoral dissertation in psychology focuses on present day transport research issues. Society is affected by the way that our transport system works. In one way or another, the use of the transport system involves different levels of human involvement and control. The development of the transport system also requires research from many different academic disciplines.

I have therefore endeavoured to write this doctoral dissertation with the hope that the layout, the theoretical introduction and the language are accessible to readers from many different academic disciplines. As a result, I thought it necessary to start with a general introduction of the pertinent models and theories before diving into the various mainstay models, theoretical backgrounds and issues of this thesis.

Developing vehicles and roads is not just about being bigger, better and faster than before. Many of the real issues lie in human factors issues such as cognitive workload, human error and driver distraction. Understanding and applying research from these areas can facilitate improved usability, safety and efficiency of use of the road transport system.

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ADAS</td>
<td>Advanced driver assistance system</td>
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<td>BAC</td>
<td>Blood alcohol content</td>
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<td>GEMS</td>
<td>Generic error model system</td>
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<td>GPS</td>
<td>Global positioning system</td>
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<td>HIPS</td>
<td>Human information processing stages</td>
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<td>HMI</td>
<td>Human machine interface</td>
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<td>ITS</td>
<td>Intelligent transport systems</td>
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<td>IVIS</td>
<td>In-vehicle information and communication systems</td>
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<td>LED</td>
<td>Light emitting diodes</td>
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<td>MTO</td>
<td>Man technology organisation</td>
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<td>NASA-TLX</td>
<td>National Aeronautic and Space Administration - task load index</td>
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<td>National Aeronautic and Space Administration – revised task load index</td>
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<td>NHTSA</td>
<td>National Highway Traffic Safety Administration (USA)</td>
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<td>PDT</td>
<td>Peripheral detection task</td>
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<td>PSF</td>
<td>Performance shaping factor</td>
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<td>RSME</td>
<td>Rating Scale of Mental Effort</td>
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<td>SMS</td>
<td>Short message service</td>
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<td>SRA</td>
<td>Swedish Road Administration</td>
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<td>STSS</td>
<td>Short term sensory store</td>
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<td>W-LAN</td>
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INTRODUCTION

Cognitive Workload and the Driver

The main focus of this thesis is to understand some important effects of cognitive workload on driving. The driver’s cognitive workload is related to human information processing capacity and the use and allocation of the driver’s attention. From a practical and causal point of view, cognitive workload and driving is concerned with traffic safety, where cognitive workload, driver distraction and traffic safety are intrinsically intertwined. From a theoretical point of view, the reader will find an orientation based on the theoretical framework by Wickens and Hollands (2000) on Human Information Processing Stages (HIPS) put in a driver cognitive workload context in this thesis. Complementary to the HIPS framework and an important concept in this thesis is Rasmussen’s skill-, rule- and knowledge-based model of human behaviour (1980; 1987). Other areas that are explored are 1) performance shaping factors (driver experience and training, and driver distraction) and 2) aspects of human error in a driver cognitive workload context.

Rasmussen (1980; 1987) presented a general framework representing the cognitive control of human behaviour. Rasmussen’s skill-, rule- and knowledge-based framework is a model of human control of behaviour in terms of a hierarchical structure. Rasmussen’s model distinguishes between three levels of cognitive control which relate to a decreasing familiarity with the environment; the skill-based, rule-based and knowledge-based levels of behaviour. Rasmussen’s model is particularly useful for analysing and understanding human operator tasks such as driving because driving involves overt and covert processes with constantly changing levels of task complexity and a combination of familiar and unfamiliar situations and environments.

The ancient human as a driver of a modern car

The world is an ever changing place. Human endeavours to improve the world around us seem insatiable and the road transport system is no exception. Despite the fact that the basic idea of the internal combustion engine has remained relatively unchanged for more than 100 years, other areas within road vehicle design, such as information technology systems, are taking hesitant steps towards making yesterday’s science fiction today’s reality. Modern cars and trucks have a plethora of information technology applications in the form of in-vehicle information and communication systems (IVIS) and advanced driver assistance systems (ADAS). These information technology systems are either integrated into the vehicle design or are in the form of nomadic devices, i.e. they
are devices that can be easily removed from the vehicle and continue to be used independently in a handheld mode.

The safe use of a motor vehicle in road traffic is in part determined by the driver’s ability to perceive, process, interpret and act upon relevant information inside and outside the vehicle. The human driver is bound by the restraints of the cognitive resource limitations of the brain. The cognitive resource allocation of these limited resources is therefore crucial for the successful execution of all aspects of driving safely. The limitation of the human information processing system puts the spotlight on cognitive workload while driving and its significance for facilitating safe driving. Clearly the world around us, at least in most developed and developing countries, has changed dramatically in the past 40 years, becoming more intense and complex; our human driver has not evolved at all in the past 40,000 years or more. The driver still has the same cognitive resource limitations as before the invention of the motor car. The incongruence between task demand in some situations (too many things to look at, think about and adjust while driving) and the limited availability of cognitive resources (can’t think of and do everything at once) forms the locus of concern for traffic safety.

There is a great deal of high technology such as IVIS and ADAS in today’s transport system. These new systems are here to stay so it is necessary to reduce the negative impact of these technologies. Generally speaking, many of the systems can 1) improve the comfort and usability of vehicles (e.g. by taking over certain monotonous tasks or by adding extra sensors and visual aids), 2) improve safety (e.g. by reducing human error, improving human performance), and 3) improve mobility (e.g. by avoiding traffic congestion or getting lost). The challenge, therefore, for system designers and developers is to introduce all of these potentially beneficial information technology systems without exacerbating old problems or creating new ones such as driver distraction or cognitive workload saturation/overload. Understanding, measuring and evaluating the driver’s cognitive workload is an essential component in eliciting the potential benefits of information technology systems in cars and trucks.

**Models and Theories**

Rasmussen defines the *skill-based behaviour* as representing sensory-motor performance during acts or activities which, according to Rasmussen, follow a statement of an intention taken place without conscious control and are smooth, automated and highly integrated patterns of behaviour (Rasmussen, 1987).

Rasmussen defines the second level of behaviour, the *rule-based behaviour*, as the composition of a sequence of subroutines, as Rasmussen describes them, that
are applicable in a familiar work situation and that are typically controlled by a stored rule or procedure. These stored rules or heuristics are derived empirically during previous occasions. Performance is goal orientated, but, as Rasmussen underlines, it is structured by a feed-forward control through stored rules/heuristics. Moreover, the goal is frequently not even explicitly formulated, but is found implicitly in the familiar situation that triggered the stored rule (Rasmussen, 1987).

In unfamiliar situations, however, where there are no subroutines or rules for control available from previous experience, the control of performance must move to a higher conceptual level in which performance is goal-led and knowledge-based. Knowledge-based behaviour requires reasoning and the internal structure of the system is explicitly represented by a mental model which may take several different forms. The levels of control are not static; in fact, during training in a particular task, control will move from the knowledge- or rule-based levels towards the skill-based control as familiarity with the work scenario is developed and automation of the task increases (Rasmussen, 1987).

In theoretical terms, Rasmussen (1987) suggested in his model of human control and behaviour (the skill-rule-knowledge based framework), that during training in a particular task, such as driving, control moves from the knowledge or rule-based levels towards the skill-based level; resulting in a reduction in mental/cognitive workload required for the operations involved in the driving task and, thereby, inherently accommodating a larger amount of available attention resources that can be allocated to other tasks or operations. The level of available attention the driver has at any given moment is partly dependent on the driver’s prioritisation between different tasks, whether primary or secondary. The driver’s prioritisation between tasks is intrinsically linked to the aspect of distraction (cf. Norman & Shallice, 1986).

In the period preceding Study I of this thesis, a sensitive workload measure within applied cognitive workload road transport research was lacking. Most of the methods that were applicable to field and simulator studies comprised subjective indices such as the NASA task load index (NASA-TLX) or the Rating Scale of Mental Effort (RSME). Due to their insensitivity, many of the subjective workload indices require substantial differences between conditions and/or large sample sizes if there is to be any hope of statistical significance between conditions and treatments.

The main focus of the four studies in this thesis is illustrated in Figure 1 and is about understanding the effects of cognitive workload on the HIPS model and the way in which the HIPS performance can be optimised with performance shaping factors – training and experience – or exacerbated by non-driving tasks.
which constitute a driver distraction. Driving and non-driving tasks involve cognitive workload demands.

Figure 1: A scheme of the task of driving and the human information processing stages model (HIPS), including the main focus of the thesis which is the relationship between HIPS, attention limitations and performance shaping factors. The tasks in Fig. 1 include driving and non-driving tasks.

Figure 1 is simplified and does not encompass all aspects of driving but does capture the essentials of human information processing and driving described in this thesis. The tasks include the driving (primary) task and non-driving (secondary) tasks that are commonly undertaken whilst driving. There are a number of different driver models (cf. Allen, Lunefeldt & Alexander, 1971; Michon, 1985; Ranney, 1994; Vogel, 2002). In this thesis, I will describe the driving task from a human information processing perspective. The human information processing stages (HIPS) refer to Wickens and Hollands’ framework (2000). Attention is an integral part of the HIPS model, although attention limitations are a crucial factor in our ability to cope with multiple and/or complex tasks. Performance shaping factors (PSFs) are factors that affect an operator’s ability to perform. A PSF is generally regarded as being neutral; for instance the lack of adequate training could negatively affect the operator’s performance, whereas the presence of adequate training could enhance the operator’s performance. PSFs are thus factors that shape performance in one direction or another. The first PSF that is addressed in this thesis is driver distraction, which derives from a non-driving task and draws on the available attention resources. The second PSF is that of training and experience with, in this case, the primary driving task and the effects that this PSF has on attention limitations and the driver’s ability to cope with the complexities of driving.
Human Information Processing

Wickens and Hollands’ (2000) model of human information processing stages (HIPS) provides a conceptual framework or schema for understanding and analysing the different psychological processes used by humans when carrying out a task such as driving. Wickens and Hollands’ framework is the theoretical backbone for this thesis, providing a context and a structure. The term *schema* refers to a diagrammatic representation of a conceptual framework for, in the case of this thesis, human information processing.

![Diagram of the stages of human information processing]

Figure 2: A model of the stages of human information processing, re-drawn from Wickens and Hollands (2000, p.11).

There are two main features of the HIPS schema found in Figure 2. The first is that information processes are shown as a series of stages. Each stage has a function to transform or convey the information for further processing or action. The second overall feature of Wickens and Hollands’ HIPS model is that there is a feedback loop from the human’s system environment. The presence of a feedback loop suggests that the stages of the information processing process are continuous. The stages in Wickens and Hollands’ HIPS model are sensory processing (including short-term sensory stores, (STSS)), perception, cognition and memory, response selection and execution, as well as feedback and attention. It should be noted, however, that where Wickens and Hollands’ HIPS framework provides a useful model for real-world applications, it may be an over-simplification of the true processes that most certainly also include simultaneous or parallel processing that is neither fully understood nor fully accommodated for in the HIPS framework. The HIPS stages are explained in more detail below, including a contextualisation to driving. The pertinent stages
are marked blue in the HIPS framework icons to the right of each sub-section title.

**Sensory processing**

The human brain receives information or stimuli from the ambient environment. The term *stimulus or stimuli* is used to describe any stimulating information or event which is often something that causes a reaction in the human organism. A stimulus can be internal or external and the sensory organs, such as the ear and the eye, are sensitive to e.g. external stimuli such as sound and images (or nuances in light). Not all image and sound spectra, however, are perceptible; the human sensory organs have a limited receivable range. In the context of driving, the main sensory input channels will be visual and auditory, although tactile and olfactory sensory channels may also provide relevant information. The brain is continuously bombarded with stimuli.

The sensory processing stage is where the input stimulus/information enters the sensory organs and brain in relative disorder and in large volumes. All of the human sensory systems have a short-term sensory store (STSS). The STSS is a mechanism in the brain and sensory organs that has a temporary function. The STSS prolongs the representation of the received but unprocessed stimuli from approximately 0.5 sec for visual stimuli, to 2-4 sec for auditory stimuli prior to perception. Auditory information may, for example, be perceived several seconds after the completion of the auditory stimulus (Wickens & Hollands, 2000). This information can still be successfully retrieved even if the human was inattentive or distracted at the original time of the *transmission* of the stimulus.

When driving, an example of the sensory processing stage would typically involve visually scanning the forward road scene, among other things, for visual cues as to the lateral position of the vehicle in the chosen lane. This is a highly automated task for experienced drivers. The visual information channels are especially important in driving, and the sensory organs need to continually scan the road-scene environment, processing vast amounts of information.
**Perception**

If the human is to perform a task effectively, sensory processing of incoming information requires *interpretation* of the unprocessed sensory data that are continuously relayed to the brain from the sensory organs. The interpretation of unprocessed sensory data is referred to as the perception stage, giving the sensory data meaning.

The perception processing stage generally requires little attention resources because the information is processed automatically and rapidly. Moreover, the perception stage of information processing, apart from being driven by sensory input, also receives input from the long-term memory regarding expectations related to similar situations, events or phenomena. The speed and the rule-based characteristics of the perception stage distinguish it from the cognition stage.

When driving, an example of the perception processing stage where unprocessed sensory data is given meaning could be our driver who has been visually scanning the road scene while, among other things, trying to maintain a stable lateral position of his vehicle. The perception processing stage of the task of lateral control of the vehicle would involve interpreting the visible road markings before continuing to the next (HIPS) stage and making the appropriate corrections to the vehicle’s trajectory. This particular vehicle control task is highly automated for experienced drivers and is on the skill-based level.

**Cognition and working memory**

The cognitive processing of information requires time and attention resources. This is because cognitive processing (such as reasoning, planning, image transformation etc.) is carried out by using the *working memory* which is a vulnerable, temporary store of relevant information (Wickens & Hollands, 2000). The central feature of the working memory in the HIPS framework is that all of the operations are “conscious activities which transform or retain
information and that they are resource limited” (Norman & Brobrow, 1975, in Wickens & Hollands, p. 12). The processes in the working memory are highly vulnerable to disruption when, for instance, attention resources are diverted to other mental tasks. Working memory and long-term memory are intimately intertwined in the processing of information; the level of intimacy is dictated by the familiarity of the task and its inherent complexity.

Long-term memory
Information that has been memorised is put into the long-term memory and is less vulnerable to disruption than the working memory information. In a similar manner, for instance, the rule-based information that is recognised and sorted during the perception stage will originate from long-term memory storage. Rule-based responses to relevant cognitive operations will also be retrieved from the long-term memory store. The long-term memory store is usually built up by experience and training and the task of driving a car is no exception. The characteristics of the information in the human’s environment create a setting for the expectations that drive the top-down perceptual processing (that is the long-term memory stored rules of thumb for perceived situations).

When driving, the cognition and working memory stage may typically involve the processing of information such as identifying and quickly classifying the road environment situation as familiar. This would be on the rule-based processing level. If the road environment in question is unfamiliar, processing between the long-term and working memory will occur in order to find a match with albeit a less-than-perfect identification/classification to an existing heuristic. The goal here is to facilitate a safe passage through the unfamiliar area. The latter of the two examples requires far more cognitive resources of the driver, increasing the likelihood of cognitive tunnelling or cognitive capture. The cognitive tunnelling occurs because the driver’s brain has most of the attention resources (energy) allocated to the unfamiliar road section task. During this period of cognitive capture the driver risks missing important cues from the road scene. The peripheral areas are particularly vulnerable. This inattentiveness increases the risk of an incident. The cognition stage will also involve selection of a response (especially) if based on a heuristic for the rule-based schema or also for the knowledge-based selection of a response.
Modification of Wickens and Hollands’ framework?

In the present context, Wickens and Hollands’ HIPS framework could be modified slightly to improve the accommodation of the skill-, rule- and knowledge-based levels of behaviour. The modification would involve the inclusion of an additional connection arrow from the long-term memory to the response selection stage. This modification would also improve the compatibility and consistency with Rasmussen’s (1987) skill-rule-knowledge framework and Reason’s (1990) generic error model system (GEMS). It could be argued that the additional connection link (arrow) between the long-term memory stage and the response selection stage is not necessary because the HIPS model in its original form has a link from the long-term memory via the working memory stage, to the response selection stage. It is however my contention that while the afore-mentioned link is sufficient for explaining the knowledge-based processing, it is not sufficient for describing the skill- and rule-based processing of information that occurs frequently in driving. The additional link from the long-term memory to the response selection stage is a minor and uncontroversial amendment. It merely illustrates the concept that rule-based processing of information also incorporates stored rules or heuristics which include standardised responses that are used in familiar situations. This additional connection arrow from the long-term memory stage to the response selection stage has not, however, been added to Figure 2 but would arguably improve the model if it had.

In actual fact, it should be noted that there could arguably be two additional links and not just the one as proposed above. The second link could be placed between the long-term memory and the response execution stage in the HIPS model. In the case of response execution heuristics in driving, the vast majority of executions would involve kinetic responses such as visually observing or scanning the immediate traffic environment, controlling the steering wheel and other vehicle controls etc. The second link has only marginal implications for the HIPS model because it could also be argued that the heuristic or stored rule for the response execution could be conveyed in the choice of response-selection heuristic in the preceding response selection stage.

Response selection and execution

The response selection stage is distinguished from the cognition and working memory stage particularly from an attention allocation perspective. The selection of a response would involve working memory and especially the long-
term memory when employing the top-down driven processing of rule-based responses for *standardised* situations, hence the necessity of an additional connection arrow from the long-term memory to the response selection stage.

When information has been perceived and processed cognitively, some sort of response selection will usually transpire and subsequently also execution of the selected response. Different types of information will require very different levels of cognition prior to the response execution. It should be noted, however, that the selection of the response per se is different from its execution. The response selection would involve deciding what to do whereas execution of the selected response would usually involve co-ordination of muscles for controlled motion to ensure that the desired response is successfully carried out according to plan. Response selection and execution in driving would involve information processed in the working memory and would require varying degrees of attention resources.

Our driver, for example, who is trying to maintain a stable lateral position of his vehicle will be doing this particular sub-task on the skill-based level and appear to be automatically correcting the vehicle’s trajectory. The execution of a highly automated action in driving such as the lateral control of the vehicle will usually require little attention resources. However, if the driver’s attention resources are captured or engaged by another task that is sufficiently complex in nature that most or all of the attention resources are engaged, the lateral task performance will deteriorate. It should be noted that even the most automated, skill-based actions require attention resources for adequate performance.

The driver selects an appropriate response (based on the information that has been processed earlier in the schema) that will be executed. The execution would usually involve the activation of muscles to handle the necessary vehicle controls e.g. the steering wheel, brakes etc.

*Feedback*

The feedback loop that Wickens and Hollands (2000) placed at the bottom of their HIPS framework indicates that actions are sensed by the driver either directly or through interaction with the vehicle. Thus the feedback loop emphasises that the information is continuous and that the process can be initiated at any point in the HIPS schema.
The kinetic activation that is usually involved in the execution of responses in driving will be fed back and is crucial for the continued control of the vehicle. The speed of the whole process of human information processing for the simplest of tasks has been estimated at approximately 2.5 correct decisions per second (Debecker & Desmedt, 1970).

Attention

Attention in the HIPS model refers to the supply of mental resources. Many of the mental operations are not done fully automatically but require the selective application of attention resources. The process of attention resource allocation to the various stages of HIPS is crucial for driving successfully, including, interaction with the vehicle and other road users. In Wickens and Hollands’ HIPS framework, attention is selectively allocated to the sensory processing stages prior to perception (cf. Figure 2). Visual perception such as visual scanning is often driven by past experience (heuristics or rules of thumb).

Driving involves many resource demanding tasks such as keeping the car in the lane, searching for signposts, changing gear, maintaining a safe distance to other road users especially in front of the vehicle and also planning the route ahead to arrive at the desired destination. The driver must therefore choose a strategy for dividing attention or allocating his/her attention resources between different tasks. When the total demand on attention from these tasks nears the maximum level of attention possible, one or more of the tasks will be disrupted, delayed or distorted and performance will deteriorate.

Attention in General

Human information processes require different amounts of effort or attention resources. Automated information processes typically require less effort and resources than elaborate consciously controlled processes (Pashler, Johnston, & Ruthruff, 2001). If the human system has redundant capacity, which is important in car driving, then there will be resources and capacity available for mobilising extra effort in cases of a potentially hazardous or critical traffic situation arising. If, however, the human system is being used to its capacity limit, then there is a reduced possibility of correctional or evasive actions, problem solving etc. by the driver. Information can also be missed, information processing delayed
and/or some ongoing tasks will be quickly abandoned to release resources for processing information in the potentially hazardous situation.

There are numerous system interactions between all parts of the human perceptual-cognitive psychomotor systems and parallel processing occurs at different levels with input from different channels (Wickens & Hollands, 2000; Pashler, 1999). Attention is suggested as having multi-perceptual parallel processing characteristics, albeit with a limited capacity (Pashler, 1999). As is also the case with human memory systems, neither domain has been fully explored nor are they fully understood. It is, however, generally accepted that attention and short-term or working memory are deeply interconnected (Pashler, 1999). Working memory is discussed in more detail in a separate section of this thesis.

Norman and Shallice (1986) suggested that there is an attention control structure which provides a source of control upon the selection of schemata in the context of actions. They referred to this mechanism of attention control as the supervisory attentional system (sic.). Norman and Shallice also cited clinical neuropsychological evidence of the supervisory attentional system, with its higher-level and lower-level control schemata, with pre-frontal lobe functions, viz. the corpus striatum of the basal ganglia.

Figure 3: A schematic relationship in approximate terms, between task complexity, attention resources that are available and task performance.
Figure 3 illustrates the relationship between supply and demand of attention resources as a function of task complexity. There is a maximum limit for how much attention resources humans have at any given time. When concurrent tasks’ total attention demand is less than the maximum, a reserve attention capacity is available. The task performance will start to deteriorate when the human’s attention level nears the maximum capacity. Figure 3 is very helpful for understanding the relationship between attention resources, task demand and how they affect task performance. Putting numbers onto Figure 3 would be of great utility for researchers and human factors specialists working with industrial applications. The role of cognitive workload and distraction is intrinsically associated to human attention resources and the effects on task performance.

**Cognitive Workload**

Cognitive workload is defined by the relationship between human cognitive resource supply and the task’s demand on the driver (Wickens & Hollands, 2000, p. 459) and as the amount of information-processing resources used per time unit, for task performance (Wickens & Hollands, 2000; De Waard, 1996). Or to embellish somewhat, cognitive workload can be conceptualised as the degree to which the operator’s cognitive and perceptual capabilities are taxed during the execution of the tasks undertaken during driving. Workload levels are continuously changing.

Automated behaviour, multiple resources and task priority time-sharing between concurrent tasks or components of a complex task are usually associated with a cost of concurrence assumed to reflect the limited capacity of the human information system (Broadbent, 1958; Broadbent, 1982). Exceptions are the concurrent performance of very easy tasks, i.e. tasks with a small demand on processing resources, or tasks that can be processed in parallel due to automatic processing, a phenomenon which is known to develop from considerable amounts of consistent training (Shiffrin & Schneider, 1977). The degree of interference between concurrent tasks can be manipulated by task structure and task priority. Results from dual-task studies (Brooks, 1968; Baddeley, 1976; Wickens & Liu, 1988) strongly suggest that verbal and spatial processing use different resource pools. In accordance with multiple-resource theory, performance decrements are less severe during concurrent performance of cross-modal tasks when compared with intra-modal ones (Wickens, Sandry & Vidulich, 1983).

Lee, Lee and Boyle (2005) found in a simulator study that drivers were sensitive to the detection of dynamic vehicle changes when driving when compared to their own subjective ratings of confidence in detecting changes. Lee et al.
suggested that the drivers were aware of experimentally manipulated changes in the driving environment. However, when cognitively loaded, the participants were only vaguely aware of their performance. Lee et al. conclude that it is when the cognitive workload is high, whether due to secondary tasks or complex primary task situations, that the drivers are more likely to inaccurately estimate their ability to handle difficult traffic situations.

**Distraction and Driving**

The term driver distraction implies that drivers do things that are not primarily relevant for the driving task (driving safely) and that this reduces the available attention that would otherwise be needed for driving safely. The problem of driver distraction for traffic safety must, in part, lie in the limitations of human attention resources and how the attention is allocated (prioritised) by humans in their management of the different tasks, whether they are primary-task related (driving) or not. The allocation of mental resources, attention, is associated to the different levels of driver (cognitive) workload (Wickens & Hollands, 2000; De Waard, 1996; Patten, Kircher, Östlund & Nilsson, 2004).

Driver distraction is only really a traffic safety problem if the general level of cognitive workload demanded for all of the (concurrent) tasks exceeds that of the system, i.e. the brain or if attention is focused on the wrong targets. Indeed a certain level of driver distraction may even have positive traffic safety effects by increasing the arousal levels of the brain. This would conceivably be in very monotonous traffic situations where, for example, drowsiness is a danger. Sheridan (2004) suggested that if, on an operational level of control, there is no effect of an additional task then there is no distraction. Central traffic safety problems with driver distraction involve 1) a loss of forward roadway attention and 2) unexpected event detection.

Driver distraction is recognised as being one of the central causes of road traffic incidents (Treat, Tumbas, McDonald, Shinar, Hume, Mayer, Stansifer & Castellan, 1979; Englund, Gregersen, Hydén, Lövsund & Åberg, 1998; Harbluk, Noy, & Eizenman, 2000; Alm & Nilsson, 1995; De Waard, 1996; Zaidel, Paarlberg, & Shinar, 1978; Martens & Van Winsum, 2000; see also NHTSA, 2000). Driver distraction may only be one factor in the chain of events leading to an accident. The loci of driver distraction may also vary greatly. Generally speaking, the focus of driver distraction research is on the competition over mental attention resources where the cognitive workload is high.

In an interesting naturalistic driving study by Stutts et al. (2005) with 70 participants that were studied for a week, it was found that driver distraction, particularly visual distraction, was a common component in everyday driving.
The most common distractors were 1) eating and drinking (including preparation thereof), 2) distraction inside the vehicle (reaching, looking at, manipulating controls etc.) and 3) distractions outside the vehicle. The measures used for distraction in this study were frequent instances of one or no hands on the steering wheel, eyes off the road and lane departures. Perhaps the most interesting result of this naturalistic driving study is that the drivers (n=70) were engaged in one or more potentially distracting activities 14.5% of the total time that the vehicles were in motion (Stutts, Feaganes, Reinfurt, Rodgman, Hamlett, Gish & Staplin, 2005).

In an epidemiological study of police reported fatal accidents in England and Wales, driver distraction was investigated. In particular focus was the use of mobile phones and entertainment systems as contributory factors in the accidents (Stevens & Minton, 2001). Between the years of 1985 and 1995, there were 41,817 reported fatal accidents whereof 5,740 accident reports remained in the police database at the time of the study; a total of 101 cases involved distraction. Stevens and Minton (2001) reported that by far the greatest source of in-vehicle distraction (conservatively estimated), based on their data, was interaction with other passengers. This was followed by entertainment systems and then by consumption of food, drink and cigarettes. Only 3 cases involved mobile phones. Mobile phone use has steadily increased since the time of this study, so the number of cases is likely to have increased.

In a simulator study by Horberry, Anderson, Regan, Triggs, and Brown (2006), the effects of distraction from handsfree phone conversations and the operation of an in-vehicle entertainment system (car radio and cassette player) were investigated. The effect of the drivers’ age was also studied. The main measurements of performance were mean speed, deviation from the signposted speed limit and the subjective workload scale NASA-TLX. The main conclusions of this study were that both of the in-vehicle tasks impaired several aspects of driving; interestingly it was the entertainment-system distractor that had the greatest negative impact on driving (n=31). Elderly drivers tended to reduce their speed more in complex traffic environments than the younger drivers, possibly as a compensatory behaviour to increase margins for recovering errors. The entertainment-interaction condition involved a series of tasks using the car radio and cassette player.

Many studies of driver distraction and impairment tend to focus on single factors, although there are some that focus on comparing factors such as distraction and alcohol intoxication (cf. Strayer, Drews, & Crouch, 2006; Rakauskas & Ward 2005). These studies have generally found that relatively high levels of blood alcohol content (BAC) at 0.08% which is the legal intoxication limit in the UK and the USA (Sweden has 0.02% BAC and most
other European countries have a BAC of 0.05%) give a comparable primary task performance (e.g. time headway, which is the distance in time to e.g. a lead vehicle) to talking on a mobile telephone (Rakauskas & Ward, 2005).

It should be noted that any comparison with distraction and driver intoxication and the effects on driver performance is potentially misleading for two main reasons. Firstly, a mobile phone conversation whilst driving impairs performance only for the duration of the phone call whereas the alcohol intoxication is present in the driver’s body for a considerable amount of time after the consumption of the beverage. Secondly, distraction interferes with driver performance predominantly on the operational level, disrupting smooth vehicle control, diverting attention resources from the immediate environment and the primary task. Impairment from alcohol at legal limits for intoxication interferes with information processing and decision making functions on strategic, tactical and operational levels of decision making and planning. That is, driver intoxication, on the strategic level, affects the driver’s judgement when intoxicated where e.g. he/she might decide or be persuaded by intoxicated friends to drive home instead of taking a taxi; on a tactical level, intoxication increases the likelihood of additional traffic violations (e.g. running through red traffic lights) and on an operational level, intoxication may ultimately result in loss of vehicle control and involve a crash.

One should bear in mind that despite the deceptively similar results between intoxication and distraction as found in e.g. Rakauskas and Ward (2005) and Strayer, Drews and Crouch (2006), alcohol intoxication affects the driver’s performance more profoundly than driver distraction. In terms of road transport fatalities, driver alcohol intoxication is more lethal than driver distraction (cf. Robinson & Campbell 2006; Holmgren, Holmgren, & Ahlner, 2005; Vägverket, 2006).

Additionally, if an intoxicated driver were to engage in a secondary task, e.g. adjusting the car radio, a mobile phone conversation, or even other performance reducing factors such as being drowsy, it is more likely to result in a critical level of performance degradation (Wang, Knipling & Goodman, 1996).

**Working Memory and Driving**

Working memory and sensory channel capacities are important components in the processing of information. The human working memory limitations influence our ability to successfully perform complex tasks in dynamic environments such as driving.
Schacter and Tulving (1994) classified human memory into five general categories, viz. procedural memory (e.g. gradual, incremental learning); the perceptual representation system (e.g. the identification of words and objects); semantic memory (e.g. retention of factual information about the world around us); episodic memory (e.g. conscious recollection of experienced events from one’s own personal past. These are multi-featured representations in which many different kinds of information e.g. spatial, temporal, contextual, form personal experiences); and working memory (e.g. the temporary holding and processing of information).

Baddeley defines the working memory as a “system for the temporary holding and manipulation of information during the performance of a range of cognitive tasks” (Baddeley, 1986, p. 34). Baddeley distinguishes two categories of working memory; general and specific working memory. General working memory refers to the temporary storage and processing of information when dealing with a range of cognitive tasks. Specific working memory refers to a more detailed model of the structures and processes involved in actually performing the general working memory task.

Baddeley and Hitch proposed an alternative model of working memory. Their model comprised a supervisory controlling system that they called the central executive. The central executive is assisted by the two assisting systems. The first was specialised for processing language which they called the articulatory loop and the second was concerned with visuo-spatial memory, called the visuo-spatial scratch pad or sketch pad (Baddeley, 1986; 1994).

Baddeley argues that there is a considerable amount of data to support the idea of separate verbal and spatial information processing. Wickens’ model of information processing stages is, however, arguably more useful for understanding the applied multitask process of driving. What is clear, however, is that the different sensory input characteristics (e.g. visual, tactile, auditory etc.) activate different parts of the brain depending on the nature and meaning of the information. Language and its comprehension, for instance, could either involve the visual input channels (e.g. reading) or the auditory input channels (e.g. listening). Conversation would involve more complexity and has different information processing characteristics. Baddeley’s work on describing the central executive is important where the central executive is described as supervisory and a scheduler of attention resources. Baddeley discusses other functions such as consciousness. The characteristics of the central executive remain a little vague, but are nevertheless a useful conceptualisation.

The concept of working memory can also be likened to consciousness. That is to say that humans are only conscious and aware of the content of the working
memory (Sweller, van Merrienboer, & Paas, 1998). Note that this does not exclude the possibility of processes that we are not consciously aware of being active.

Working memory is severely limited in making absolute judgements when conceptualised in situations where observers assign stimulus into multiple categories along a sensory dimension (Wickens & Hollands, 2000). When studying the ability of observers to discriminate, on a single dimension, using four discrete levels along a stimulus continuum (representing 2 bits of information), performance is usually perfect. However, when the number of stimuli is increased and performance is mapped with five, six, seven or more discrete stimulus levels, errors tend to start occurring at about the five to six stimuli level, and the situation worsens increasingly with additional stimuli. The observer is said to have a maximum channel capacity (Wickens & Hollands, 2000).

In Miller’s classic paper from 1956 on the “Magical Number Seven, Plus or Minus Two” he discussed the limitations of the human working memory for processing information (Miller, 1956). Miller was interested in exploring the boundaries of our sensory capacity for information processing or absolute judgements of unidimensional stimuli. Miller draws on a number of early experimental studies principally presenting results on unidimensional stimuli but does also discuss multidimensional stimuli. The unidimensional channels discussed by Miller include auditory pitch and loudness, saltiness, visual position and for multidimensional stimuli, visual position of a dot in a square (horizontal and vertical position identification), brightness and hue and binary digits, decimal digits, letters of the alphabet and monosyllabic words.

The results presented in Miller’s paper are given in bits. A bit is expressed as a choice between two possibilities, thus a binary digit. Miller (1956) defines a bit as the amount of information that is needed to make a decision between two equally likely alternatives. Four equally likely alternatives would consist of two bits of information. Three bits consist of eight equally likely alternatives, four bits consist of sixteen alternatives, five bits consist of thirty-two, six bits consist of sixty-four equally likely alternatives, and so on. If there are sixty-four equally likely alternatives, one must make six successive binary decisions (at one bit each) before arriving at the correct alternative. When the performance of the human participants started to level off and become asymptotic, the asymptotic value was taken to be the channel capacity of the participant.

The channel capacity of the human listener for absolute judgement of pitch (unidimensional stimulus) was found to be 2.5 bits. The channel capacity for absolute loudness was estimated at 2.3 bits. Taste intensities was estimated at
1.9 bits, visual position (unidimensional) 3.25 bits and as much as 3.9 bits for long exposures of unidimensional visual position stimuli. Miller concludes in his discussion on unidimensional channel capacity with the supposition that the mean capacity was 2.6 bits with a standard deviation of 0.6 bits in terms of distinguishable alternatives which correspond to approximately 6.5 categories with a one-standard deviation range of approximately 4 to 10 categories, hence the magical number 7 +/- 2 (Miller, 1956).

Based on the results in Miller’s paper, it can be concluded that the human capacity is finite and also rather small, when making unidimensional judgements and moreover, that this capacity does not vary greatly between sensory modes.

Miller’s 7 +/- 2 hypothesis applies to the channel capacity for absolute judgement of unidimensional stimuli. Everyday life, however, often involves judgement of multidimensional stimuli. In a study of the visual channel capacity for absolute judgement of the position of a dot in a square, a two-dimensional task involving horizontal and vertical positions, the absolute capacity was estimated at 4.6 bits which should be compared with the 3.25 bits for the unidimensional position task. The increase from 3.25 to 4.6 bits, from one to two dimensional judgements is a great increase, but not the doubling (3.25 x 2 = 6.5 bits) that Miller had expected. This characteristically imperfect improvement in channel capacity when adding dimensions was found for all of the sensory modes. Performance improved at a decreasing rate with the additional dimensions (Miller, 1956).

Miller sums up the results for the multidimensional stimuli by suggesting that when more variables are added to e.g. a display, the total capacity is increased but the accuracy for any particular variable decreases. Participants can, therefore, make relatively crude judgements of several things simultaneously. In regard to the addition of dimensions such as in the case of linguistics, Miller refers to a study where the tonal stimuli (multidimensional) were measured, and the channel capacity was found to be 6.9 bits or approximately 120 recognisable tones or sounds (Miller, 1956).

Miller (1956) maintains that the limit or span of absolute judgement for unidimensional judgements is around seven; humans, however, use different techniques for getting around this limitation. Miller names three techniques, 1) we make relative rather than absolute judgements, 2) we increase the number of dimensions along which the stimuli can differ, or 3) we rearrange the task so that there is a sequence of several absolute judgements instead of a simultaneous judgement. Absolute judgement, therefore, is limited in the amount of information that it can process.
The immediate memory or working memory (which is not to be confused with the channel capacity) is also limited by the number of items that can be processed, which incidentally is also approximately seven items or chunks of information. The span of the immediate or working memory is suggested by Miller as being almost independent of the number of bits per chunk. That is to say that one single chunk of information can contain a great deal of information (bits). The chunking function of items of information is a process of organisation or arranging stimuli input into familiar units or chunks. This recoding of information enables us to process more information. Chunking is the result of learning and experience within a particular field or task and can be likened to the formation of heuristics such as in the case of driving. The size of each chunk can be increased, building larger and larger units within the same chunk.

The human cognitive limitations of working memory are of central importance in studying task complexity and the interface in the driver cockpit. Despite the conspicuous limitations of working memory, human ability to operate in complex situations and tasks such as driving implies that the locus of human intellect lies in the long-term memory rather than the working memory (Sweller, van Merrienboer, & Paas, 1998). Moreover, the capacity of the long-term memory would appear to be almost limitless, containing schemata or sequences of stored information.

**Visual Perception, Cognition and Human Information Processing**
Visual perception, cognition and human information processing are important factors in the assessment and study of driver behaviour and performance. A commonly used measure of cognitive workload in driving is based on a visual secondary task. Visual secondary tasks are primarily indicators of visual workload demand, which is highly prevalent and important in driving. In an early study, Lee and Triggs (1976) found that increased environmental complexity during driving affected the detection of peripherally presented stimuli. They also reported a stronger effect in the left visual hemi-field than in the right one. Later, Miura (1986) demonstrated that task demand rather than visual complexity affected eye movement patterns as well as sensitivity in the driver’s visual periphery. Results obtained in contexts other than traffic support the assumption that peripherally presented stimuli are less likely to be detected at high levels of perceptual load in the foveal field of view (see Rinalducci & Rose, 1986; Williams, 1988). Chan and Courtney (1993) demonstrated that variance in cognitive demand also affected sensitivity in the visual periphery at a constant level of perceptual load in the foveal field. Their subjects were required to either name or add digits, presented in the foveal field and these instructions were found to affect the detection of peripheral stimuli although the stimuli were
identical in both conditions. A study of visual search for hazards in videotaped traffic scenes (Crundall, Underwood, & Chapman, 1999a; 1999b) has demonstrated that the presence of traffic hazards on videotapes resulted in lower detection rate for peripherally presented stimuli. Apparently, detection of simple stimuli presented in the visual periphery is sensitive both to perceptual load in the foveal field and to task load.

Evidence from studies of perceptual workload and visuocortical processing suggests that perceptual workload can modulate attention focus early in visuocortical processing (Handy, Solitani, & Mangun, 2001). Furthermore, Handy et al. (2001) results also suggest that increasing the workload of the foveal targets decreases the amount of residual attention capacity available for allocation to task-irrelevant parafoveal locations. The parafoveal or peripheral stimuli detection capacity is important for the driver of a vehicle. If the driver feels a serious decrease of his/her attention capacity for driving the car, then he or she can reduce the vehicle’s speed in a conscious or subconscious compensatory behaviour thereby reducing the speed of the visual information flow. Therefore, driving speed and perceptual stimulus detection capacity are important indicators of how mobile phone conversations may affect traffic safety when driving.

The entire visual field of view is approximately 210’. However, the central field of view (i.e. foveal vision) in humans is merely 2’ (Miura, 1990). This means that drivers have to rapidly direct the eyes to scan areas of the road scene to gather relevant and necessary information.

The primary function of the peripheral field of view is the acquisition of cues. In some important work, Miura (1990) found that apart from a narrower functional field of view resulting from increased workload demands, there is also an optimising process where the drivers showed a stronger inclination towards acquiring information in the peripheral field when more heavily cognitively loaded. Miura interprets this finding as a trade-off function (by experienced drivers) to optimise the allocation of processing the limited attention resources for coping with increased attention demands.

Visual performance generally declines when the distance from the fovea increases. Visual foveal acuity declines by a factor of three when moving the target from the fovea to a 10’ eccentricity. This decline is similar to the decline in cone density on the retina between the fovea and the 10’ parafoveal eccentricity. The larger the eccentricities from the fovea, the greater the decreases in visual acuity (Ma, Chan, & Courtney, 2004).
Foveal acuity is defined as the ability of the eye to discriminate fine detail and is a basic visual function for many tasks including driving (Chan & Courtney, 1996). The functional binocular visual field has been found to be ovaloid along a horizontal axis. There are, however, typically large variations between participants. The area was also found to be irregular and contained insensitive patches (Chan & Courtney, 1996).

**Functional field of view**

The functional field of view is an area of perceived visual acuity (e.g. visual target detection whether static or moving) that can change in size. Perception of visual stimuli in the functional field of view reduces in increasing eccentricities from the fixation point. That is, the target is increasingly less likely to be detected/perceived the further it is moved away from the fixation point. This phenomenon is also referred to as a cognitive tunnelling effect (cf. Martens & van Winsum, 2000). Miura (1986) tested a hypothesis that suggested that the functional field of view becomes smaller with increased cognitive demand. Miura examined eye movement and the functional field of view at the same time. The test participants’ task was to detect a visual stimulus and respond orally, using reaction times and eye movements as dependent variables. In summary, Miura (1986) showed that with increased task demand, the functional field of view narrowed and correspondingly, the reaction times for the detection of peripheral visual targets increased. Miura (1987) suggests further that this phenomenon reflects an optimisation of allocation of limited processing resources and a strategy for coping with increased cognitive demand.

Miura (1994) also went on to investigate the effects of visual attention at different distances when in a moving vehicle. A tunnel driving simulator was used and found that reaction times for targets in close proximity to the vehicle were shorter than those at greater distances from the vehicle. This is referred to by Miura as an asymmetrical viewer centred mode of attention shift. Moreover, the difference in reaction times was also greater in moving vehicle conditions than in stationary conditions (Miura, 1994) suggesting a sensitivity to changes in cognitive workload. Miura’s findings (1986; 1987; 1994) regarding the mechanisms behind the functional field of view form the foundation for the subsequent development of the peripheral detection task (PDT) method that is used in this thesis.
Figure 4: An illustration of the functional field of view in visual perception where “X” marks the fixation point, the solid-lined circle represents the central field of vision and the dashed-lined circle represents the functional field of view. The functional field of view is not static. Figure 4 is not drawn to scale.

The X marks the fixation point illustrated in Figure 4, the solid-lined circle represents the central field of view (foveal vision) and the dashed-lined circle is a parafoveal area that is referred to as the functional field of view. The size of the functional field of view changes or rather the human’s ability to perceive stimuli changes, depending on the level of cognitive workload. The eye can still register or see the parafoveal stimuli, but when the cognitive workload levels are high, a form of cognitive tunnel vision occurs and the functional field of view is said to narrow (Martens & van Winsum, 2000).

Martens and van Winsum (2000) used the peripheral detection task (PDT) to test whether the width of the functional field of view was due to a perceptual or a cognitive tunnelling effect. The PDT reaction times and the hit rate were calculated as a function of visual and non-visual tasks. Their results, however, did not support their hypothesis of perceptual/visual tunnelling; they rather suggested that the narrowing of the functional field of view was due to cognitive tunnelling because their results suggested, in part, that the PDT performance was also sensitive to the complexity of non-visual (tactile and auditory) task modes in the traffic scenarios used in the study. This is an important distinction because it suggests that the PDT method is an indirect measure of cognitive workload rather than merely a visual measure.

Ma, Chan and Courtney (2004) found that although there is visual target detection sensitivity to stimuli on the vertical axis, the horizontal, peripheral target detection performance was greater. This has some relevance for the future
development of the PDT method in regard to the target (the visual stimuli) placement.

**Driver Experience and Training**

Driver experience and training are essential components in the task of reducing slips, lapses and mistakes in the transport system, thus assisting traffic safety and mobility improvements. A driver who is well trained and experienced in the task of driving will have acquired a large repertoire of heuristics or rules of thumb for different traffic scenarios or situations. The ability of the experienced driver to utilise these heuristics reduces the general cognitive workload created by the driving task. The driver is said to be operating on the skill- and rule-based levels of behaviour (Rasmussen 1980; 1987).

Underwood, Chapman, Berger and Crundall (2003) in their laboratory study of traffic events found, inter alia, that experienced drivers had better recall of immediately prior events than novice drivers. They also noted that as skill and experience increase, drivers increase their sampling of events from their immediate traffic scene; they also sample from more locations in their traffic scene. Similar results were reported by Crundall, Chapman, Phelps and Underwood (2003). In a more elaborate and earlier study by Crundall and Underwood (1998), novice and experienced drivers’ distribution of visual attention was studied during exposure to different levels of cognitive workload. Crundall and Underwood induced different levels of complexity with different road traffic environments. As with other studies in this field, the main dependent variable was the visual search strategy of the individual participant. Crundall and Underwood found that experienced drivers select visual strategies according to the complexity of the road traffic environment and that novice drivers’ visual search strategies were inflexible to changes in (visual) demand.

In terms of visual search patterns, distinct differences were noticeable between novice and experienced drivers, and especially so in situations that were particularly demanding (Chapman, Underwood & Roberts, 2002). Chapman and Underwood (1998) suggested that the duration of eye fixation, whilst driving, represents the time spent processing hazard-related information in the road scene. Moreover, newly qualified drivers appeared, in Chapman and Underwood’s study, to be more affected by increased complexity than the experienced drivers. Several studies have noted narrower visual search patterns among novice drivers (cf. Chapman & Underwood, 1998; Mourant & Rockwell, 1972; Crundall & Underwood, 1998) but do not explore the element of workload and inexperience as an effect of this narrowed search pattern. These studies have, however, focused more on the lack of skill which is evident when the subjects are untrained novice drivers (cf. Chapman, Underwood & Roberts,
Mourant and Rockwell’s field study (1972) at an early stage clearly differentiated between experienced and novice drivers when studying their visual search patterns. In contrast to the experienced drivers, the novice drivers tended to fixate their gaze to a small area not far ahead of the vehicle. Novice drivers also used their mirrors less frequently, and on the motorway sections made pursuit eye movements whilst the experienced drivers only glanced. Furthermore, Mourant and Rockwell (1972) suggested that the visual acquisition process of novice drivers was unskilled and overloaded.

**Peripheral Detection Task**

The peripheral detection task (PDT) method is a secondary task method and is used as an indirect measure of cognitive workload. The PDT equipment used in the three experimental studies in this thesis were all designed, developed and constructed by Volvo Technology Corporation in Gothenburg, Sweden. The software and the hardware underwent improvements honing the apparatus. The stimulus frequency and criteria were not, however, altered after the initial developments in *Study 1*.

The PDT method was first used in a simulator study in which different designs and functions of an advanced driver assistance system (ADAS) were evaluated (Martens & Van Winsum, 1999). Olsson (2000) successfully transferred the PDT method to field conditions. She used the same road types as the two previous studies and related PDT performance to participants’ monitoring of in-car equipment during driving.

It was Miura (1990) who found in a field study of peripheral vision performance that with increases in demand generated by the complexity of traffic environment, reaction times increased, the functional field of view narrowed and the number of saccades increased. Miura’s findings suggested that peripheral vision performance decreased when there was an increased demand on attention.

The peripheral detection task (PDT) method has been used in several field and high fidelity simulator studies and shown itself to be a sensitive measure of cognitive workload, especially where visual demand is high such as in driving (Martens & Van Winsum, 1999, 2000; Harms & Patten, 2001, 2003; Olsson & Burns, 2000; Patten, Kircher, Östlund, & Nilsson, 2004; Patten, Kircher, Östlund, Nilsson & Svenson, 2006; Kircher, Törnros, Vogel, Nilsson, Bolling, Patten, Malmström & Ceci, 2004; Crundall, Underwood, & Chapman, 1999b). The PDT method is continuous and differs from more traditional reaction time measures (often used for evaluating situation awareness), such as brake-reaction time, which are only really ecologically valid for a few situations because the participants quickly learn that certain events or situations will crop up at some
stage during the experiment. The PDT method in contrast, also by being a secondary task, is in the background throughout the entire experiment. Large quantities of data can be collected and baseline or reference data (within-subject design) can easily be included in the experiment design. Furthermore, the measurement of available cognitive resources also provides a more valid reflection of the driving task and its demands on the driver.

The PDT equipment used in Studies II and IV of this thesis and illustrated in Figure 5 below, had one LED illuminated at a time, the selection of which was random. The interval between illuminations of the LED signal was between three and five seconds, also at random within that range. The period of illumination was a maximum of two seconds unless the participant extinguished the LED signal by depressing the micro-switch. The light signals from the LED were reflected up onto the left-hand side of the windscreen in the form of a head-up display. The LEDs had a light intensity of 8.2 cd, a projection angle of ±3 degrees and a wavelength of 660 nm (red). The LED reflections appeared approximately 6.8-21.8˚ left of the centre of the steering wheel and approximately 3.8-5.3˚ elevated above the car console as shown in Figure 5. The participants’ performance was recorded in the form of a PDT miss rate and their reaction times in milliseconds (ms). The PDT data was synchronised with all the instrumented-vehicle data (e.g. speed, steering wheel angle, distance travelled, etc.).

![Figure 5: An illustration of the PDT equipment as set up in the instrumented vehicle used in Studies I, II and IV. The illustration is not drawn to scale.](image)

There are some important points regarding the PDT as a workload measure that need airing. Most notably, and importantly, the PDT method is an indirect measure of cognitive workload. However, in certain traffic situations that are complex and require the driver to look in different directions other than forward,
the number of missed responses will increase. It is suggested that the PDT performance, especially the hit rate performance in these road sections is nevertheless an indirect measure of workload but perhaps more visual and psycho-motor workload demands (in driving) (Jahn, Oehme, Krems, & Gelau, 2005). In normal driving, however, the duration of complex traffic situations requiring high visual and psycho-motor workload are brief in terms of total travel time and distance travelled. Furthermore, a visually demanding task also involves cognition and thereby denotes a cognitive workload function. A purely cognitive task will induce the same sort of cognitive workload demand on the driver, the level of which is determined of course by factors such as task complexity and performance shaping factors.

The PDT is sensitive to the demands of the driving task (cf. Martens & van Winsum, 1999; Harms & Patten, 2001; 2003; Patten, Kircher, Östlund & Nilsson, 2004; Patten, Kircher, Östlund, Nilsson & Svenson, 2006), to peaks in workload (Harms & Patten, 2001; Jahn, Oehme, Krems & Gelau, 2005) and importantly the PDT appears to have a high reliability between studies (Jahn et al. 2005).

**Primary Tasks**

The primary task in driving usually involves getting from point A to point B without unintentionally speeding or violating other traffic regulations, maintaining a centre of lane vehicle position, maintaining a safe distance to other vehicles, especially in front of the driver and driving with due care and attention, i.e., not putting oneself or other road users in danger.

Measures of primary task performance such as lateral deviation may not, however, be a good performance measure of driver workload even if changes in lateral control of the vehicle can be observed. In the case of lateral control recent research (cf. Harbluk & Noy 2002; Törnros & Bolling, 2005) has found that high levels of cognitive workload tend to reduce lateral deviation (the opposite of what one might expect if the correlation between workload and lateral control was linear) for cognitively demanding processes, whereas e.g. visual distraction outside of the central forward visual field increases lateral deviation.

There is usually the problem of how to interpret the results and also the temptation and (dubious) validity of relating the primary task metrics to traffic safety risks. This task is fraught with causal deduction misconceptions such as the case of lateral position. Common sense suggests that inadvertent lane departures are not good for traffic safety; however, rigid lane positioning also suggests a decrement in traffic safety. The curvilinear characteristic of the lateral position measure is interesting and at the same time a little frustrating because it
complicates the interpretation of the primary task measure by not being linear in its relationship to cognitive workload.

An interesting and effective but somewhat narrow primary task measure of visual distraction and task time is the visual occlusion method. The visual occlusion technique is controlled by the participant. A screen or shutter occludes the participant/driver from seeing the road scene. The participant has to press a button that removes the screen and it automatically closes again when visual information is not needed. The shutter will typically be opening and closing rapidly depending on the experiment. The visual occlusion method is an effective method for gauging task time requirements and in particular task interruptability which is synonymous with greater usability (Noy, Lemoine, Klachan & Burns, 2004). Unfortunately visual occlusion is not suitable for field studies.

In a road traffic context, the primary task of a driver in normal driving conditions is the safe operation of the vehicle in respect to other road users and themselves. The primary task involves activities that support the driver and safe driving, e.g. decision making, route planning, lane keeping, adapting and using an appropriate speed etc. Secondary tasks, however, are activities that may be undertaken by the driver but do not directly support the driving task, e.g. listening to music, conversing with a passenger or talking on a mobile phone or similar device. Quite often, the secondary tasks will compete for the driver’s available mental resources.

**Secondary Tasks**

The secondary task performance of the peripheral detection task (PDT), i.e. where the participants receive a visual stimulus to respond to every 3-5 seconds, is continuous and is therefore in the background demanding a constant level of attention and is thus included in attention demand throughout; and in the context of driving, constitutes a *baseline* level of attention resources required for driving in particular traffic situations. The PDT reaction times are a reflection of the level of primary task complexity as suggested in *Study II* of this thesis. If the traffic intensity changes and the road comes to an intersection for example, so too does the level of attention resource demand which also affects the PDT performance.

When a driver has plenty of reserve attention capacity at any given point in time, the addition of a secondary task such as having a simple conversation will not greatly affect the primary task performance because there will still be an attention capacity *reserve* to deal with changes that might occur in the driver’s immediate environment as illustrated in Figure 3.
Pros and cons of a visual secondary task

The driving task requires high levels of visual attention (i.e. visual information processing). Visual perception demand has been estimated at approximately 90% of the total perceptual demand (Hills, 1980). The remaining perceptual input to the brain accounts for the remaining 10% through the auditory, tactile and olfactory perceptual channels. Driving is, therefore, a visually demanding task. The use of a visually based secondary task as an indicator or measure of cognitive workload levels may be construed as problematic. Mainly because it may be argued that the visual perceptual channel is already heavily loaded. Wickens and Hollands (2000) have, inter alia, suggested in their multiple task theory that the perceptual channel that is already loaded is more likely to be sensitive to changes in cognitive demand. This being the case, it may be hypothesised that a visual secondary task is nevertheless, because of heavy demand on vision, a useful and valuable method for evaluating cognitive workload when driving in road traffic.

The importance of visual perception for safe driving further enhances the validity of visual secondary task measures in human factors research of driver performance. Attention resources are multiple and in that sense multimodal tasks will only seriously compete for attention resources if the task draws on the same source, e.g. two separate visual tasks. Thus, when two tasks require attention from the same source the human performance becomes more impeded than two tasks requiring different modes, e.g. visual and auditory (cf. Wickens & Hollands, 2000; Harms & Patten, 2001).

Human Error Model

Reason (1990) developed an important theoretical model pertaining to human error that was related to human performance. Reason’s generic error-modelling system (GEMS) can be applied to many areas of human performance and human error. GEMS is, however, particularly useful for driver performance and driver error research.

The structure of Reason’s GEMS model is largely derived from Rasmussen’s (1980; 1987) skill-rule-knowledge based classification of human performance. The GEMS model integrates two previously distinct areas of human error research: 1) slips and lapses, and 2) mistakes.

There are three basic unintentional error types outlined in Rasmussen’s classification that are relevant for Reason’s GEMS:

1) skill-based slips (and lapses)
2) rule-based mistakes and
3) knowledge-based mistakes.
There is also a fourth category which is relevant to human performance research, namely violations. Violations are intentional deviation from what is considered necessary for performing/driving safely, i.e. intentionally unsafe acts.

Reason (1990) defines \textit{slips and lapses} as actions that deviate from current intentions and are due to execution failures and/or storage (memory) failures. \textit{Mistakes} on the other hand are actions that run according to plan, but where the plan is inadequate for achieving the desired goal or outcome.

Generally speaking, the skill-based slips and lapses in GEMS precede the detection of a problem. The rule-based and knowledge-based mistakes occur during resulting attempts to find a solution for the problem or task at hand.

In the context of cognitive workload, its effect on the driver’s attention is associated with the skill-based slips and lapses when referring to human error. High levels of cognitive workload reduce the driver’s performance and the driver’s ability to successfully process and act upon the \textit{right} information in the immediate traffic environment necessary for safe driving.

The human’s performance at the skill-based and rule-based levels is characterised by \textit{feed-forward control} that comes from stored knowledge structures (Reason, 1990). This stems from Rasmussen’s model where he describes the knowledge structures as “very flexible and efficient dynamic internal models of the world” (Rasmussen, 1986, p. 101). These internal models (heuristics) are individual and may evolve and change over time either from experience or training. These models or rules may not necessarily be explicitly formulated and are usually selected from previously successful experiences in similar situations. When the battery of problem-solving rules is exhausted, the driver is forced to “work online, using slow sequential, laborious and resource-limited conscious processing [of information]” (Reason, 1990, p. 57), which is of a slow feedback-cycle nature; thus describing the nature of the knowledge-based level.

When it comes to predicting error types and the expertise of the driver, one is generally much more likely to find that the biggest differences between experts and novices are found in the frequency of errors on the skill-based and rule-based levels. An expert driver will have a larger contingency of appropriate routines or rules for dealing with a wider range of situations. However, once this repertoire has been exhausted and the knowledge-based level of control is being used, the expert’s performance will start to converge with the performance of the novice (Reason, 1990).
MAIN THEMES OF THE THESIS

The main theme of this thesis has three distinct stages that move towards creating a better understanding of the effects of cognitive workload on driving from a human information processing perspective.

The first main stage concerns the need to find an objective and sensitive measure of cognitive workload for driving. The second is to understand the effects of cognitive workload on driving and task complexity created by different traffic environments and in-vehicle technologies. The third stage is to look more closely at performance shaping factors such as driver experience and driver distraction. The study of performance shaping factors can improve our understanding and application of the cognitive mechanisms of driving and possibly help researchers and system designers to avoid the major pitfalls involved in introducing new technologies into the road transport system.

A Sensitive Quantitative Workload Measure
The need for a sensitive quantitative workload measure arises from the less than satisfactory evaluation tools that existed prior to the commencement of this dissertation. However, it may be a fairly safe assumption to say that we will not be able to directly assess the level of cognitive workload on the brain within the foreseeable future. An improvement on the imprecise subjective workload scales and rather crude primary task measures, such as lateral control, were desperately needed. Study I explores the characteristics of an indirect, secondary task measure of cognitive workload, namely the peripheral detection task (PDT).

In-vehicle Technologies
Cars and trucks are becoming more advanced in terms of the computerised technologies that are finding their way into the transport system and society in general. It is not possible to describe all of the systems and services that are either driving or non-driving related. The driving related technologies are collectively termed intelligent transport systems (ITS). There are two vehicle based subdivisions of ITS: in-vehicle information and communication systems (IVIS) and advanced driver assistance systems (ADAS). The objective of the IVIS and ADAS is usually to improve mobility and/or traffic safety. [Note: For legal reasons, safety is seldom used in the automotive industry’s marketing of ADAS; the term comfort is preferred to avoid punitive lawsuit damages, especially in the USA.]
In the case of non-driving related systems and services in the road transport system, mobile phones (including all of their functions such as video calls, short message services (SMS), wireless Internet (W-LAN), global positioning system (GPS) navigation systems in the phone, music and TV viewing) possibly constitute the largest source of preoccupation or distraction and comprise the most widespread of in-vehicle technologies.

All of the experimental studies (I, II, IV) in this thesis use GPS aided navigation systems or mobile telephones. Studies III and IV focus on non-driver related technology-use tasks including different modes of mobile telephones and different levels of conversation complexity.

Performance Shaping Factors
Risk and safety are closely linked with performance shaping factors (PSFs). PSFs have a direct effect on risk and safety, the nature of which is dictated by the characteristics of the PSF and their relevance to increased or decreased risks and safety.

Risk and traffic safety are always contentious subjects in research, politics, society and the media. Many financiers of transport research are interested in traffic safety and risks in one way or another because of the broad effects of transport on society. Industrial and developing countries alike are sensitive to the condition of their respective transport systems. The transport system influences individuals’ personal economy (e.g. fuel prices), their health (e.g. accidents, pollution) and their social circumstances (e.g. mobility, career prospects).

The human element or factor, in terms of traffic safety cannot be understated. Treat, Tumbas, McDonald, Shinar, Hume, Mayer, Stansifer and Castellan (1979) estimated that human error in one form or another was involved in 92.6% of accidents. More recent studies of driver distraction alone estimate the figure at approximately 25-30% (cf. Stutts, Feaganes, Rodgman, Hamlett, Meadows, Reinfurt, Gish, Mercadante & Staplin, 2003; Shelton, 2001; Wang, Knipling & Goodman, 1996; Robinson & Campbell, 2006).

As mentioned earlier in the introduction, performance shaping factors (PSFs) play an important role in the performance of drivers. Performance shaping factors are factors that affect an operator’s ability to perform. PSFs may include fatigue, intoxication and lack of training or even organisational or man-technology-organisation (MTO) constraints such as managerial cost cutting, inadequate breaks, time pressure and stress. A PSF is generally regarded as being either negative or positive for performance, for instance the lack of
adequate training could negatively affect the operator’s performance, whereas the presence of adequate training could enhance the operator’s performance. PSFs are thus factors that shape performance in one direction or another.

Study II explores the characteristics of driver experience and its effect on cognitive workload. Driver distraction is also a PSF but has a negative effect on performance, and mobile phones are one of many potential distractors that interfere with driver performance in the road transport system.

Driver distraction comes in many forms and mobile telephones are increasingly intruding into everyday life. Driver distraction is a PSF that can be especially detrimental in situations where the driver is already subjected to increased levels of cognitive workload due to primary task demands on attention. Studies III and IV explore the characteristics of mobile phone use on drivers in the road transport system.
SUMMARY OF STUDIES

Study I


Study I sets out to establish a means to effectively gauge driver distraction and workload in road transport. The driver distraction issue is intertwined with limited cognitive/attention resources and where the level of cognitive workload is crucial. A sensitive cognitive workload measure needs to be investigated to evaluate the characteristics of the peripheral detection task (PDT) as a viable cognitive workload performance measure.

The impact of in-vehicle information and communication systems (IVIS) on attention may depend both on the design and the function of these devices. It is therefore possible that minor physical differences between devices with the same general functions affect driver attention, and methods sensitive to such differences would produce valuable information for safer IVIS design useful to authorities, users and producers of advanced driver assistance systems (ADAS). The secondary-task method is a frequently used tool for the measurement of human capacity limitations. Although the theoretical status of dual-task and secondary-task methods has been debated, many secondary tasks have been used (cf. Ogden, Levine, & Eisner, 1979; Wierwille & Gutman, 1978; Wierwille, Rahimi, & Casali, 1985) in an attempt to objectively measure cognitive workload or *spare capacity* in applied contexts including driving in real traffic.

Study I outlines two main lines of research with secondary-task methods particularly in traffic related contexts. The sensitivity of the then, recently developed peripheral detection task (PDT) method to the modality of navigation messages during driving in a built-up area was tested and also compared the PDT method with 1) established subjective workload measures such as the NASA-TLX and 2) primary task measures such as mean speed. Study I uses a relatively small sample size which has cost efficiency and viability implications when choosing a workload measure.

In Study I, all participants were exposed to the two types of navigation conditions (their own memory-based navigation and Global Positioning System (GPS) aided navigation). In the GPS navigation condition, the participants were
randomly assigned to one out of three groups with different message modalities. The navigation messages were presented either visually, verbally or both visually and verbally (full instruction), thus using a within-subject design between the two types of navigation, memory vs. GPS aided navigation.

There were 24 male professional drivers who were compensated for their participation in the experiment. Eighteen participants were local taxi drivers and the remaining six were also local professional drivers. All participants were highly skilled drivers, familiar with having IT equipment in their vehicles and familiar with driving in the built-up area in which they were required to drive.

An instrumented car (Volvo, Model 850S, 2.5, 1996 with manual gearbox) was equipped with a GPS aided navigation system (VDO Dayton, MS 5000). The PDT equipment comprised a circuit board (3 x 20 cm) with 23 light emitting diodes (LEDs).

Participants responded to the onset of a stimulus by pressing a button attached to their index finger. If the participants responded, reaction time was measured in milliseconds (ms), otherwise a missed response was recorded.

All the participants were instructed to drive one route by memory and another route with guidance from the GPS navigation system. The memorised route was pointed out on a city map. The participants were given enough time with the city map to memorise the route prior to driving it. The GPS navigation system guided route was not described to the drivers beforehand. They were just told to follow the navigation instructions from the navigation system. The memory navigation was used as a reference condition where navigation using a memorised route is generally speaking normal practice for taxi drivers.

After each trial the participants filled in the simplified version of the NASA-TLX subjective workload index questionnaire. Data registered during the experiment were PDT data, driving speed, brake activity, steering wheel angle, lateral position and distance headway at a frequency of 5 Hz.

The main results shown in Study I are that the main effect of the navigation condition (memory vs. GPS aided navigation) was found to be significant (F (1, 23) = 7.77, p < .01) while the difference between the three groups across navigation condition (full navigation, visual and verbal instructions) was not (F (2, 21) = .02, p > .98).
Comparisons of navigation condition within each message modality group revealed, however, a somewhat mixed effect of navigation condition on participants’ reaction times. In the group receiving full navigation messages the difference in PDT reaction time between the two navigation conditions was found to be significant ($F(1, 7) = 6.23$, $p < .04$), but no significant differences in reaction time were observed between the two navigation conditions and the visual message group ($F(1, 7) = 3.95$, $p > .09$) nor between the two navigation conditions and the verbal-navigation messages group ($F(1, 7) = .31$, $p > .59$). When PDT reaction time results are inconclusive, usually as a result of the proximity between two or more conditions, one can turn to the PDT hit rate performance results. The PDT hit rate results are less precise than the PDT reaction times but can nevertheless provide some useful pointers.

The main effect of hit rate differed significantly between navigation conditions (memory vs. GPS aided navigation), ($\chi^2(1) = 10.9$, $p < .001$); so too did the between-group difference across navigation conditions (full navigation, visual and verbal instructions) ($\chi^2(2) = 15.52$, $p < .001$). Pairwise comparison of hit rate between navigation conditions for each of the three groups showed a significant effect of navigation condition on hit rate in the visual navigation group ($\chi^2(1) = 4.07$, $p = .04$), and a significant effect for the full navigation

![PDT-Reaction-Time-Graph.png](attachment:Figure%206%3A%20Mean%20reaction%20time%20in%20ms%20for%20the%20navigation%20conditions%20(memory%20or%20navigation)%20and%20message%20modality%20groups%20(full,%20visual%20or%20verbal%20navigation%20messages).)
group ($\chi^2 (1) = 4.02, p = .0448$) but not for the verbal navigation group ($\chi^2 (1) = 2.81, p = .09$).

The importance of these findings is that the participants in the visual message condition were most sensitive to visual demand expressed by the lower hit rate frequencies. Driving speed and the other aspects of driving behaviour observed in the present study (i.e. primary task performance measure such as brake frequency and brake force), were virtually unaffected by navigation conditions and message modality, while PDT performance showed sensitivity to navigation condition (i.e. driving with or without a navigation system) even with a relatively small sample size (n= 24).
The main question being asked in Study II was whether levels of cognitive workload whilst driving differ between experienced and inexperienced drivers. Rasmussen’s (1980; 1987) theoretical model of human behaviour suggests that there should be a clear difference in the cognitive workload between the two driver groups; thus finding empirical data to support Rasmussen’s model was undertaken.

Two driver groups were used in Study II. The first group had extensive driving experience and a high annual mileage. The second group comprised drivers that had a low annual mileage but were nevertheless not novice drivers.

The importance of measuring the workload of non-professional drivers lies in the applicability of workload research for drivers with a more average or modest driving experience. Moreover, when generalising workload results, there is a great benefit in knowing the relative distance between experienced and professionally trained drivers, and drivers who have little or only modest driving experience but who were not novice drivers.

The main purpose of this study was, therefore, to evaluate the effect of driver experience on workload demand using a secondary task method, the peripheral detection task (PDT), in a real-life driving context. An additional objective of this study was to evaluate the effects of route complexity on the secondary task (i.e. PDT) being used when comparing two driver groups. Here, the focus was on the ability of drivers to cope with different levels of additional cognitive or mental workload introduced through primary task complexity variations. In this way, the competition over mental attention resources increases as an effect of the level of driver experience and route complexity.

A total of 75 participants successfully completed the experiment with 37 of these participants in the high mileage, experienced driver group and 38 in the low mileage, inexperienced group.

An instrumented vehicle was used in this field study; a Volvo 850S, 2.5 litre engine, manual gearbox and the model year was 1996.

The PDT method was used in this study to evaluate the participants’ workload whilst driving. The PDT task required the participants to react to a light stimulus
(an LED) that appeared in the participants’ periphery (in respect to the main driving focal point – straight ahead) and the light stimulus was illuminated for two seconds. The participants reacted by depressing the micro-switch attached to the left index finger. The LED was upon depression, subsequently extinguished. If the response was classified as correct (response within two seconds) the reaction time was recorded in milliseconds (ms), otherwise the response was recorded as a late or missed response.

The taxonomy by Fastenmeier (1995) was used to define and select road sections of a particular complexity. Each high/high complexity section had at least five turns which were considered to have high demands on information processing and high demands on vehicle handling, hence the term high/high. A simplified description of the three levels of route complexity used in this study is provided below:

The classification of route complexity:

1). High demands on information processing/high demands on vehicle handling, (high/high complexity). Typical examples from this group of situations occur when driving within city centre environments.

2). High demands on information processing/low demands on vehicle handling (high/low) and low demands on information processing/high demands on vehicle handling (low/high), (medium complexity). Typical examples from this group of situations occur at intersections regulated by road signs and where the driver has right of way, and at intersections regulated by traffic lights.

3). Low demands on information processing/low demands on vehicle handling, (low/low complexity). Typical examples from this group of situations occur in urban and rural areas and on motorways where free driving is possible.

The use of GPS navigation systems per se was a means to an end and not a primary objective in itself. The automated driving instructions from the navigation system provided us with the means to create an equal task for the two driver groups with a realistic (driving) task for the participating drivers. The drivers had no prior knowledge of the planned test route. The participants received visual and auditory route guidance instructions from the navigation system.

The study’s setup comprised a 2 x 3 experimental design (two driver groups and three levels of route complexity). The dependent variables reported in this study were PDT reaction times and PDT miss rates. The independent variables were driving experience (two groups) and traffic environment complexity (three levels). The route, which was a circuit in a real city centre, comprised seven segments (low/low, medium, high/high, medium, high/high, medium, low/low) and to counter the order of route complexity the 7 segments were condensed into
their respective levels of route complexity. The distances travelled for each level of route complexity were all approximately equal.

![Figure 8: A line chart, including standard error of mean bars, illustrating the mean PDT reaction times over three levels of traffic environment complexity and for two driver groups. The reaction times are in milliseconds (ms).](image)

The main results of this study, illustrated in Figure 8, showed a large and statistically significant difference in the cognitive workload between the two driver groups. The differences in mean PDT reaction times between the two driver groups were significant for each of the road sections (low/low, medium and high/high). Low mileage drivers had approximately 250 ms longer mean reaction times than the high mileage drivers.

This shows how drivers with better training and experience are able to automate their driving more effectively than their less experienced counterparts. Ipso facto, the more experienced drivers had more available mental resources that could be allocated to peripheral information. In line with this, the cognitive tunnelling effect appears to be greater for the less experienced, low mileage driver group when directly compared to the experienced drivers doing the same task.

The results of this study are in line with the view that there are safety benefits to be gained for drivers in maintaining a certain level of driving experience. This is because training and experience reduce the driver’s cognitive workload and increase the level of available attention resources thus improving the driver’s capacity for safe driving (cf. Broadbent, 1958, 1982; Baddeley, 1976; Wickens & Lui, 1988; Debecker & Desmedt, 1970; Wickens & Hollands, 2000).
Study III


The main purpose of Study III was to give a summary of the research investigating the relationship between the use of mobile phones and driving performance. More specifically, the review of the research was on the effects of mobile phoning while driving, on perception, cognition, workload, distraction and road traffic safety. Study III is a published article of a full technical report by the authors, found in Patten (Ed.) (2003).

In a road traffic context, the primary task of the driver is the safe operation of the vehicle in respect to other road users and themselves. Secondary tasks, however, are activities that may be undertaken by the driver but do not directly support the driving task, e.g. talking on a mobile phone or similar device. Quite often, the secondary tasks will compete for the driver’s available mental resources. This may also occur at a time when the operator or driver’s mental focus is needed to deal with the execution of the primary task. This is when distraction (from the primary task) due to secondary task activities can result in incidents or accidents (Alm & Nilsson, 2001).

There are different views on the issues of parallel processing and a common energetic resource pool for all information processes. The view that was adopted in Study III was that information processing can be viewed as parallel and although there is a common resource pool setting limits to processing, there are energetic resources available and used for specific purposes (e.g. visual processing), but only to a certain extent. When the common energetic resources are taxed this affects all processing. Time sharing and buffering of information (e.g. for output) is also assumed to be a characteristic of human information processing. Shallice (1991) describes attention, actions and the allocation of energetic resources as hierarchically controlled. There are corresponding models of the driver in a car (e.g. Allen, Lunefeldt & Alexander, 1971; Michon 1985; Ranney 1994; Vogel, 2002).

In such a hierarchical supervisory model a general-purpose system can use representations of the environment and intentions and abilities of the driver. The system selects higher-level schemata, which attenuate lower-level schemata in turn controlling specific subsystems. To exemplify, when allocating focal attention over time a certain schema is selected (e.g. looking out the windscreen to control the car) provided its activation level exceeds a certain level (e.g. the car starts moving which activates the schema with a certain intensity above the threshold). When some other (lower-level) schema is activated (e.g. by a phone
signal), the original schema may be retained, but is allowed a certain time interval to try to reach the goal of the lower-level schema (e.g. to answer the phone). However, the higher-level schema is still active and only a certain limited time interval is normally allowed to carry out the lower-level schema (of answering the phone). Most of the schemata in driving are automatic and only partly available to conscious control, in particular lower level schemata on the operational level. A lower-level schema like answering the phone may seriously disrupt the higher-level schema of driving a car safely. In this study, some simplifying distinctions of human information processing and action were made by dividing them into input, central and output system components. This was done to make later analyses of the research simpler and more transparent (cf. Wickens & Hollands, 2000). There are four main contexts within traffic research where human factor aspects are studied; in laboratories, in simulators, in field and test track studies, and in epidemiological studies.

When discussing mobile phones and traffic it is important to keep in mind that the disadvantages should always be seen in relation to the advantages in each particular situation. The empirical research covered in the present review was performed mainly from a driving performance perspective.

The research includes laboratory studies, simulator studies, field and test track studies and epidemiological studies. These different methods all have their advantages and disadvantages. Haigney and Westerman (2001) presented a critical review of methods used in research on mobile phones and driving. In particular, they emphasised the problems of ecological validity when drawing conclusions from laboratory and simulator studies to everyday driving and phoning. Experimental laboratory and simulator studies investigating the effects of mobile phones and driving have the advantage of greater control of driving conditions and they are performed in order to obtain indisputable results that also generalise to driving in real traffic.

In general, most modern simulator studies seem to be at least as sensitive as field studies when some effects of mobile phones are studied, such as lane keeping and reaction time measures. Even though validation may be lacking in many cases, some fundamental fact in the areas of e.g. human vision, attention and motor reactions are applicable in all situations. Other findings, such as the priorities given to driving and talking respectively do not necessarily generalise from the laboratory to on-the-road driving conditions. Quite often, the participants are told to answer the telephone, but older or expert drivers in particular might ordinarily prefer to defer or avoid answering a phone call in high workload situations in real traffic. The idea that attention priorities are different in the simulator than on the road is also illustrated by the more frequent inadvertent road-departure incidents in simulators. Note, however, that the
problem of generalising priorities to real traffic conditions cannot be avoided in test track and real traffic investigations either.

Test track and in particular field studies are reasonably ecologically valid. It is true that they do not offer the same opportunities to test limits of driver behaviour as simulator studies, but if an effect can be found in a field or test track study it is likely to be found in normal traffic. If a certain type of behaviour found in the simulator cannot be found in field and track studies, this may be a result of the smaller number of critical observations in the field or because energetic resources are mobilised to temporarily compensate for behaviour tendencies (e.g. track deviations).

Epidemiological studies use real traffic data. There are problems both in collecting data, for example from police reports that may not have uniform and relevant reporting categories, and in interpreting data, such as covariances found in accident analyses. Epidemiological studies have been mainly post hoc studies, such as incident and accident analyses. Although, for example, analyses of accidents often seem close to real-life facts with a high degree of face validity, there are problems when attempting to draw valid causal conclusions and in particular when attempting to establish the statistical significance of causal relationships and to estimate them quantitatively. The discrepancy between subjective intuitive interpretations of causal relations in data (intuitive interpretations have a tendency to rely on covariance) and scientific conclusions about causal relationships is a problem. This is because accident data brought to the public and the political eye may lead to a focus on less important factors and the neglect of more important causal factors.

The benefits of mobile telephones may be viewed from different perspectives; individual benefits and socio-economic or community benefits (Lissy, Cohen, Park & Graham, 2000). Some of the societal benefits include faster accident reporting and also more detailed information on accident sites etc., thus improving medical assistance and survival rates. The possibility of real-time reporting of abhorrent behaviour such as suspected drink driving also aids apprehension of suspects by the police. Some of these benefits are, however, possible to obtain without having the phone switched on whilst driving. Other socio-economic benefits are those of productivity, for e.g. business-related calls. This kind of benefit must be put into a context of a business-related call becoming possible which would not otherwise have been possible. From the individual perspective, being contactable gives peace of mind, may reduce the number and duration of trips and expands possibilities of being productive on a more personal level, e.g. private phone calls (Lissy et al. 2000). Other benefits may be that a driver can receive route-guidance information over the phone whilst driving thus supporting the driving task and reducing unnecessary
detours, reducing an exaggerated visual search for road signs, driver insecurity and stress.

In summary, using a mobile phone when driving, among other things, disturbs driving through a diminished field of attention, longer detection times to e.g. changes in dynamic traffic conditions, longer braking reaction times to brake lights on preceding vehicles and greater lateral deviations on the road. Contrary to what people assume handheld phones have not been shown to impair driving quality more than handsfree phones. Moreover, in contrast with public opinion, the content of a conversation is more important in determining the degree of distraction; complex conversations disturb driving far more than simple conversations.

The distracting effects of mobile phoning while driving are estimated to increase the risk of having an accident in traffic two to four times. Based on research cited in Study III, only banning handheld phones would have relatively small effects on safety. A total ban on all mobile phone use would be more appropriate in light of the distracting effects of an engaging conversation. The question of whether the societal benefits outweigh the costs is subject to regular debate.
Study IV


Study IV addressed the use of mobile telephones when driving. In particular, it explored mobile phone usage and their effect on cognitive workload and attention resource allocation needed for safe driving. Study IV compared handsfree and handheld mobile telephone conversations. The conversations themselves were also examined and were either simple or complex. A condition of just driving (i.e. no conversation) is used as a baseline or control condition.

Mobile telephones had been a focal point for traffic safety concerns for some time. These traffic safety concerns, however, had different loci of concern. A widespread belief had existed, in particular among laymen, that driver distraction caused by mobile telephones lay in the mode of telephone, i.e., handsfree or handheld units.

Study IV was set in a real traffic environment; on a public motorway and used two mobile telephone modes, handsfree and handheld. The handsfree unit had a separate microphone and loudspeaker and the handheld unit was simply held in the driver’s hand while driving. The telephone conversations per se were examined. Tasks such as dialling and other manual tasks were not included.

To evaluate the workload of the participants whilst driving in a real-life field study, the participants were asked to perform a high response-frequency parallel task (i.e. the peripheral detection task method). Driving a vehicle is normally dominated by visual perception demands on attention, that is, successfully driving a vehicle in traffic requires large amounts of mental resources (Hills, 1980). This is due to the fact that most of the information for safe driving needs to be gleaned from the driver’s immediate physical environment – assuming that the driver is qualified and experienced. Other sources of information may be auditory, haptic or even olfactory, but to a lesser degree.

The route chosen for this field study was characterised by a low level of road complexity in the form of vehicle handling and information processing according to the taxonomy of complexity by Fastenmeier (1995) and van Benda Hoyos Graf and Schaible-Rapp (1983). The road was a motorway section of the E4 (European inter-nation highway no. 4) with a maximum permitted speed of 110 km/h. The total distance used for this study was circa 74 km. The participants started travelling northbound from the city of Linköping to Norrköping (approx. 37 km). The participants turned off the motorway at an
appropriate intersection on the E4 and drove the 37 km back to Linköping. The total driving time, including stops for the NASA–RTLX evaluations, was approximately one hour.

The main reason for selecting a motorway section with a low/low classification according to the taxonomy by Fastenmeier (1995) and van Benda et al. (1983) was to reduce the amount of noise in the experimental data. That is, the motorway route chosen would have a low level of interactions with other road users whom we experimentally would have no control over. Moreover, the data generated would also reflect a best-case scenario from a driver workload/distraction and a traffic safety perspective. Any additional complexity would exacerbate driver workload and thereby even traffic safety risks.

The handheld telephone mode is defined as a mobile telephone that is held in the user’s hand and positioned close to the ear. The handsfree mode is defined as a device consisting of a separate microphone and a separate loudspeaker connected to the mobile phone so that it is possible to talk on the phone without using a hand to hold it. However, depressing a button on the telephone itself will activate the telephone.

An instrumented vehicle was used in this study; a Volvo 850S, 2.5 litre engine, manual gearbox and the model year 1996. All of the data were collected at a rate of 5 Hz and stored in an onboard laptop computer. The vehicle’s cruise control was disabled.

The peripheral detection task (PDT) equipment was built by Volvo Technical Development Corporation; the mobile telephone was a Nokia, model 6150 with a CARK 91 handsfree unit.

The PDT equipment was modified from Study I in co-operation with the Swedish National Road and Transport Research Institute (VTI) and Volvo Development Corporation. The PDT equipment comprises a display with six red light emitting diodes (LEDs) set in a display panel, a modified micro-switch with increased depression feedback and a computer unit for control, calibration of settings and data logging.

The participants selected for this study were professional drivers (taxi drivers, couriers) with at least three years of holding a higher classification of drivers licence. Professional drivers were selected mainly because they have an established experience of driving and also usage of information technology (IT) systems in their vehicles, e.g. logistical systems, communication radios and/or mobile telephones. Forty participants completed the route, 8 were female and 32 were male.
For the mobile phone task, the participants were informed that they would receive an unspecified number of phone calls (eight phone calls in actual fact) during their drive, in one direction (outward or homeward) on the motorway to or from Norrköping. The mobile phone was held in their right hand when using the handheld mode. The incoming call was opened by pressing the “accept call” button on the phone. The same participant would after completing one route, change telephone modes. The order of use was balanced. The handsfree unit required only a depression of the “accept call” button on the telephone to open the communication link. A microphone was attached to the roof above the driver’s head for optimum sound quality and loudspeakers were also placed close to the driver’s seat.

The conversation task was divided into three distinct levels of conversation; complex, simple and no conversations. The conversation task that was classed as complex involved responding to questions that involved single digit addition and memory tasks. The research assistant read aloud (from a protocol) two single-digit numbers (e.g. 2 and 3) to the participants (via the mobile telephone). The participants were required to add the numbers and reply with their (correct) answers (i.e. 2+3=5) conveyed verbally to the research assistant (their performance was recorded). After the first pair of numbers, only one single-digit number was read aloud to the participants (e.g. 4). This new number would then be added to the last number read out by the research assistant (in this case, 3). The correct answer (i.e. 3+4=7) would again be conveyed verbally to the research assistant. The process was repeated with one single-digit number at a time, for a minimum period of one minute and thirty seconds. This task required abstract thinking (mental arithmetic) and memory.

The simple conversation task required the participants to verbally repeat single digit numbers, which were read aloud to them by the research assistant (via the mobile telephone). The numbers were also read from a protocol.

The duration of the phone calls was approximately two minutes, of which the actual telephone task was a minimum of one and a half minutes.
The main findings in Study IV were that there was a significant effect of the task (conversation type) on the peripheral detection task (PDT) performance (reaction time) but no effect of telephone modality (handsfree or handheld) on PDT performance. A significant effect of telephone modality was found for the mean speed variable. This is a very interesting finding because the PDT measure has been found to be a sensitive measure of cognitive workload as also found in Marten and Van Winsum (2000), Olsson (2000), Harms and Patten (2001) and Burns et al. (2000).

The PDT reaction times increased by 45% from the baseline condition to the complex conversation condition. When converted to theoretical stopping distances, certain traffic safety considerations become apparent. When travelling at 110 km/h, a vehicle moves at 30.5 m/sec. An average motorway lane in Sweden is approx. 3.5 m wide. At a rate of 30 m/sec, even small lapses in concentration may result in alarming situations for the driver, especially if unexpected situations occur such as a slow-moving vehicle in front of the driver. If, however, the mean reaction time for complex telephone tasks had a delay of 261 ms, then this system retardation of the human brain may have a snowball effect on the information detection, processing, analysis and response execution. In other words the driver engaged in a complex conversation is appreciably less likely to detect changes in his/her traffic (road and vehicle) environment than when he/she is not distracted and can fully attend to the primary (driving) task.
In summary, for *Study IV*, driving on motorways and larger rural roads, the mobile telephone modality would appear to be of little consequence when solely considering the conversational aspect of telephoning. Far more important for driver distraction and cognitive workload levels, in regard to mobile telephones and traffic safety, are the content and the complexity of the conversation per se.
MAIN RESULTS AND DISCUSSION

The goal of this thesis is to provide an orientation in the effects of cognitive workload on driving from a human information processing perspective. There is a logical thread that starts with the need to explore and develop a sensitive and objective measure of cognitive workload using the peripheral detection task (PDT) method. The next step continues to study the effects of cognitive workload in the human information processing stages (HIPS) framework and the way in which human information processing can be affected by performance shaping factors. One of the performance shaping factors had a beneficial effect on performance (experience) and one had a detrimental effect on performance (distraction).

In summary, the PDT method was used and was found to be sensitive to changes in cognitive workload. One form of driver distraction was mobile telephone use where modes (i.e. handsfree and handheld units) and different complexities of conversation were examined. In this direct comparison between handsfree and handheld mobile telephone conversations when driving, no difference was found between the units. There was, however, a strong effect of conversation complexity on performance. It was concluded that the conversation complexity per se was more important for the deterioration in performance than the mode of telephone system. Driver experience was a performance shaping factor (PSF) that facilitated lower levels of workload for experienced drivers when directly compared to inexperienced drivers. These results are important because together they suggest that by improving driver training and experience, some of the cognitive workload related traffic safety problems may be mitigated; thus providing a means for coping with at least some of the potential disadvantages of in-vehicle technologies.

The main results are discussed in more detail below. The topics that are discussed are the effects of driver experience on workload; route and task complexity; handheld vs. handsfree mobile telephone use; cognitive workload in terms of HIPS and human error; and cognitive workload thresholds.

Effects of Driver Experience on Workload
The effect of experience in a specific task on cognitive workload should, from a theoretical point of view, enable a reduced level of cognitive workload. The main results from Study II provided empirical support for Rasmussen’s theoretical model (cf. Rasmussen, 1980; 1987). The process of acquiring skills and experience in a task such as driving is clearly visible.
Drivers in the process of learning to drive have to cognitively acquire formal and informal rules, traffic scenario heuristics and motor skills (i.e. vehicle handling, controls, etc.). Experienced drivers will already have mastered vehicle controls, formal and informal rules and heuristics, and will be able to utilise the skill- and rule-based levels of control for negotiating the complexities of driving.

Study II tangibly showed some of the benefits of training and experience. The results of Study II provide support for encouraging regular driver/operator training programmes to maintain a high level of proficiency and skill for intermittent or seasonal drivers/operators. The results from Study II also support a staged or staggered approach to driver licence classification. The first period of solo driving, i.e. driving without an instructor, is sensitive to disruption in attention processes and is also a highly accident-prone period. Many of the novices’ schemata or heuristics for driving will still need to be acquired which requires the novice to be on a knowledge-based level and this is very demanding for the driver because it greatly increases the workload levels. However, generally speaking drivers tend to subjectively perceive their own ability as above average (Svenson, 1981). This is concerning because in objective terms, there are clearly differences in performance between inexperienced and experienced drivers.

Route and Task Complexity
The aggregated results found in Table 1 and Figure 12 and separately in Studies II and IV highlight the variations in PDT reaction times as an effect of task complexity. This indirectly reflects the variations in cognitive workload as an effect of traffic environment complexity or the complexity of the primary task plus the secondary task (e.g. driving plus talking on a mobile phone).

Handheld vs. Handsfree
Prior to the publication of Study IV in particular, the often highly politicised issue of handsfree mobile telephone requirements in road traffic lacked scientific evidence. At the time, many of the earlier studies did not specifically compare the mode of use (i.e. handsfree and handheld). The handheld mode of use was, I suspect, merely assumed to impair the driver’s performance more than the handsfree mode. Moreover, at about the time of the publication of the Swedish Road Administration (SRA) inquiry in 2003, many of the European countries had already rushed ahead with legislation banning handheld mobile phone usage but not handsfree usage. These decisions were largely politically motivated and were not based on scientific evidence.
With the development of the PDT method and its sensitivity to changes in cognitive workload, it was possible to demonstrate in clear, quantitative terms (cf. Study IV) that the locus of the problem was more a matter of the inherent complexity of the conversation than the actual mode used (i.e. handsfree or handheld). This meant that there was no quick and easy solution to the problem of driver distraction caused by mobile phone conversations when driving, that is, if a total ban on conversations was out of the question.

The SRA governmental inquiry’s conclusions were that driving and mobile telephone use were not compatible with safe driving in certain traffic environments, however, a total ban was deemed neither desirable nor viable from a societal cost-benefit perspective. The inquiry could not recommend a ban on handheld mobile phones and at the same time allow handsfree use because this would do nothing to resolve the problem of driver impairment; rather it was more likely to exacerbate it!

At the time of the inquiry, the Swedish Government, therefore, decided not to ban handheld mobile telephone usage when driving; however, this is very much a political issue and political winds are whimsical. There is to date still no body of evidence to support the banning of handheld mobile phone use while at the same time allowing handsfree mobile phone use when driving. The body of evidence only supports a total ban due to the negative effects of conversation (distraction) on driver performance (cf. Dragutinovic & Twisk, 2005; Brace, Young & Regan, 2007; Horrey & Wickens, 2004; Svenson & Patten, 2005; Alm & Nilsson, 1995).

**Cognitive Workload in Terms of HIPS and Human Error**

The human information processing stages (HIPS) framework can be overlaid with Rasmussen’s skill-, rule- and knowledge-based levels of behaviour. This means that James Reason’s (1990) generic error model system (GEMS), which is founded on the skill-rule-knowledge based levels of behaviour, can also be used on HIPS when investigating errors or failures in information processing.

The key to understanding the source of slips, lapses and mistakes comes primarily from the lack of adequately directed attention resources bearing in mind the limited amount of resources we have available at any given moment. There may be many reasons for the inadequate direction of attention, e.g. improper training, distraction, etc. In the context of the HIPS model, skill-based slips and lapses will often occur when there are insufficient attention resources for the perception stage, the response selection stage and especially for the response execution stage.
Rule-based mistakes are more likely to occur when insufficient attention resources disrupt an initially correct selection and interpretation of stimuli such as in the perception stage. This may result in the correct response for one task, but it may unfortunately not be relevant to the actual task at hand. Anecdotally, a driver might be waiting inattentively at a red traffic light and is eager to go. His mobile phone rings and off he goes, jumping the red light. What happened? The inattentive driver was waiting for the traffic light to turn green; the green traffic light being the stimulus to drive off. However, when the phone rang, another stimulus requiring an action (i.e. to answer or to ignore) interjected. The phone heuristic (to answer or ignore), in the response execution stage, was mismatched to the previous task expectation of the pending green traffic light (and the action would have been to drive off), resulting in a rule-based mistake. A rule-based mistake is also just as likely to occur in a mismatching of stored responses or heuristics in the response selection stage.

Knowledge-based mistakes are more likely to occur in the processing of information between the working memory stage and the long-term memory, typically where the repertoire of rules of thumb or heuristics has been exhausted and an inadequate response is selected. Knowledge-based processing of information is highly demanding on the attention resources, which can increase the likelihood of additional errors (especially in the response selection and execution stages) due to lack of adequate attention resources, further exacerbating the deterioration of the driver’s performance.

Human factors, including human errors, dominate the risks encountered by complex systems such as industrial plants, transport systems etc. Accident analyses have shown that the causal sequence moves from what Reason (1990) terms fallible decisions transpiring through a number of stages, ending up with the incident or accident. Reason defines an accident as:

...the unplanned and uncontrolled release of some destructive force, usually in the presence of victims. (p. 203)

Reason identifies five stages before the accident apparent viz. 1) fallible decisions, 2) line management deficiencies, 3) psychological precursors of unsafe acts, 4) unsafe acts and 5) inadequate defences, followed by the accident itself.

The first three stages are latent failures, i.e. failures associated with activities that are removed from the task at hand. The last two stages are active failures or errors and are associated with operator performance, e.g. the driver. The effects of active failures are usually felt immediately whereas the latent failures may
remain dormant for long periods but become apparent when combined with other factors in the prelude to an accident (Reason, 1990).

Although the tackling of latent failures within a system is crucial to maintaining safety and avoiding accidents, in the context of this thesis and human information processing I will, however, focus on the active failures. The first active failure described by Reason is the unsafe act.

An unsafe act is defined in the presence of a particular hazard. As Reason comments, there is nothing inherently unsafe about e.g. not wearing a seatbelt or a crash helmet, it is only unsafe when hazardous situations are present such as when the vehicle is moving (and has energy). “An unsafe act is more than just an error or a violation – it is an error or a violation committed in the presence of a potential hazard” (p. 206). The result of the driver’s actions that occur after processing information, selecting and executing decisions etc. based on the traffic situation is open to errors. These errors can transpire on different levels in the processing of information or stimuli as summarised in Figure 10. Figure 10 has been redrawn from Reason (1990) and classifies the unsafe acts into intentional and unintentional actions, specifying the basic error types and also classifying the type of error in terms of Rasmussen’s skill-, rule- and knowledge-based levels of behaviour. Figure 10 provides a tangible summary of the basic error types in terms of human behaviour and human performance in driving.

Figure 10: A summary of the psychological characteristics of unsafe acts, redrawn from Reason (1990, p. 207).
Most unsafe acts do not result in actual damage or personal injury. This is often due to the defences or safeguards existing within the system. These defences may be of a low level of sophistication such as seatbelt warning systems in cars, or they may be highly sophisticated such as the defences in depth found in nuclear power plants. When an accident occurs, it is because certain actions have broken through the various defences that would otherwise have mitigated or hindered an accident at that particular point in time.

**Cognitive Workload Thresholds**

It is difficult to ascertain the exact point on the chart in Figure 11 where all of the driver’s attention resources are being utilised. One reason is that the driver tends to alter his/her management of the tasks by delaying, excluding or omitting certain elements. An example of this is when two people who are walking and talking together will tend to slow their pace of walking as the conversation gets more complex and intense. Similar patterns of behaviour can also be observed in traffic where drivers may reduce their speed, filter out peripheral information (and thereby not observe pedestrians and signposts), as well as neglecting non-essential vehicle handling tasks such as changing gear efficiently or using turn indicators.

Increasing cognitive workload results initially in a deterioration of the secondary task performance with longer reaction times and an increased miss rate and also leads to an increasing deterioration in the primary task performance. When the driver’s level of reserve attention capacity becomes progressively smaller due to increased task complexity, the deterioration in the primary task performance becomes increasingly evident. This deterioration in the primary task performance will also become progressively greater when the driver’s attention nears the maximum limit in the risk zone (cf. Figure 11).

Deterioration in the driver’s primary task performance will converge in proximity to the point where the attention demand nears the maximum attention capacity of the driver. A risk zone is created for when the driver’s performance with one or all of the parallel tasks being performed whilst driving become delayed and/or disrupted completely. This will lead to a breakdown of human information processing with resulting errors at different levels of the processing, either slips, lapses or mistakes, and this will also increase the likelihood of and incident or accident because the driver loses his/her ability to deal with even basic driving functions. Dealing with unexpected or even moderately more complex situations will often entail errors. At this point, the vigilance of other road users is quite likely to be the only barrier impeding a collision.
When the driver nears the exhaustion of cognitive/attention resources, the driver will also try to reduce cognitive demand created by the additional tasks by delaying responses, reducing speed of information flow (e.g. by reducing the velocity of the vehicle and/or taking pauses in the conversation). The driver will also start to make mistakes, slips or lapses on different levels of information processing (cf. GEMS). Information may be missed entirely; the peripheral field of vision is particularly susceptible to reduced attention resources (many signposts and pedestrians are in the peripheral field). The general vehicle handling will also become less smooth and precise; gear changing optimisation deteriorates, braking behaviour changes, becoming more forceful/harsh and less planned. Eye fixation increases with cognitive tasks so that the eyes are on the road straight ahead but the mind, however, is not. This deterioration in the human’s performance (primary task) will increase the risk of an incident with other road users and could lead to serious injury or death.

One question begging to be asked in the context of cognitive workload research is at what point the PDT reaction time (or another comparable measure) is acceptable or unacceptable in terms of risk for cognitive overload. In Figure 12 below, an illustration of a hypothetical risk zone or threshold for a potential cognitive overload is marked.
Figure 12: A bar chart highlighting a hypothetical zone (indicated by the arrow) for an increasing risk of cognitive overload represented indirectly by the secondary task performance measure; PDT reaction time in milliseconds (ms). The results are from Studies II and IV. The blue bars (●) are the experienced, high mileage drivers and the green bars (■) are the inexperienced or moderately experienced, low mileage drivers. Further details of the different categories are detailed in Table 1.

The PDT reaction time results from Studies II and IV have been put into the same figure, Figure 12, for comparative purposes. The results in Figure 12 are from field studies in real traffic. The y-axis represents the PDT reaction times in milliseconds (ms) and the x-axis represents the different categories of task and participant groups. Full details of the categories are found in Table 1. The blue bars (●) are the experienced, high mileage drivers and the green bars (■) are the inexperienced or moderately experienced, low mileage drivers. The complexity of the tasks varied which is also reflected in the differences in mean reaction times. The blue category bars IV-High mileage-1, IV-High mileage-2 and IV-High mileage-3 are from Study IV and contain the PDT reaction times for mobile telephone conversation on a motorway with experienced, high mileage drivers.

The green category bars II-Low mileage-1 and II-Low mileage-2 contain the results from the inexperienced or moderately experienced drivers. Category bars II-High mileage-1 and II-Low mileage-1 are driving in the low traffic environment complexity urban area and have the same task but different driver groups (experienced and inexperienced). Correspondingly, the same is true for the II-High mileage-2 and II-Low mileage-2 categories respectively, driving in the high traffic environment complexity section.
Table 1 contains the details of the driver groups for the respective tasks and the subsequent mean PDT reaction times. The results are derived from *Studies II* and *IV*.

<table>
<thead>
<tr>
<th>Driver mileage</th>
<th>Traffic environment</th>
<th>Task</th>
<th>Mean PDT r/t (ms)</th>
<th>Distance travelled if driving at 110 km/h (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV-High mileage-1</td>
<td>High mileage (Ŷ) Motorway (Low/low classification) Study IV</td>
<td>Driving only (baseline-1)</td>
<td>584</td>
<td>17.85</td>
</tr>
<tr>
<td>IV-High mileage-2</td>
<td>High mileage (Ŷ) Motorway (Low/low classification) Study IV</td>
<td>- Driving - Simple mobile phone conversation-2</td>
<td>656</td>
<td>20.05</td>
</tr>
<tr>
<td>IV-High mileage-3</td>
<td>High mileage (Ŷ) Motorway (Low/low classification) Study IV</td>
<td>- Driving - Complex mobile phone conversation-3</td>
<td>845</td>
<td>25.82</td>
</tr>
<tr>
<td>II-High mileage-1</td>
<td>High mileage (Ŷ) Urban (Low/low classification-1) Study II</td>
<td>- Driving - GPS aided navigation</td>
<td>713</td>
<td>21.79</td>
</tr>
<tr>
<td>II-High mileage-2</td>
<td>High mileage (Ŷ) Urban (High/high classification-2) Study II</td>
<td>- Driving - GPS aided navigation</td>
<td>844</td>
<td>25.79</td>
</tr>
<tr>
<td>II-Low mileage-1</td>
<td>Low mileage (Ŷ) Urban (Low/low classification-1) Study II</td>
<td>- Driving - GPS aided navigation</td>
<td>929</td>
<td>28.39</td>
</tr>
<tr>
<td>II-Low mileage-2</td>
<td>Low mileage (Ŷ) Urban (High/high classification-2) Study II</td>
<td>- Driving - GPS aided navigation</td>
<td>1067</td>
<td>32.61</td>
</tr>
</tbody>
</table>

The findings of the studies comprised in this thesis, as shown in Figure 12 and Table 1, would appear to indicate that cognitive workload levels, as represented by the PDT reaction time secondary task performance measure, approaching 1000-1200 ms are in a zone where there is an increasing risk of cognitive overload. This zone can be likened to the area marked in Figure 11 as *cognitive overload*. PDT reaction times that are greater than 1200 ms are clearly a traffic safety concern because they suggest an excessive level of workload. Moreover, the STSS cannot retain old information and process new information sufficiently where e.g. visual information can only be delayed for approximately 0.5 sec. The information processing system becomes less efficient and task performance deteriorates rapidly.

In Table 1 the theoretical distance travelled by a car has been calculated at a speed of 110 km/h for the respective PDT reaction times. This distance is not the calculated stopping distance, which would be much longer, but merely the length of road covered by a driver in the time it takes to react to a stimulus when travelling at 110 km/h. The mean distance travelled by the high mileage drivers in the control condition of *Study IV* would theoretically be approximately 18 m before the drivers reacted to the stimulus.

The issue of an acceptable/un acceptable cognitive workload threshold is difficult to gauge, but what is apparent is that the drivers become far less sensitive to unexpected events that might occur and their situation awareness is
reduced when driving with high workload levels. Moreover, the benefits of greater experience and training are also evident. More experienced drivers have better strategies for dealing with high levels of task driven cognitive workload. Drivers highly trained and experienced in advanced driving techniques (e.g. racing drivers, traffic police) are likely to be better equipped to prioritise and process information for optimum performance using a minimum of cognitive resources. The majority of non-professional drivers will muddle their way through most situations with varying degrees of success depending on the number and complexity of the tasks.

**Epilogue**

In summary, it is clear that the human driver is limited in the number and complexity of the tasks he or she can perform at any given time. Moreover, making mistakes, to err, is part of being human; we are fallible. It is impossible to eliminate all driver error so it is important, therefore, to create an environment for the driver so that his/her slips, lapses and mistakes can be detected and recovered.

Increasing our knowledge of human information processing limitations will help researchers, system and product designers to improve traffic safety for all.

Research topics to be pursued within the area of cognitive workload and human information processing stages (HIPS) are, inter alia, establishing a maximum acceptable limit for safe driving in terms of indirect measures of cognitive workload. Moreover, driver training programmes could benefit from insight into HIPS, limited attention resources, experience acquisition effects on cognitive workload and the human propensity to err.
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Peripheral detection as a measure of driver distraction.  
A study of memory-based versus system-based navigation in a built-up area

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Abstract

The effect of in-vehicle information systems (IVIS) on traffic safety is currently under debate and suitable methods for measuring and comparing the impact of such devices on driver behaviour are urgently required. The secondary-task technique may be a good tool for objective measurement of driver distraction caused by IVIS.

The present study summarises previous results of secondary-task studies in traffic contexts and investigates the suitability of one secondary-task method, the peripheral detection task (PDT)-method, as a standard procedure for safety testing and evaluation of IVIS. The study was concerned with the effect of navigation messages on PDT-performance (reaction time and hit rate) taking into account also behavioural variables. Professional drivers served as subjects. They had extensive prior local-knowledge and experience of driving in the built-up area in which the experiment took place. They were required to drive two different routes, one after memory and the other in accordance with navigation messages a standard navigation system installed in the car. In the navigation system condition subjects were subdivided into three groups, receiving either verbal, visual or both visual and verbal (full) navigation messages.

Driving behaviour was virtually uninfluenced by navigation condition (memory versus navigation system) and message modality (full, visual or verbal) whereas PDT-performance, showed some effects of navigation condition on subjects' reaction times and hit rates. Pairwise comparison of message modality within each three groups showed a prolongation in reaction time and a marginally significant decrease in hit rate with full navigation messages (combined visual and verbal ones). Visual navigation messages affected only hit rate and no significant differences between navigation conditions were observed for the group presented with verbal messages. The pattern of results suggests that the PDT-method is biased toward
visual sources of information from IVIS. As visual information processing is an important component in safe driving, the PDT-method is suitable as a predominant method in a test battery, but for unbiased measurement of distraction, methods less dependent on mode of presentation would be more appropriate. © 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** Driver distraction; In-vehicle information systems; Advanced driver support systems; Navigation systems; Secondary task; PDT; Capacity limitations

1. Introduction

New in-vehicle technologies such as navigation systems, vision enhancement systems and on-board Internet connections are presumed to increase in popularity and number in the not-so-far-away future vehicle. A subdivision has been made between advanced driver assistance systems (ADAS) with driving support functions and in-vehicle information systems (IVIS) that have other functions than those related to driving. Both car drivers and passengers may benefit from new technology, but some in-vehicle systems may not be suitable or appropriate for use in moving vehicles in the current road transport system. It is generally acknowledged that IVIS can cause distraction by diverting the driver’s attention from the driving task. In fact, even some driver assistance systems may occasionally call for attention. However, being an integrated part of the driving task, their impact is usually not classified as distraction but as cognitive load. Regardless of type, IVIS and ADAS require drivers to sometimes divide their attention between in-vehicle information and information in the driving environment. The impact of these devices on attention may depend both on the design and on the function of such devices. Therefore it is possible that minor physical differences between devices with the same general functions affect driver attention, and methods sensitive for such differences would produce valuable information for safer IVIS design useful to authorities, users and producers of ADAS and IVIS.

The secondary-task method is a frequently used tool for the measurement of human capacity limitation. Although the theoretical status of dual-task and secondary-task methods has been under debate, many secondary tasks have been used (see Ogden, Levine, & Eisner, 1979; Wierwille & Gutman, 1978; Wierwille, Rahimi, & Casali, 1985) in the attempt to objectively measure cognitive load or “spare capacity” in applied contexts including driving in real traffic. The present paper outlines two main lines of research with secondary-task methods particularly in traffic-related contexts. Moreover, the sensitivity of the recently developed peripheral detection task (PDT)-method to the presence and to the modality of navigation messages during driving in a built-up area is tested.

1.1. Factors affecting processing efficiency under dual-task conditions: Automaticity, multiple resources and task priority

Time-sharing between concurrent tasks or components of a complex task is usually associated with a cost of concurrence assumed to reflect the limited capacity of the human information system (Broadbent, 1958; see also Broadbent, 1982). Exceptions are the concurrent performance of very easy tasks i.e. tasks with a small demand on processing resources or tasks that can be
processed in parallel due to automatic processing, which is known to develop from considerable amounts of consistent training (Shiffrin & Schneider, 1977).

The degree of interference between concurrent tasks can be manipulated by task structure and task priority. Results from dual-task studies (Brooks, 1968; see also Baddeley, 1976; Wickens & Liu, 1988) strongly suggest that verbal and spatial processing use different resource pools. In accordance with multiple-resource theory, performance decrements are less severe during concurrent performance of cross-modal tasks compared with intra-modal ones (Wickens, Sandry, & Vidulich, 1983).

Instructions about prioritisation of concurrent tasks have been found to affect performance accordingly (Schneider & Fisk, 1982; see also Wickens & Hollands, 2000) and in fact a most popular example of spontaneous task prioritisation is a car driver interrupting an ongoing conversation due to increased traffic task demand. Apparently, during driving, the driving task has a natural first priority while tasks unrelated to driving have a lower priority. However, spontaneous prioritisation of traffic-related information over other sources of information, should not be overestimated. Recent research indicates that in-car activities such as the use of cellular phones are associated with an increase in accident risk (Sagberg, 2001; see also Stevens & Paulo, 1997). Numerous results from basic research also indicate vulnerability of visual search to automatic capture of attention by salient stimulus features (Theeuws, 1994). A most intrusive stimulus feature relevant to the secondary-task technique is abrupt onset and offset of stimuli (see Yantis & Jonides, 1990).

1.2. Studies with cross-modal and intra-modal secondary tasks during driving

Secondary tasks have been used in real traffic for measuring variation in drivers' cognitive load while driving. Brown and Poulton (1961), Wiegand (1974) and Harms (1991) used mental arithmetic i.e. calculation tasks as secondary tasks during driving in different traffic environments. The purpose of these studies was to investigate the relationship between "cognitive load" or "spare capacity" and variation in the driving environment. Both Brown and Poulton (1961) and Wiegand (1974) reported that subjects completed fewer calculation tasks in more complex driving environments than in simpler ones. The former study also included analysis of speed variations and a lower speed was found in complex driving environments (city traffic) than in simpler ones (residential areas). In the studies reported by Harms (1991) prolonged reaction time to calculation tasks was consistently found, in combination with a lower driving speed in more complex driving environments—i.e. different village areas and close to rural junctions—than on the observed adjoining road segments.

The general interpretation of the results in the above-mentioned studies in terms of "cognitive load" or "spare capacity" is reasonable since the calculation tasks were presented verbally, were presented on a regular basis and required verbal responses. Regular presentation supports task prioritisation and reduces intrusiveness of secondary-task stimuli. Moreover, separation of the auditory-verbal secondary task from the task of driving (visual-motor) by sense modality should have reduced structural interference to a minimum in all these studies.

Another line of research on cognitive load in traffic is that based on visual secondary tasks. Visual secondary tasks are primarily indicators of visual demand, which is most prevalent in driving. Some studies have suggested that detection of simple visual stimuli is also sensitive to
variation in cognitive load. In an early study, Lee and Triggs (1976) found that increased environmental complexity during driving affected the detection of peripherally presented stimuli. They also reported a stronger effect in the left visual hemi-field than in the right one. Later, Miura (1986) demonstrated that task demand rather than visual complexity affected eye movement patterns as well as sensitivity in the driver’s visual periphery. Results obtained in other contexts than traffic support the assumption that peripherally presented stimuli are less likely to be detected at high levels of perceptual load in the foveal field of view (see Rinalducci & Rose, 1986; Williams, 1988). Chan and Courtney (1993) demonstrated that variance in cognitive demand also affected sensitivity in the visual periphery at a constant level of perceptual load in the foveal field. Their subjects were required to either name or add digits, presented in the foveal field and these instructions were found to affect the detection of peripheral stimuli although these were identical in both conditions. Recently, a study of visual search for hazards in videotaped traffic scenes (Crundall, Underwood, & Chapman, 1999a, 1999b) has demonstrated that the presence of traffic hazards on videotapes resulted in lower detection rate for peripherally presented stimuli. Apparently, detection of simple stimuli presented in the visual periphery is sensitive both to perceptual load in the foveal field and to task load.

1.3. Previous work with the PDT-method

The PDT-method is based on the above-mentioned findings. The method involves frequent presentation of simple visual stimuli at random positions with eccentricities ranging between 5° and 25° left of the driver’s normal line of sight, and 2–5° over the horizon (in a driving simulator) or over the car console during driving (in a real car) (see Fig. 1). Subjects are instructed to detect as many stimuli as fast as possible without, at any moment of driving, withdrawing attention from the road scene. The method was first used in a simulator study in which different designs and functions of an ADAS was evaluated (Martens & Van Winsum, 1999). In the first part of this study, PDT-performance on baseline sections on motorways and rural roads was compared with PDT-performance on the same road segments where subjects were exposed to critical traffic scenarios. Compared to road sections without prespecified scenarios a decrease in hit rate and an increase in mean reaction time was found on road segments with unexpected traffic events and road scenarios requiring immediate action. The subjects were subdivided into three groups, a control group, and two experimental groups, equipped with an ADAS. Experimental groups were provided with visual warnings in case of critical traffic scenarios. In addition to visual warnings, one group received tactile warnings while the other group received verbal warnings. PDT-performance was analysed from the onset of a warning until 10 s after (corresponding to the duration of the visual message). Analysis of reaction times and hit rates in those intervals showed that tactile warnings were less damaging to PDT-performance than were verbal warnings. Olsson (2000) successfully transferred the PDT-method to field conditions. She used the same road types as the two previous studies and related PDT-performance to subjects’ monitoring of in-car equipment during driving. Subjects were presented with three different tasks, one (the radio task) was to report the preset car-radio frequency and find a specific radio station, the other (the CD-task) was to turn on the CD, play a specific track on a specific CD and then to return to the radio mode. Subjects in this experiment were also presented with a third task, mental calculation, which demand neither visual nor motor activity. Compared to a baseline, both reaction time and hit rate
were generally affected by the presence of in-car tasks. Some differences between tasks were reported: Counting-backwards increased PDT reaction time dramatically and more than any other task but this effect was only found on the rural road. A higher hit rate was observed for the radio task than for the CD task. Some difference in PDT-performance between in-car tasks and different road types remained unexplained in this study. However, the finding that the counting-backwards task affected PDT-performance essentially the same as the tasks that demanded motor and visual activity, strongly suggested that PDT-performance is also sensitive to cognitive load.

1.4. Another test of the PDT-method: Is it sensitive to the modality of equivalent IVIS messages?

The results of the previous studies make the PDT-method a promising candidate for a standard procedure for the estimation of distraction from IVIS and ADAS, but it requires some further testing. In fact, the PDT-method is based on a visual secondary task and although previous studies suggested that this method is also sensitive to cognitive load, it might be sensitive to the sense modality of equivalent messages as well. This assumption is consistent with findings reported by Verwey (1993) that variance in traffic scenes affected a visual secondary task—regardless of its demand on processing (naming versus adding visually presented digits)—more than an equivalent verbal secondary task. Prior to the use of the PDT-method for comparative measurements of the impact of IVIS on driver attention, it is important to test the method with equivalent visual and verbal information primary sources of information. This would clarify the
importance of stimulus modality to PDT-performance. However, sensitivity to task demand variation in the driving environment might easily overshadow the occasional captures of attention by IVIS messages. This would even be more likely in built-up areas with greater variation in traffic scenarios and road user categories than on the rural roads or motorways as used by Olsson (2000). In the present study, all subjects were exposed to the two navigation conditions (memory-based versus navigation system based). However, in the navigation system condition the subjects were randomly assigned to one out of three groups with different message modalities: Navigation messages were presented either visually, verbally or both visually and verbally (full instruction). Assuming that variance in traffic task demand would not overshadow the occasional captures of attention caused by navigation messages, the effect of the modality of the navigation messages on PDT-performance can be analysed and the importance of sense modality of the messages to PDT-performance can be clarified.

2. Method

2.1. Subjects

Twenty-four male, professional drivers were paid for their participation in the experiment. Eighteen subjects were taxi-drivers in the local area (Linköping) and the other six were professional drivers in the same area. All subjects were highly skilled drivers, familiar with having IT-components in their vehicles and familiar with driving in the built-up area in which they were required to drive. Their reported total annual mileage was 10,000–120,000 km with a mean of 60,000 km. The subjects were aged 30–60 years, fourteen subjects were between 40 and 50, six were younger than 40 and four were older than 50.

2.2. Apparatus

An instrumented car (Volvo, Model 850S, 2.5, 1996 with manual gearbox) equipped with an IVIS for navigation (VDO Dayton, MS 5000) was used for the experiment. The test vehicle was equipped with advanced data collection systems that included full video coverage of the trials, headway, speed variation, brake activity, lateral position, etc. The vehicle was also equipped with the same PDT-equipment as had been used by Olsson (2000). It consisted of a (3 × 20 cm) base with 23 light emitting diodes (LED). The base was fixed to the vehicle console and shielded from direct view (see Fig. 1).

A stimulus (LED) would appear as a reflection of a red light on the windscreen in the form of a head-up display. Prior to experimental trials the stimulus intensity was adjusted to the individual drivers and lighting conditions (sun or cloud), to ensure that stimulus onsets could be detected while the driver looked out on the road scene. The LED reflections would appear approximately 6.8–21.8° left of the centre of the steering wheel and approximately 3.8–5.3° elevated over the car console.

The LED panel was controlled by a microcomputer switching the LED on and off in random order. The time separation between successive stimuli was 3–5 s and the duration of each stimulus was 1 s. The microcomputer registered and stored the time and position of the stimulus presented.
Subjects responded to the onset of a stimulus by pressing a button located within reach of the subjects' index finger. If the subjects responded, reaction time was measured in milliseconds (ms).

2.3. Procedure

We used a mixed design with within-subject variations of navigation condition and between subject variations of navigation message modality. Thus, the number subjects could be reduced to a minimum compared to a complete between-subject design or a design with repeated measurements of message modes. All the subjects were instructed to drive one route after memory and another route with guidance from the navigation system. The memorised route was pointed out on a city map and the street names were mentioned to the subject. The subjects were given enough time with the city map to memorise the route prior to driving it.

The navigation system guided route was not described to the drivers beforehand. They were just told to follow the navigation messages (instructions) from the navigation system. All drivers had one trial based on memory and were randomly assigned to a modality of navigation messages. These were identical with respect to content only the required sense modality was different: Eight subjects had navigation messages presented visually (the sound was turned off), eight subjects had navigation messages presented verbally (the display was concealed) and eight subjects had full navigation messages (both visual information and voice messages).

Navigation conditions (memory versus navigation system) were balanced between subjects and routes. After each trial the subjects filled in the simple version of the NASA-TLX subjective workload questionnaire by marking on a paper sheet the experienced level of each dimension of workload on a 100 mm long horizontal line.

The subjects were instructed to respond as fast as possible to as many PDT-stimuli as possible without withdrawing their attention from the road scene at any moment of driving. All subjects were given a short test drive prior to the final acceptance of participation in which the subjects had sole responsibility for their driving at all times.

A research assistant in the backseat of the car monitored the equipment and made some manual registrations during driving. Apart from PDT-registrations, driving speed, brake activity, steering wheel angle, lateral position and distance headway were registered automatically with a frequency of 5 Hz.

3. Results

Reaction times between 200 and 2000 ms after a stimulus onset were analysed. The total number of stimulus presentations in the entire experiment was 10,450 and with 918 responses, thus the mean hit rate was 0.89. Mean reaction time averaged 650 ms across navigation conditions and message modality groups. The difference in reaction time between navigation conditions was 45 ms while the difference between the three message modality groups across navigation conditions was only 12 ms. Reaction times were subjected to analysis of variance with repeated measurement of navigation condition on (driving from memory versus driving with a navigation system) and between group differences in navigation message modality across navigation conditions. The effect of navigation condition was found significant ($F(1, 23) = 7.77, p < .01$) while the
difference between the three groups across navigation condition was not \( F(2, 21) = .02, p > .98 \). Comparisons of navigation condition within each message modality group revealed however a somewhat mixed effect of navigation condition on subjects’ reaction time. In the group receiving full navigation messages the difference in reaction time to PDT-stimuli between the two navigation conditions was found to be significant \( F(1, 7) = 6.23, p < .04 \), but no significant differences in reaction time was found between navigation conditions were observed in the group receiving visual messages \( F(1, 7) = 3.95, p > .09 \) nor in the group receiving verbal navigation messages \( F(1, 7) = .31, p > .59 \).

Hit rate differed between navigation conditions and the differences was found significant \( \chi^2(1) = 10.9, p < .001 \); so was the between group difference across navigation conditions \( \chi^2(2) = 15.52, p < .001 \). Pairwise comparison of hit rate between navigation conditions for each group showed a significant effect of navigation condition on hit rate in the visual navigation group \( \chi^2(1) = 4.07, p = .04 \), a marginally significant effect for the full navigation group \( \chi^2(1) = 4.02, p = .0448 \) but no significant effect for the verbal navigation group \( \chi^2(1) = 2.81, p = .09 \). Figs. 2 and 3 show subjects’ mean reaction times and hit rates for separate navigation conditions and message modality groups. The overall tendency is similar with lower hit rates and longer reaction times in conditions with the navigation system but few of these differences were found significant.

Driving speed was generally very low—it averaged 37.9 km/h—as were the differences in driving speed between navigation conditions and message modality groups. The maximum difference in driving speed between message modality groups was 1.52 km/h and the speed difference was only .5 km/h between navigation conditions. Neither these differences or within group differences between navigation conditions were found significant. Fig. 4 shows calculated mean speed for navigation conditions and message modality groups, respectively.

The possibility that other behavioural variables are sensitive to navigation conditions and message modality was tested by including brake force and brake frequency in the analysis. Brake force averaged 1.10 m/s² and maximum brake force averaged 5.2 m/s². Observed difference in

![PDT Reaction Time](image)

Fig. 2. Mean reaction time in ms for the navigation conditions (memory or navigation) and message modality groups (full, visual or verbal navigation messages).
maximum brake force was 0.62 m/s² between navigation conditions and 0.8 m/s² between groups with different message modalities. Within message modality groups the maximum difference between navigation condition was found for full navigation (1.56 m/s²). This difference was not statistically significant ($F(1, 7) = 4.15, \ p > .05$) nor was the difference between navigation condition within the two other message modality groups, receiving verbal or visual navigation messages, respectively.

The total number of brake events in the entire experiment was 1185 distributed between 600 in memory-based driving and 585 in driving trials with the navigation system.

3.1. Subjective workload—NASA-Tlx

In the present study subjects judged the items on the NASA-TLX subjective workload test very differently. Their indicated marks on the lines were measured and stated millimetres (see Table 1).
Table 1
Average subjective scores in mm for workload according to the simplified NASA-TLX workload questionnaire for combinations of navigation conditions and message modalities

<table>
<thead>
<tr>
<th></th>
<th>Full navigation N = 8</th>
<th>Visual navigation N = 8</th>
<th>Verbal navigation N = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Navigation</td>
<td>Memory</td>
<td>Navigation</td>
</tr>
<tr>
<td>Mental demand</td>
<td>47</td>
<td>50</td>
<td>53</td>
</tr>
<tr>
<td>Physical demand</td>
<td>25</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Time pressure</td>
<td>28</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>Performance</td>
<td>73</td>
<td>80</td>
<td>69</td>
</tr>
<tr>
<td>Effort</td>
<td>38</td>
<td>36</td>
<td>39</td>
</tr>
<tr>
<td>Frustration</td>
<td>26</td>
<td>27</td>
<td>51</td>
</tr>
</tbody>
</table>

The subjects' judgements are based on the markings on a continuous line with a length of 100 mm.  
*Denotes statistical significance.

Although the differences appear large, pairwise t-tests for each variable within each group (18 comparisons) showed a significant difference ($p < .05$) only for frustration between navigation conditions in the group presented with full navigation messages. However, out of the total of 18 possible comparisons, 15 represent a more positive assessment of memory-based driving compared with navigation-based driving. This represents an unequal distribution of positive and negative assessments ($p < .01$) and indicates a generally more positive judgement of memory-based driving.

4. Discussion

Whereas driving speed and the other aspects of driving behaviour observed in the present study (i.e., brake frequency and brake force), were virtually unaffected by navigation conditions and message modality, PDT-performance showed sensitivity to navigation condition (i.e., driving with or without navigation system). The small difference in driving speed is somewhat surprising since variation in driving speed often indicates variation in workload. However, free adjustment of speed is a precondition for a relationship between speed and task demand. In the present study mean speed was generally low which is probably due to the relatively short road sections and the presence of many other road users categories in the built-up area in which the experiment took place. Thus, demand on manoeuvring and interaction with other road users may have affected speed more than the navigation conditions and overshadowed a possible effect of navigation condition on driving behaviour. Mean reaction time to PDT-stimuli was longer and hit rate was lower during driving with a navigation system compared to driving a memorised route. However, comparing the effect of navigation condition within the three groups of navigation message modality, a significant effect of navigation condition was found only in the group that received full navigation messages (both visual and verbal). In the other two groups, i.e., those provided with verbal and the visual navigation messages, differences in reaction times were smaller and although reaction time was longer during driving with the navigation system, the effects were not found significant. The subjects' hit rates were influenced by navigation condition and within group analysis of navigation conditions showed a significant effect of visual navigation on hit rate for the
group presented with visual navigation messages. A marginally significant effect ($p = .0448$) may be noticed in the group presented with full navigation messages, whereas the difference in the verbal navigation group failed to reach significance.

Although the results of the present study are very much in accord with those obtained in the previous PDT-studies some important difference can be noted: In the present study only those navigation messages including visual information—visual navigation messages and combined visual and verbal messages—had a statistically significant effect on PDT-performance. Driving a vehicle in a real traffic is predominately visually demanding and, according to Wickens and Hollands (2000), resources are multiple and concurrent processing of visual sources of information causes structural interference. The results of this study are in accordance with this theory with the finding that only navigation messages including visual information affected the subjects PDT-performance, subjects' reaction times became longer (full navigation messages) and their hit rate was reduced (visual messages). Moreover, the results would appear to concur with previous results by Wickens et al. (1983) who found advantages of cross-modal over intra-modal tasks. Furthermore, Parkes and Coleman (1990) also found that certain driver performance advantages of presenting route guidance information audibly rather than just visually in a simulator study.

The finding that full navigation—including both verbal and visual navigation messages—affected PDT-performance, whereas effects of verbal navigation messages on PDT-performance were small and failed to reach significance, is delicate. It is generally recommended (Burnett & Joynder, 1996; Parkes & Burnett, 1993; Verwey, 1993; see also Zaidel & Noy, 1996) that navigation systems should use verbal and visual information in parallel. It is obviously premature to question this recommendation on the basis of this study. This result may more than likely indicate a comparatively stronger sensitivity of the PDT-method to visual information.

Subjects in the present experiment were professional drivers who were familiar with driving in the built-up area in which the experiment took place. As taxi-drivers, the subjects were also familiar with having IVIS in their cars, but none of them were familiar with driving with a navigation system. It is a promising and surprising result that, despite the relatively small number of subjects and their level of local and driving skill, effects of navigation condition on PDT-performance were actually observed in the calculated overall means for entire driving routes. After all, navigation messages were presented only occasionally and with short intervals of driving on these routes.

It would have been tempting to argue that the observed effects were due to the artificial nature of navigation tasks in this experiment. Skilled drivers, driving in a familiar environment, may experience uncertainty when they are forced to wait for navigation messages and thus are prohibited from anticipating the route. However, induced uncertainty cannot account for the difference between navigation messages within the different navigation conditions. In fact, full navigation resulted in a prolongation of reaction times and a marginally significant decrease in hit rates as compared to memory-based driving. Visual navigation affected the drivers' hit rates and only effects of verbal navigation failed to reach significance. This pattern of result does not support the assumption that the effect could have been caused by general uncertainty.

Subjective ratings of workload showed great individual variability and only small effects but generally memory-based driving received more positive judgements than driving based on a navigation system. This may be explained both by the novelty of driving with a navigation system and by the fact that the drivers were familiar with the driving environment and had no problems
with driving after memory. In an unfamiliar driving environment the subjects might have appreciated the navigation system more.

The choice of professional drivers as test subjects, who all had extensive local knowledge of the city of Linköping and a high annual mileage, warrants further comment. We propose that these subjects will be least likely to squander cognitive resources (see Wickens & Hollands, 2000) due to the following; (i) subjects’ uncertainty due to the use of informal local traffic rules and customs idiosyncratic for the test site in Linköping will be reduced; (ii) the subjects were professional drivers (mostly taxi-drivers), who all regularly use some form of in-vehicle information and communication system. That is, they are accustomed to using a plethora of electronic equipment that can be perceived as being anything but standard for cars; (iii) professional drivers are used to using memorised routes on a regular basis in their professional lives. The summed effect of these three points is a reduction of “noise” (Wickens & Hollands, 2000) in our analysis of the PDT on navigation support systems. Moreover, a certain amount of increase in cognitive workload and even stress should be expected when the subjects follow the navigational messages of the test system without having any prior knowledge of the destination. This would be concurrent with the fact that the subjects were not able to plan their driving ahead and, as a consequence, were more likely to experience feelings of diminished control over their driving situation (in the planning stage). However, this possible impairment should be put in relation to a naturalistic traffic situation in which a navigation aid would be required. The two situations are in fact very similar; if the driver knew where he/she was going and how to get there, then the navigation aid would be redundant. Furthermore, the fact that our subjects were professional drivers, with extensive local knowledge of Linköping city does not in anyway mar the effect of the experimental navigation task (not the memory navigation) because the subjects did not have prior knowledge of the route.

Memory-based navigation was used as a reference or baseline in order to establish a normative condition for naturalistic driving behaviour. The PDT-performance results from this study indicate that memory-based navigation tended to be less resource demanding when driving with a navigation system, although the effects were only significant in the group of drivers receiving combined visual and verbal messages for navigation messages.

5. Conclusions

In line with results from previous studies, PDT-performance showed a remarkable sensitivity to calls for attention due to navigation messages in the present experiment. By presenting subjects the navigation messages with the same content and on identical locations during driving, only the mode of presentation was varied in the present experiment. It was demonstrated that PDT-performance was not unrelated to the mode of presentation. On the basis of this finding it may be questioned whether the PDT-task is suitable as the only standard method for measuring distraction from IVIS. Apparently, a method or combination of methods, being less dependent on mode of presentation, would be more useful for measuring distraction and cognitive load more generally. On the other hand, the driving task requires continuous visual information processing and visual distraction is a very important component in safety evaluation of IVIS, therefore the method should have a prominent status in a test battery for safety evaluation of IVIS and ADAS.
Acknowledgements

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Driver experience and cognitive workload in different traffic environments

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Abstract

How do levels of cognitive workload differ between experienced and inexperienced drivers? In this study we explored cognitive workload and driver experience, using a secondary task method, the peripheral detection task (PDT) in a field study. The main results showed a large and statistically significant difference in cognitive workload levels between experienced and inexperienced drivers. Inexperienced, low mileage drivers had on average approximately 250 milliseconds (ms) longer reaction times to a peripheral stimulus, than the experienced drivers. It would, therefore, appear that drivers with better training and experience were able to automate the driving task more effectively than their less experienced counterparts in accordance with theoretical psychological models. It has been suggested that increased training and experience may provide attention resource savings that can benefit the driver in handling new or unexpected traffic situations.

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Keywords: Cognitive workload; PDT; Driver experience

1. Introduction

Do levels of cognitive workload whilst driving differ between experienced and inexperienced drivers? The idea that an inexperienced operator or, as in this case, an inexperienced driver, would experience higher levels of cognitive workload when operating a machine/system is not new (Sweller, 1993; Sweller et al., 1998; Wickens and Hollands, 2000). It also fits Rasmussen’s (1980, 1987) theoretical model of human behaviour. However, showing the extent and importance of the difference between experienced and inexperienced drivers, using objective/quantitative measures is less well explored and is therefore the focus of the present study.

The importance of measuring the workload of non-professional drivers lies in the bigger picture of workload research and the applicability of workload research for drivers with a more ‘average’ or modest driving experience. We studied experienced, professional drivers, because they would normally have more training and experience than ‘average’ drivers and therefore, from a scientific point of view, should have less ‘noise’ in the workload data. However, when generalising workload results, there is a great benefit in knowing the relative ‘distance’ between experienced and professionally trained drivers and drivers who have little or only modest driving experience but who were not unqualified or novice drivers.

In theoretical terms, Rasmussen (1987) suggested in his model of human control and behaviour (the skill-rule-knowledge-based framework) that during training in a particular task, such as driving, control moves from the knowledge or rule-based levels towards the skill-based level, resulting in the reduction in mental/cognitive workload required for the operations involved in the driving task and, thereby, inherently accommodating a larger amount of available attention that can be allocated to other tasks or operations. The level of available attention the driver has at any given moment is partly dependent on the driver’s prioritisation between different tasks, whether primary or secondary. The driver’s prioritisation between tasks is intrinsically linked to the aspect of distraction.

The term driver distraction implies that drivers do things that are not primarily relevant to the driving task (driving safely) and that this reduces the available attention that would otherwise be needed for driving safely. The problem of driver distraction for traffic safety must, in part, lie in the limitations of human attention resources and how the attention is allocated (prioritised) by humans in their management of the different tasks, whether they are primary-task related (driving) or not. The allocation of...
Crundall and Underwood, 1998) but do not explore the element Chapman and Underwood, 1998; Mourant and Rockwell, 1972; complexity than the experienced drivers. Several studies have suggested that the duration of eye fixation, whilst driving, represents the time spent processing hazard-related information in the road scene. Moreover, newly qualified drivers appeared, in Chapman and Underwood’s study, to be more affected by increased complexity than the experienced drivers. Several studies have noted narrower visual search patterns among novice drivers (cf. Chapman and Underwood, 1998; Mourant and Rockwell, 1972; Crundall and Underwood, 1998) but do not explore the element of workload and inexperience as an effect of this narrowed search pattern. These studies have, however, focused more on the lack of skill which are evident when the subjects are untrained novice drivers (cf. Chapman et al., 2002). Mourant and Rockwell’s field study (1972) at an early stage clearly differentiated between experienced and novice drivers when studying their visual search patterns. In contrast to the experienced drivers, the novice drivers tended to fixate their gaze to a small area not far ahead of the vehicle. Novice drivers also used their mirrors less frequently, and on the motorway sections made pursuit eye movements whilst the experienced drivers only glanced. Mourant and Rockwell (1972), furthermore, suggest that the visual acquisition process of novice drivers was unskilled and overloaded. Underwood et al. (2003) in their laboratory study found, inter alia, that experienced drivers had better recall than novice drivers. They also noted that as skill and experience increases, drivers increase their sampling of events from their immediate traffic scene, they also sampled from more locations in their traffic scene. Similar results were reported by Crundall et al. (2003). In a more elaborate and earlier study by Crundall and Underwood (1998), novice and experienced drivers’ distribution of visual attention was studied during exposure to different levels of cognitive workload. Crundall and Underwood induced different levels of complexity with different road traffic environments. As with other studies in this field, the main dependent variable was the visual search strategies of the participants. Crundall and Underwood found that experienced drivers select visual strategies according to the complexity of the road traffic environment and that novice drivers’ visual search strategies were inflexible to changes in (visual) demand. 

Lee and Triggs (1976) found that increased environmental complexity during driving affected the detection of peripherally presented stimuli negatively. Later, Miura (1986, 1999) demonstrated that task demand rather than visual complexity affected eye movement patterns as well as sensitivity to stimuli in the drivers’ visual periphery, Chan and Courtney (1993, 1996, 2000) demonstrated that variations in cognitive demand also affect sensitivity in the visual periphery at a constant level of perceptual load in the foveal field. Handy et al.’s (2001) study of perceptual workload and visuocortical processing indicated, inter alia, that increasing foveal target detection, i.e. increasing the visual workload, such as driving in an information-rich environment (e.g. a busy high street with delivery trucks, cyclists, pedestrians, children, crossing traffic, etc., all in close proximity to each other), decreases the residual attention capacity available for allocating to parfoveal stimuli.

The peripheral detection task (PDT) method has been used in several field and high fidelity simulator studies and shown itself to be a sensitive measure of cognitive workload, especially where visual demand is high such as in driving (Martens and Van Winsum, 1999; 2000; Harms and Patten, 2001, 2003; Olsson and Burns, 2000; Patten et al., 2004; Kircher et al., 2004; Crundall et al., 1999). Another advantage of the PDT method is its continuousness. Unlike more traditional reaction time measures (often used for evaluating situation awareness), such as brake-reaction time, they are only really ecologically valid for a few ‘situations’ because the participants quickly learn that certain ‘events’ or ‘situations’ will at some stage pop up. The PDT method in contrast, also by being a secondary task, is in the background throughout the entire experiment. Large quantities of data can be collected and baseline or reference data (within-subject design) are easily included in the experimental design. Furthermore, the measurement of available cognitive resources also provides a more valid reflection of the driving task and its demands on the driver.

1.1. Purpose

The main purpose of this study was to evaluate the effect of driver experience on workload demand using a secondary task method, the PDT, in a real-life driving context. An additional objective of this study was to evaluate the effects of route complexity on the secondary task being used (i.e. PDT) when comparing two driver groups. Here the focus was on the ability of drivers to cope with different levels of additional cognitive or mental workload introduced through primary task complexity variations. In this way, the competition over mental attention resources increases as an effect of the level of driver experience and route complexity.

2. Method

2.1. Participants

Participants were recruited from newspaper advertisements and compensated approximately €75 euros (including travel expenses to and from the study site). This compensation was for 1h of briefing, donning of physiology electrodes, 5–10 min of familiarisation with the study apparatus and approximately 1h of actual experimentation. A total of 79 participants were recruited for this study with 40 of these participants in the “high mileage”, experienced driver group and 39 in the “low mileage”, inexperienced group.

The selection criteria for the participants in the ‘high mileage’, experienced driver group were that they were required to be professional drivers, and had held a professional driver’s...
licensure for at least 3 years, aged from 21 to 60 years, a minimum annual mileage of 15,000 km in the last year, and were very familiar with the town where the experiment was held. There were 40 participants who completed the experiment for the high mileage driver group; however, due to incorrect classification of 2 participants and 1 participant who disregarded the task, there were only 37 participants. 29 males and 8 females, who successfully completed the experiment for the ‘high mileage’ driver group. Their average age was 39.9 years; their age range was from 22 to 59 years; the average annual mileage was 47,200 km. If the participants were not sure about the exact mileage they had to state their estimated minimum annual mileage.

The selection criteria for the participants in the ‘low mileage’, inexperienced driver group were that they were non-professional drivers, with a maximum estimated annual mileage of 15,000 km and who had little or no experience of driving in Linköping town. There were 39 participants who completed the experiment for the high mileage driver group; however, due to incorrect classification of 1 participant, there were only 38 participants who successfully completed the experiment for the low mileage group. There were 20 male and 18 female drivers; their average age was 32.9 years; their age range was from 19 to 56 years; the average annual mileage was 9900 km. These participants were not to be novice drivers (as there are other mechanisms in play when considering driving errors, such as inexperience, learned handling skills and also learning rates are likely to be inhomogeneous), merely modestly experienced, low mileage, qualified drivers. This driver group, due to their modest driving habits, had some difficulty in estimating their annual mileage. When in doubt, they were asked to estimate their maximum annual mileage.

Based on the elimination of participants from each group as previously stated, a total of 75 participants were actually used for the subsequent analyses. All participants were Swedes or fluent in the Swedish language. This was important since the audio guidance from the navigation systems used in the study was in Swedish.

2.2. Equipment and materials

An instrumented vehicle was used in this field study; a Volvo 850S, 2.5l engine, manual gearbox and the model year was 1996. The Volvo, an estate (or station wagon) version was, for the driver, apparently quite ordinary. The driver could not see any of the video cameras mounted in the car; they were concealed and also very small. All of the data collection equipment was in the boot of the Volvo. Data were collected in the vehicle at a rate of 5 Hz and stored in an onboard laptop computer. The vehicle’s cruise control was disabled.

The PDT method is an indirect measure of workload and measures cognitive workload by evaluating reaction times to secondary-task stimuli. In this case a visual stimulus was in the form of a light emitting diode (LED), placed in the peripheral area of the driver’s line of forward sight. The PDT equipment comprised a display with six red LEDs set in a display panel, a modified micro-switch with increased depression feedback and a computer unit for control, calibration of settings and data logging.

One diode at a time was illuminated, the selection of which was random. The interval between illuminations of the LED signal was between 3 and 5 s, also at random within that range. The period of illumination was a maximum of 2 s unless the participant extinguished the LED signal by depressing the micro-switch. The light signals from the LED were reflected up onto the left-hand side of the windscreen in the form of a head-up display. The PDT LEDs had a light intensity of 8.2 cd, a projection angle of ±3° and a wavelength of 660 nm (red). The LED reflections appeared approximately 6.8–21.8° left of the centre of the steering wheel and approximately 3.8–5.3° elevated above the car console. The participants’ performance was recorded in the form of PDT miss rate and their reaction times in milliseconds (ms). The PDT data were synchronised with all the instrumented-vehicle data (e.g. speed, steering wheel angle, distance travelled, etc.).

For greater generality, we used two navigation systems with equal voice and visual message presentation on different screens. The size and location of the systems used were typical for the navigation systems commonly available on the market. The number of participants between the two systems and the two driver groups was evenly balanced (20 low mileage and 18 high mileage participants used the small system; 18 low mileage and 19 high mileage participants used the large navigation system).

Both systems gave exactly the same auditory guiding information and used the same digital map information. The main differences between the two navigation systems were that the ‘small’ system, a VDO Dayton MS4200, had a smaller, monochrome display and only basic indicator shapes for roads and intersections for route guidance and was placed in the car audio rack. The ‘large’ system, a VDO Dayton MS5000, had a colour monitor with larger route and driving information available. Their position in the vehicle was also different. Fig. 1 shows the two navigation systems as installed in the instrumented vehicle.

![Fig. 1. An interior view of the instrumented vehicle. The two navigation systems are pointed out with arrows (MS4200 and MS5000). The PDT is also visible on the left-hand side of the windscreen. During the experiments only one navigation system was installed at a time.](image)
Note, however, that during the experiment, only one navigation system was installed and operational at a time. The small navigation system was positioned 36 cm to the right of the centre of the steering wheel (horizontally), and 21 cm below the centre of the speedometer (vertically). The screen was turned 7° horizontally and 18° vertically to the driver. The large navigation system was positioned 32 cm to the right from the centre of the steering wheel (horizontally), and 4 cm below the centre of the speedometer (vertically). The screen was turned 7° horizontally and 5° vertically to the driver. The vertical distance between the two navigation systems was 17 cm. All distance measurements relate to the centre of the screen of the navigation systems.

2.3. Procedure and design

All participants were instructed about the experiment and signed informed-consent forms regarding their liability and responsibilities when driving. Video footage consent forms were procured post-experimentally. The participants were further instructed to drive as they would ‘usually’ do, but to keep in mind their legal responsibilities regarding traffic violations. The participants were prepared with physiology electrodes prior to driving (not reported). Training was also provided for the PDT. All adjustments of seats, mirrors, and temperature and seat belts were done before leaving the Swedish National Road and Transport Research Institute (VTI) garage. This familiarisation phase typically took about 5–10 min. Finally, the participants were instructed to prioritise the driving task first and respond to the light signals of the PDT diodes second.

Throughout the entire journey, a VTI technician was present in the test vehicle, sitting behind the driver. His role was to coordinate the navigation route inputs, to follow the design protocol, to attach electronic markers to the vehicle data at predetermined points, to administer the NASA-RTLX subjective workload protocols and to deal with any problems. The participants were instructed to have no contact with the technician during the driving task.

The PDT was used in this study to evaluate the participants’ workload whilst driving. The PDT task required the participants to react to a light stimulus (the LED) that appeared in the participants’ periphery (in respect to the main driving focal point—straight ahead) and the light stimulus was illuminated for 2 s. The participants reacted by depressing the micro-switch attached to the left index finger. The LED is, upon depression, subsequently extinguished. If the response was classified as ‘correct’ (response within 2 s) the reaction time was recorded in milliseconds, otherwise the response was recorded as a late or missed response.

The use of navigation systems, per se, was a means to an end and not a primary objective in itself. The automated driving instruction provided by the navigation system provided us with the means to create an equal task, in its structure, for the two driver groups with a realistic (driving) task for the participating drivers. The drivers had no prior knowledge of the planned test route. The participants received visual and auditory route guidance instructions from only the navigation system.

The route was 8.6 km long and extended from the western periphery of the city to the centre of Linköping, which has about 130,000 inhabitants. The selected urban environment consisted of sections with low to high complexity and the drive took approximately 40 min to complete. This included stops for NASA-RTLX and navigation system programming but did not include time for familiarisation which was done prior to departure. The weather conditions ranged from sunny to rainy; however, the roads were never icy or snowy. The speed limit was 50 km/h along the whole route.

The taxonomy by Fastenmeier (1995) was used to define and select road sections with a certain complexity. Each high/high complexity section had at least five turns which were considered to have high demands on information processing and high demands on vehicle handling, hence the term high/high. A simplified description of the three levels of route complexity used in this study is provided below.

The classification of route complexity:

1. High demands on information processing/high demands on vehicle handling (high/high complexity): typical examples from this group of situations occur when driving within city environments.
2. High demands on information processing/low demands on vehicle handling (high/low) (medium complexity): typical examples from this group of situations occur at intersections regulated by road signs and where the driver has right of way, and at intersections regulated by traffic lights.
3. Low demands on information processing/low demands on vehicle handling (low/low complexity): typical examples from this group of situations occur in urban and rural areas and on motorways where ‘free driving’ is possible.

There were five stops on the route, where the technician programmed the next destination in the navigation systems. During the stops, which took approximately 25 s each, the drivers were asked not to look at the navigation system screen, to prevent them from seeing the next destination. The route included two high/high complexity sections, three medium and two low/low complexity sections. The order of the route complexity was low/low, medium, high/low, medium, high/medium, high/low, medium and low/low with the participants returning to their point of departure, i.e. the VTI garage. Stop number 1 was after approximately 1800 m, stop 2 was after approximately 2500 m, stop 3 was after approximately 4300 m, stop 4 was after approximately 5100 m and stop 5 was after approximately 5900 m. The final stop was at the journey’s point of origin. The location of these stops was dictated by the need to reprogram the GPS guided navigation system in order to facilitate an exact adherence to the planned route.

The study’s setup comprised a 2 × 3 experimental design (two driver groups and three levels of route complexity). The dependent variables reported in this study were PDT reaction times and
PDT miss rates. The independent variables were driving experience (two groups) and traffic environment complexity (three levels). The route, which was a circuit in a real city centre, comprised seven segments (low/low, medium, high/high, medium, high/high, medium and low/low) and to counter the order of route complexity, the seven segments were condensed into their respective levels of route complexity. The distances travelled for each level of route complexity were approximately equal.

3. Results

The sections of road where the drivers inadvertently left the designated route were excluded from the analyses; they were few in number and short in duration and did not affect the overall data. The parts where the driver was stopped in order to reprogram the navigation system were also excluded from the analyses. After resuming the drive after such a stop, 2 s of data were excluded, since this time was needed by the driver to regain normal cruising speed.

The PDT reaction times and the PDT miss rates are in a sense two sides of the same coin. Therefore, any individual miss rate greater than two-thirds on a route complexity section (66%) was deemed to involve a potential bias for the corresponding PDT reaction time. These particular PDT reaction times were therefore omitted from the analysis to avoid potential biases in the reaction time results. The corresponding miss rate values were, however, retained.

The main results of the study are shown in Figs. 2 and 3. In Fig. 2, there is a clear and statistically significant effect of the relative level of driver experience on the PDT reaction times. Low mileage drivers had on average approximately 250 ms ($X = 245.67$ ms) longer reaction times than the high mileage drivers. All statistical analyses were performed using a standard SPSS (11.0) software package.

The analysis of variance between the two navigation systems (small and large) for traffic environment complexity was not significant; the low/high traffic environment complexity PDT reaction times and PDT miss rates, respectively ($F(1,73) = 0.105, p = n.s.$); the high/high traffic environment complexity PDT reaction times and PDT miss rates, respectively ($F(1,73) = 0.212, p = n.s.$). The data sets for the navigation systems were condensed into one set for the following analyses. These results were also consistent with a previous, unpublished study using the same type of navigation systems (Kircher et al., unpublished).

For the PDT reaction times, the main effect of traffic environment complexity was significant in a $2 \times 3$ repeated ANOVA ($F(2,142) = 41.683, p < 0.001$). Mauchly’s test of sphericity was not significant; therefore, the univariate results are reported. The main effect of driver experience (high mileage and low mileage driver groups) was also significant ($F(1,73) = 56.944, p < 0.001$). The traffic environment complexity by driver experience interaction was significant ($F(2,142) = 3.694, p = 0.027$).

In post hoc analysis, using the Bonferroni approach ($a/c$), to control the familywise error rate (FW), $a$ decreased from 0.05 to 0.008 (FW = 0.05/6 = 0.008). The analysis of the effect of route complexity (cf. Fig. 2) used paired $t$-test analyses on the PDT reaction time measure of cognitive workload. We interestingly found that the difference in the mean PDT reaction times between low/low and medium traffic environment complexity was statistically significant for the low mileage drivers ($t = -3.991, d.f. 37, p < 0.001$) but not for the experienced drivers ($t = -1.895, d.f. 34, p = n.s.$). The difference in mean PDT reaction times between the medium complexity and the high/high complexity route sections was, however, significant for the experienced driver group ($t = -6.572, d.f. 34, p < 0.001$), but not for the low mileage drivers ($t = -1.567, d.f. 37, p = n.s.$).

The difference between the low/low and the high/high complexity traffic environments was significant for the low mileage drivers ($t = -5.443, d.f. 37, p < 0.001$) and for the experienced drivers ($t = -8.613, d.f. 35, p < 0.001$). The mean and standard deviation values are reported in Table 1 for the respective driver groups and the three levels of traffic environment complexity.

In additional post hoc analyses of the driver groups for PDT reaction times, using the Bonferroni approach ($a/c$), to control the familywise error rate, $a$ decreased from 0.05 to 0.017 (FW = 0.05/3 = 0.017). The difference between the mean PDT reaction time for low mileage drivers (929 ms) and high mileage

![Fig. 2](image-url)  
**Fig. 2.** A line chart, including standard error of mean bars, illustrating the mean PDT reaction times over three levels of traffic environment complexity and for two driver groups. The reaction times are in milliseconds (ms).

![Fig. 3](image-url)  
**Fig. 3.** A line chart, including standard error of mean bars, illustrating the mean PDT miss rate, as a percentage rate, over three levels of traffic environment complexity and for two driver groups.
Drivers (713 ms) in the low/low complexity traffic environment was statistically significant ($F_{(1,73)} = 34.852, p < 0.001$). The difference between the mean PDT reaction time for low mileage drivers (1034 ms) and high mileage drivers (736 ms) in the medium complexity traffic environment was statistically significant ($F_{(1,73)} = 65.568, p < 0.001$). The difference between the mean PDT reaction time for low mileage drivers (1067 ms) and high mileage drivers (844 ms) in the high/high complexity traffic environment was also statistically significant ($F_{(1,73)} = 32.852, p < 0.001$).

In Fig. 3, there is also a clear effect of the level of driver experience on the mean PDT miss rate. The main effects of traffic environment complexity and driver experience were statistically significant as shown in the following analyses.

For the PDT miss rates, Mauchly’s test of sphericity was significant and therefore the Pillai’s Trace multivariate results were reported. The main effect of traffic environment complexity was significant (Pillai’s Trace $= 0.648, F_{(1,73)} = 66.283, p < 0.001$). The main effect of driver experience (high mileage and low mileage driver groups) was also significant ($F_{(1,73)} = 7.688, p = 0.007$). The traffic environment complexity by driver experience interaction was significant (Pillai’s Trace $= 0.354, F_{(2,72)} = 19.687, p < 0.001$).

In post hoc analysis, using the Bonferroni approach ($α$), to control the familywise error rate, $α$ was moved (FW = 0.0536 = 0.0083). In the paired $t$-test analyses of the effect of route complexity (cf. Fig. 3), using the PDT miss rate as the primary measure, we found that the difference in the mean PDT miss rates for the low mileage drivers was statistically significant between low/low and medium traffic environment complexity ($t = -10.531, d.f. 37, p < 0.001$), and between medium and high/high ($t = 6.770, d.f. 37, p < 0.001$). The differences in the mean PDT miss rates for the high mileage drivers were also statistically significant between low/low and medium ($t = -5.467, d.f. 36, p < 0.001$), and between medium and high/high ($t = -3.379, d.f. 36, p = 0.002$).

In additional post hoc analysis of the driver groups for PDT miss rates, using the Bonferroni approach ($α$), to control the familywise error rate, $α$ decreased from 0.05 to 0.017 (FW = 0.0533 = 0.017). The difference between the mean PDT miss rates for low mileage drivers (21%) and high mileage drivers (14%) in the low/low complexity traffic environment was statistically significant ($F_{(1,73)} = 6.608, p = 0.01$). The difference between the mean PDT miss rates for low mileage drivers (39%) and high mileage drivers (24%) in the medium complexity traffic environment was statistically significant ($F_{(1,73)} = 17.575, p < 0.001$). The difference between the mean PDT miss rates for low mileage drivers (33%) and high mileage drivers (29%) in the high/high complexity traffic environment was not statistically significant ($F_{(1,73)} = 1.064, p = n.s.$).

4. Discussion
The main results of this study showed a large and statistically significant difference in the cognitive workload between the two driver groups. The differences in mean PDT reaction times between the two driver groups were significant for each of the road sections (low/low, medium and high/high). Low mileage drivers had approximately 250 ms longer mean reaction times than the high mileage drivers.

An interesting aspect of the PDT reaction time data was that the low mileage drivers’ reaction time performance did not significantly differ when comparing performance between the medium and the high/high traffic environment complexity sections. The high mileage drivers’ performance did, however, noticeably deteriorate from the medium to the high/high traffic environment complexity. Moreover, the opposite of this situation is found for the two driver groups from the low/low to the medium complexity sections. A possible explanation of this pattern in the PDT data is that the high mileage drivers generally had a better ability to chunk information and also experienced the low/low and medium sections as having a relatively similarly low workload burden. The high/high complexity was, however, noticeably more taxing for the experienced drivers. When comparing the two driver groups, it is evident that the high mileage drivers’

### Table 1

Mean and standard deviation values for the PDT reaction times (PDTms) and miss rates (missed PDT responses) for the respective mileage groups and traffic complexity conditions (low/low, medium and high/high)

<table>
<thead>
<tr>
<th>Mileage groups</th>
<th>PDTms</th>
<th>Missed PDT response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low/low</td>
<td>Medium</td>
</tr>
<tr>
<td>Low mileage drivers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>928.986</td>
<td>1034.432</td>
</tr>
<tr>
<td>N</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>179.848</td>
<td>182.347</td>
</tr>
<tr>
<td>High mileage drivers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>713.313</td>
<td>736.322</td>
</tr>
<tr>
<td>N</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>132.254</td>
<td>124.028</td>
</tr>
<tr>
<td>Total</td>
<td>822.587</td>
<td>891.503</td>
</tr>
<tr>
<td>N</td>
<td>75</td>
<td>73</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>190.960</td>
<td>216.423</td>
</tr>
</tbody>
</table>
level of cognitive workload is much less in all of the traffic complexity sections than the low mileage drivers.

This shows how drivers with better training and experience are able to automate their driving more effectively than their less experienced counterparts. Ipsos fact, the more experienced drivers had more available mental resources that could be allocated to peripheral information. In line with this, the visual/cognitive tunneling effect appears to be greater for the less experienced, low mileage driving group when directly compared to the experienced drivers doing the same task.

The size and location of the navigation systems used did not significantly add to the level of complexity when driving in this study, as also was the case in an earlier, unpublished report using the same type of navigation systems (Kircher et al., unpublished). The data sets for the two navigation systems were therefore condensed into one set for the main analyses. The auditory guidance information from the navigation systems was identical, thus suggesting that the participants focused primarily on the auditory information provided. The visually displayed information was secondary and had a supportive or strengthening function for the auditory conveyed information. This would explain, in part, the lack of differences found between the two navigation systems used in this study.

When drawing on theory (cf. Rasmussen, 1980, 1987) it leads us to verification of the view that increased experience reduces the driver's mental workload. This may be especially so for novice drivers in the process of learning to drive, when everything that is required for driving safely has to be acquired cognitively (formal and informal rules, traffic scenarios, etc.) and as motor skills (vehicle handling, controls, etc.). However, even experienced drivers will experience greater cognitive workload when encountering new situations (e.g. driving in new cities in foreign countries). This study, using objective or quantitative cognitive workload measures, supports this theoretical conjecture on workload and experience. Additionally, with respect to the PDT method and the use of reaction times, it is important to be able to map the relative difference or distance in reaction times between well-trained and experienced drivers with more modestly experienced, average drivers. Such knowledge will have consequences for analyses of accidents in which attention failures played a role, illustrating the applicability of PDT data in traffic research.

The results of this study are also in line with the view that there are safety benefits to be gained for drivers in maintaining a regular level of driving experience. This is because training and experience reduce the driver’s cognitive workload and increase the level of available attention resources where limitations of attention resource allocation are dimensional for the human capability for safe driving (e.g. Broadbent, 1958, 1982; Baddeley, 1976; Wickens and Liu, 1988; Debecker and Desmedt, 1970; Wickens and Hollands, 2000).

The NASA-RTLX results were inconclusive with no significant differences. The indices were not sensitive enough in the present study to measure changes or differences in cognitive workload. It is possible that more frequent ratings or another, perhaps simpler subjective workload index, may have been more effective.

The PDT miss rate data are an indication of the quality of the corresponding reaction time data. Where there is a PDT miss, there will be no PDT reaction time for that particular stimulus. There is usually a certain percentage of missed stimuli for each participant, depending on the complexity of the primary task, and this is reflected in the mean PDT miss rate. With correct responses to the PDT stimulus, the reaction times are recorded and reflected as a mean PDT reaction time for the respective condition and participant. However, if there is a very large number of misses, the mean reaction time will comprise of a smaller number of correct responses. This could lead to biases in the data for that participant and condition. Therefore, we deemed it prudent to have a cut-off point for the mean PDT reaction time data for a traffic complexity section, whose corresponding miss rate data were greater than two-thirds (66%). The miss rate data were, however, retained because an increase in the PDT miss rate is also an indication of the reduction in the drivers’ available attention in the different experimental conditions.

In future research, it would be of great interest to observe inexperienced, low mileage drivers and also novice drivers under longer periods of high workload where a waning of cognitive resources may well occur more rapidly. This intermittent level of driving experience, i.e. where manual driving skills are relatively developed but experience of driving and development of rule-based strategies for traffic scenarios are less well developed, is of interest for driver-training professionals, licensing authorities and accident epidemiologists.

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Mobile phones and driving: a review of contemporary research

Abstract This study reviews research on the effects of using a mobile phone when driving. First, it is should be pointed out that the availability of a mobile phone in a car is of great value, for example, in emergencies and accidents. However, the results from the research covered in this review show that using a mobile phone in a car while driving impairs driving performance significantly. To exemplify, a driver’s attention to traffic and traffic information is impaired and the control of the car becomes less precise and smooth when talking over a phone. The conversation in itself impairs attention and manoeuvring performance as well as the motor activities needed for phoning. Based on the research available, the present review gives numerical estimates of the disturbing effects of different aspects of mobile phoning on driving performance. Contrary to what people assume, hand-held phones have not shown to impair driving quality more than hands free phones. Instead, in contrast to public opinion, the content of a conversation is most important in determining the degree of distraction; complex conversations disturb driving much more than simple conversations. Analyses of accidents have shown that the impairment of driving while phoning leads to an increased risk of having an accident for both hand-held and hands free mobile telephones.

Keywords Mobile phone · Driving · Attention

1 Introduction

There are advantages and disadvantages of mobile phones and their use in the traffic system. In the discussion part of this contribution we will return to the benefits of mobile phones in traffic, but the main purpose of the present study is to give a summary of the research investigating the relationship between the use of mobile phones and driving performance. More specifically, we want to review research on the effects of mobile phoning while driving, on perception, cognition, workload, distraction and road traffic safety.

In a road traffic context, the primary task of a vehicle operator (the driver), is the safe operation of the vehicle in respect to other road users and themselves. The primary task involves activities that support the driver and safe driving, i.e., decision-making, route planning, lane keeping, adapting and using an appropriate speed etc. Secondary tasks, however, are activities that may be undertaken by the driver but do not directly support the driving task, i.e., listening to music, conversing with a passenger or, inter alia, talking on a mobile phone or similar device. Quite often, the secondary task will compete for the driver’s available mental resources. This may also occur at a time when the operator or driver’s mental focus is needed to deal with the execution of the primary task. This is when distraction (from the primary task) due to secondary task activities can result in incidents or accidents (Ahl and Nilsson 2001).

One major contributing cause of traffic accidents is speeding, i.e., an inappropriately high vehicle speed for the road and traffic conditions at hand, but attention and perception errors are also major contributory factors (Smiley and Brookhuis 1987). There are many reviews of attention and human information processing (e.g., Gaillard et al. 1996; Hockey et al. 1986; Pucher 1999; Kahneman 1973; Wickens and Hollands 2000). Human information processes require different amounts of effort and energetic resources. Automated information processes typically require less effort and resources than elaborate consciously controlled processes. If the
human system has redundant capacity, which is impor-
tant in car driving, then there will be resources and
capacity available for mobilising extra effort in case of a
potentially hazardous or critical traffic situation arising.
If, however, the human system is used to its capacity
limit, then there is a reduced possibility of correctional
evasive actions, problem solving etc. by the driver.
Information can also be missed, information processing
delayed and/or some ongoing tasks will need to be
quickly abandoned to release resources for processing
information in the potentially hazardous situation.

There are numerous system interactions between all
parts of the human perceptual-cognitive psychomotor
systems and parallel processing occurs at different levels
with input from different channels (Wickens and Hol-
lands 2000). There are different views on the issues of
parallel processing and a common energetic resource
pool for all information processes. The view we will
adopt here is that information processing can be viewed
as parallel and although there is a common resource
pool setting limits to processing, there are energetic re-
Source available and used for specific purposes (e.g.,
visual processing), but only to a certain extent. When
the common energetic resources are taxed this affects all
processing. Time sharing and buffering of information
(e.g., for output) is also assumed to be a characteristic of
human information processing. Shallice (1986) describes
attention, actions and the allocation of energetic re-
Source as hierarchically controlled. There are corre-
sponding models of the driver in a car (e.g., Allen et al.
1971; Michon 1985; Ranney 1994; Vogel 2002). In such a
hierarchical supervisory model a general-purpose system
can use representations of the environment and inten-
tions and abilities of the driver. The system selects
higher-level schemas, which attenuate lower-level sche-
mas in turn controlling specific subsystems. To exem-
plify, when allocating focal attention over time a certain
schema is selected (e.g., looking out the window to
control the car) provided its activation level exceeds a
Sertain level (e.g., the car starts moving which activates
the schema with a certain intensity above the threshold).
When, some other (lower-level) schema is activated (e.g.,
by a phone signal), the original schema may be retained,
but is allowed a certain time interval to try to reach the
goal of the lower-level schema (e.g., to answer the
phone). However the higher-level schema is still active
and only a certain limited time interval is normally al-
lowed to carry out the lower-level schema (of answering
the phone). Most of the schemas in driving are auto-
matic and only partly available to conscious control, in
particular lower level schemas on the operational level.
A lower-level schema like answering the phone may
seriously disrupt the higher-level schema of driving a car
safely.

In this paper, we make some simplifying distinctions
of human information processing and action by dividing
them into the input, central and output system components.
This will be done to make the later analyses of the re-
search simpler and more transparent (cf., Wickens and
Hollands 2000). There are four main contexts within
traffic research where human factor aspects are studied;
in laboratories, in simulators, in field and test track
studies, and in epidemiological studies. These
approaches will be covered in the following after an
introduction about the use of mobile phones when
driving.

2 Mobile phone use in cars

Mobile phones have permeated all levels of our society
and the number of drivers who use mobile phones is
likely to increase every year in the near future. In the late
nineties, Horberry et al. (2001) reported road exposure
rates of hand-held mobile phones in Australia and com-
pared the results with two occasions (Goodman and
1998 and 1999). A total of 19 locations were used during daylight hours
and the phone use peaked in the morning, with 2% of
the drivers phoning, and decreased over the day result-
ing in an overall average of 1.5%.

In 1998, about 50% of the drivers in Norway used
mobile phones in the car (Sagberg 1999) where 20% of
the drivers used hands-free and 80% hand-held phones.
About two in three mobile phone users called out less
than once a day and hands-free drivers used the phone
more frequently than drivers with hand-held phones.

In Finland, Lambe et al. (2001) reported that in 1998
56% of the drivers used mobile phones while driving and
that percentage increased to 68% in the following year.
In Sweden, Thulin and Ljungblad (2001) found that
59% of drivers had mobile phones and 30% of them
used the phones while driving (18% of the driving
population) in 1998. The researchers estimated that
about 2% of total driving time was done while using a
how mobile phones in Australia were used in the context
of hazards, emergencies and accidents using a random
national telephone survey. The results (referring to
1987–1997) showed that 65% called ahead about being
late and 66% that they calmed down or slowed down
after such a call. Dangerous situations had been com-
municated over the mobile phone by 28% of the
respondents and 12% had reported accidents in the
same way. About 5% of the calls to the emergency
number came from mobile phones in Australia in 1997.

Cain and Burris (1999) reported that in September
of 1998 there were 68 million subscribers to mobile phones
in USA. Over the years the ratio business/private calls
has decreased from 1.5 (1990) to about 0.35 (1998). Only
about one in four drivers report that they use the phone
every second trip or more when driving. About 40% of
the respondents said that they had used the phone to call
for help for another’s disabled vehicle and 40% reported
the same for their own vehicle. The mobile phone had
been used by 25% of the respondents to call for assis-
tance in medical emergencies. Goodman et al. (1999)
report from survey data that 85% of the US mobile
phone users also use the phones in cars some times while
driving and 27% that they use the phones on half or more of their trips. In summary, mobile phone use is increasing and they are often used in different kinds of emergencies.

3 Laboratory studies

In this section we focus on some laboratory studies relevant for driving and mobile phoning. Some of the studies use experimental contexts with some elements similar to road contexts, but these contexts were not advanced enough to be classified as simulator studies.

We will first present studies of driver perceptual input components followed by investigations that include central processing components and thereafter studies of psychomotor output of relevance for mobile phoning and driving.

3.1 Information input components

McKnight and McKnight (1993) investigated the effects of mobile phone conversations of different complexity on attention using a video with a sequence of highway driving situations. The participants used simple modes of responding to indicate how they thought they would react in a real situation. The mobile phone was of a simulated hands-free type for receiving but not for placing calls. There were four different conditions in addition to the main task of responding to the video situations: (1) radio tuning (control condition), (2) call placing (the participant's home phone number), (3) "casual conversation" (uncontrolled, e.g., about what the participant did for a living, what to do the next free time etc) and (4) "intense conversation" (solving algebraic problems and short term memory problems). The mean proportions of participants who failed to respond to highway traffic situations were 0.44, 0.41, 0.41 and 0.44 in the four conditions. When no extra task was introduced the corresponding number was 0.34. Although small in number, the difference between radio tuning and intense conversations and the other two conditions was statistically significant. There were no effects of prior experience with mobile phones. The detection task was difficult and partly artificial and the differences in detection rates were relatively small. However, the results do indicate that having a conversation and in particular the nature of a conversation can affect drivers' visual input efficiency in different ways.

Samuelson and Nilsson (1996) presented an overview of research on perceptual attention to peripherally presented information and related it to IT systems in the car. They also summarized references to studies of "head up display" (HUD) presentations of information as compared to "head down display" (HDD) presentations because he driver does not have to shift his/her gaze from the road while focusing on the display. The design of the information (e.g., no colours) and the content (e.g., simple content) is also of crucial importance for reliable HUD transmission of information. HUD presentations also have the advantage of saving time for switching focus from the driving scene to the display as compared to HDD presentations. Keifer (1995) estimated the time saved to be in the range of 200 to 300 ms.

Graham and Carter (2001) investigated the effects of "driving" (tracking) in a laboratory setting and phoning on peripheral target detection. The peripheral target was a "C" shape growing in size over 10 s and located in the upper part of the PC screen used in the tracking task. The researchers reported that tracking and phoning increased the mean detection time for the peripheral target by 200 to 350 ms, depending on phone design, compared to detection time when no phone call was made. The effect took longer for the hands-free speech phone than for the hand-held manually controlled phone, but the former reduced both tracking and detection errors.

McCurley et al. (2002) used eye tracking data to investigate the effects of a mobile phone conversation (a casual conversation about television shows, hobbies etc.). The participants were instructed to react to any change of a scene on a big display in front of them. The researchers found that the number of fixations increased during a phone conversation. Older participants had longer reaction times to changes than younger participants, but were less affected by the causal phone conversation than were the younger participants. Here, ratings of subjective allocation of attention priorities between the tasks would have been informative. Did the older and younger participants prioritise in the same ways in the two conditions?

3.2 Central processing components

Garcia-Larrea et al. (2001) investigated to what extent the increased reaction time to a stimulus of a participant using a mobile phone depends on the impairment of attention and/or response (motor preparedness) subprocesses. The authors used a non-driving situation, in which the participants answered questions in two different calls (one about business conversation, job studies etc, the other about the ongoing experiment, settings, characteristics of stimuli etc). There was a "hands-free" condition with the participant holding the phone to his/her ear with his/her non-dominant hand (the other hand was used to respond to the stimuli through pressing a button). The "hands-free" condition was a loudspeaker and a microphone in the same set in front of the participants. The data analysed were motor reaction times and errors as well as event-related brain potentials (ERPs). The average reaction times were 348, 409 and 418 ms in the no-phone, "hands-free" and phone "hand-held" conditions respectively. Based on a rather complex analysis, the authors concluded that both the attention and response subprocesses are affected by mobile phone...
use and that the response readiness process is affected more in the hand-held than in the hands-free condition, although this difference did not increase the participants' mean reaction time significantly.

In a similar vein, Strayer et al. (2002) investigated the reaction to "traffic" signals in a tracking task. In particular they were interested in finding out whether it was the detection of a signal that was impaired or if it was a suppression of the response that occurred during a mobile phone conversation. Using an implicit memory design they found that they could rule out the suppression of the response alternative hypothesis: it was found that implicit perceptual memory was strong when a conversation was not engaging, but weak when the conversation became more engaging. Thus, a conversation that involves the driver may significantly divert attention from the primary task of driving so that the driver misses other important information.

3.3 Psychomotor output components

Smith (1988, p. 192) cites a study by Kames (1978), stating that tuning a radio to a particular station (using a knob) has the same effect on car driving as dialling a phone number. However, using driver behaviour data, the original paper does not demonstrate this and the result should be interpreted as a hypothesis rather than as a fact. Breen and Hedman (1995) used a tracking task to investigate the effects of conversing over a hands-free mobile phone—"simple conversation" (about current political issues) and "difficult conversation" (a problem solving task with judgments if sentences were logical or illogical and memorisation of first word in last four sentences). A "radio controlling" task was also investigated. The results showed that the radio condition and the psychomotor processes (when receiving and ending calls) affected lateral "road" position deviations most. Driving without an extra task was performed with less lateral position deviations and "collision errors". Just having a phone conversation gave values between these extremes with the difficult conversation producing more lateral deviations and errors.

Strayer and Johnston (2001) used a computer display and a joystick control in a tracking task to mimic driving activities. They tested the effects of speaking over hand-held and hands-free phones on tracking behaviour. They found no difference in effects on tracking depending on whether the phone was hand-held or hands-free. The reaction time to "traffic signals" increased by 50 ms, from an average of about 535 to 585 ms when the participants had a phone conversation. When an easy phone conversation (shadowing the other speaker) and a more complex one (word generation) were analysed, the more complex task caused more tracking errors and in particular when the tracking task was more difficult.

Graham and Carter (2001) also used a tracking task to measure driving related skills, the difficulty of which was calibrated to real driving in terms of subjectively rated mental effort. They tested how different mobile phone designs affected "driving" (e.g., deviations from track), attention (e.g., detection of stimuli on the PC screen). The phones had different interfaces (1) standard button phone ("manual"), (2) speech recognition with auditory feedback ("speech-audio") and (3) speech recognition with auditory feedback plus a visual display ("speech combined"). For the speech recognition phone conditions there were three levels of accuracy (0, 3 or 6% errors added).

The results showed that tracking performance was impaired and that the manual condition was worse than the other phone conditions. Actually, the results (in terms of deviations from the track) indicate that just waiting for a manual mobile phone call impairs the quality of driving (Graham and Carter 2001; Fig. 1 p. 38). Phones with both audio and visual feedback ("speech combined") impaired driving slightly more than phones with only auditory feedback. Measuring the time from the start of dialling until a connection had been reached showed that the manual dialling was faster than speech audio and speech combined dialling both while driving and when not driving. Driving increased the manual dialling time from about 10 to about 22 s. The speech recognition systems took longer both with and without driving. Note, however, that this system processed one digit at a time and there was no name associated with a number as a shortcut. Driving increased the dialling time from about 28 to about 34 s for both the speech audio and speech combined conditions. The time of distraction was longer for the voice-controlled device, which may have decreased the apparent advantage of this kind of phone. The acceptance of voice-controlled phones was high and this included also imperfect systems making recognition errors.

From the laboratory studies it is clear that talking over a mobile phone requires significant energetic resources that could otherwise be allocated to visual attention and this leads to impairments of visual detection capacity. Talking over a mobile phone may also impair response readiness, that is, the possibility to react to an incoming stimulus and control a focal activity. Using a mobile phone increases reaction times to other stimuli compared with a no phone condition with 50 to 200 ms in laboratory settings. The time of dialling varies between different mobile phone systems and numbers and between 10 s and about 40 s are needed for dialling. Mounting information displays "head up" saves time compared to a "head down mounting" (saving 200 to 300 ms).

4 Simulator studies

4.1 Information input components

Voice driven dialling systems do not always identify the correct number. Still, voice driven dialling systems have been found to be quite efficient for up to a maximum of
10% errors (Ross, 1950), higher than the percentages investigated in the laboratory studies summarised in the previous section. Ross also found that verbal feedback (e.g., “seven”) to the driver decreased the dailing time in comparison with the faster tone feedback (e.g., “beep”). Voice driven dailing systems require the driver to move his/her attention to a memory search for the telephone number to be dialled which is a knowledge based function and also mentally taxing per se.

Strayer et al. (2002) used a simulator to investigate the effects of a hands-free mobile phone conversation on visual awareness. Visual awareness was measured as explicit recognition memory for billboards in simulator driving and as implicit memory for words presented at the point of fixation in a confirmatory laboratory experiment with the same mobile phone conversation. The results showed that explicit memory for billboards presented decreased from about 6.8 to 3.6 billboards and that implicit perceptual memory was also impaired during a mobile phone conversation. This illustrates how mobile phoning draws resources (to auditory and central processes) from the common energetic resource pool affecting both input and processing of visual information.

4.2 Central processing components

Brown et al. (1969) conducted a mobile phone study in a simple simulator. They investigated the effects of a rather complex reversing task transmitted via loudspeakers and responded to via a telephone headset. This extra load on central processing resulted in impaired judgments concerning whether the car would fit into a gap or not as well as increased speed. A surprising result was reported by Alm and Nilsson (1990) who found that braking reaction time when phoning was affected more in an easy driving condition than in a hard driving condition. They suggested an explanation in terms of changes of priorities. In the hard driving condition, the driving was supposed to take over relatively more the mobile phone task to receive relatively less attention resources. Detection of the red signals used to trigger braking was seen as part of the driving task and therefore prioritised accordingly. Alm and Nilsson reported the results of the performance on a memory task, so it is possible to elucidate the hypothesis of changing priorities by analysing the results of the memory task. Unfortunately, the participants’ performance varied a lot in the memory task and in this between subjects design no significant effect was found. Still, the drivers in the hard condition recalled on the average about 12% less items in accordance with the “change of priorities hypothesis”, given that the extra attention needed for hard driving comes from a common attention pool. Self-ratings of workload were higher when the mobile phone was used, but there was no effect of driving condition.

Indeed, centrally governed attention priorities given to different tasks, are very important for the validity of conclusions from all studies on the effects of mobile phones and driving. Using a driving simulator, de Waard et al. (2001) investigated the effects on driving of using a hand-held phone, answering and searching for a telephone number on an alphabetically ordered list clipped on the dashboard. The participants were asked explicitly to give priority to safe driving and there were no crashes reported only crossings of the lane marking. The participants rated that the effort elicited in the simulator increased from an overall rating of “a little effort” when driving normally to “considerable effort” when the phone task was added. Activation increased from 50 to 60 (on a normalised scale from 0 to 100). The results indicated that the participants were fully aware of their impaired driving behaviour. On a scale from 0 (drove very badly) to +100 (drove very well), they rated normal driving as +9 and decreased the rating for the phone condition to −42.

When subjective workload is measured, the results typically indicate higher workload when talking over a mobile phone while driving as compared to just driving (e.g., Alm and Nilsson 1995). Cnossen et al. (2000) asked their simulator drivers to rate mental effort and they also registered heart rate during drives with the instructions to (1) drive fast, (2) as if taking a driving test and (3) as if following a fast car. The results indicated that when an “extra” memory task was added to the driving, heart rate went up and heart rate variability decreased. The heart rate was highest for the fast condition and lowest in the driving test condition with and without the extra memory task. Looking at the performance on the extra memory task it could be assumed that the quality would increase when the driving was requiring less energetic resources in the driving test condition than in the high-speed condition requiring more energetic resources. The quality of the driving improved in the driving test condition, but there was no increase in the quality of the extra memory task. So, the drivers seem not to allocate the extra resources available to the extra memory task. The Cnossen and co-worker study also shows the importance of task priorities in studies of the use of mobile phones and IT in cars.

Alcohol affects central processing and thereby both input and output functions of a driver. Direct line (2002) refers to a study in which the effects of using a mobile phone were compared with those of drinking a (in the UK) barely legal quantity of alcohol. Overall, the results showed that the effects on driving of talking on a mobile phone were more pronounced than those of the alcohol. This study was not, however, reported in a scientific manner even if the actual execution of the study was certainly done professionally. The study is included, nevertheless, to illustrate the issue of driver impairment due to alcohol intoxication on the one hand and impairment due to increased mental workload and distraction from the primary task, on the other. The drivers in this study were of course not talking on mobile
phones all the time when they are driving, while mildly intoxicated drivers tend to remain in the intoxicated state during an entire trip. The difference in exposure makes the comparison of effects complicated and speaks in favour of safer driving with mobile phones than with alcohol.

Haigney and Taylor (2001) reported that mean heart rate increased less when drivers were driving with an automatic gearshift transmission and added a mobile phone call than when they drove a manual gearshift simulator and added a call. Tokunaga et al. (2002) presented a graph showing a positive correlation between measures of subjective mental workload and reaction times for a number of activities that can take place in a car (e.g., drinking, using the radio, the mobile phone). The measures came from a driving simulator study and gave the highest subjective mental workload for “to place a call using a hand-held mobile phone”.

4.3 Psychomotor output components

Kames (1978) used an early simulator and investigated the effects of different phone dialing pads on driving but did not find any significant effects on secondary task performance. Zwahlen et al. (1985) investigated the effects of the position in which the phone was mounted in a car. They found that a low position gave greater lateral driving deviations than a high mounting position. Dialing 11 digits decreased driving quality substantially in their study.

In the Alm and Nilsson (1990) simulator study, the effect of using a mobile phone mounted on the dashboard at the height of the steering wheel. The results showed that when the driving route was easy, the phone conversation increased the brake reaction time by about 400 ms (from about 950 ms to about 1350 ms). However, when the driving task was hard, there was no such difference (Alm and Nilsson 1994). This result can be explained, along with earlier findings in the present review, in terms of attention priority changes. The mean lateral position in the simulator varied from about 1.4 m (no phone) to 1.7 m (with phone) for both easy and hard driving.

Using the same simulator as in the previous study but with more traffic, Alm and Nilsson (1993) studied the effects of solving problems given in a hands-free mobile phone on braking reaction time, headway and lateral position. The participants were forced into a car following context and 16 times during a session they had to respond as quickly as possible. This was arranged by using a sophisticated way of controlling and adjusting the simulator to each participant while on route. The results showed that the participants had longer braking reaction times (in response to a lead vehicle braking in front of the participant’s car) when they were phoning. The longer braking reaction time was not compensated through a choice of slower speed and/or a longer average headway distance. The average minimum headway distance was also shorter during the mobile phone task than in the control condition. Older drivers drove more slowly and kept longer headway distances than younger drivers, but the older drivers also had shorter headway distances when they were solving problems over the phone than when they drove in the control condition. This study shows that the drivers did not adjust their speeds and/or headway distances to match their longer braking reaction times while talking over a phone. In other words, they did not compensate for the increased risk by choosing longer headways.

In a study by Reed and Green (1999) 12 participant drivers made mobile phone calls on a modified hand-held mobile phone. The mean lateral position was (from left edge of the lane-driving to the right (traffic) 1.62 (0.33) m reaction time and the highest subjective mental workload for “to place a call using a hand-held mobile phone”.

Haigney et al. (2000) used a driving simulator and their study showed that using a mobile phone was associated with lower speed and standard deviation of the accelerator pedal travel. In addition, the control of the car was poorer (the car was off the road significantly more often) with a hand-held phone than with a hands-free phone.

Hand-held mobile phones interfere not only with cognitive processes used in driving but also with manual control of a car and in particular with manual gear-shifting. Haigney and Taylor (2001) performed a series of studies in which, the mean following distance was shorter when driving with an automatic gearshift than when driving with a manual gearshift. Using a hands-free phone did not significantly change that distance when driving an automatic car (but it increased marginally) in comparison to a manual car, in which the hands-free condition tended to decrease the following distance (and did not enough to reach statistical significance). Unfortunately, these effects were not statistically significant with the restricted number of participants of
the study (30), but still worth notice and a follow-up study. The speed during a phone call decreased in comparison with the before and after periods for all phone and gear shift combinations.

Strayer et al. (2002, experiment 2) studied the effects of mobile phone conversation on driving in a simulator with vehicle dynamics, traffic scenario and road surface software. The participants were instructed to follow a lead or pace car on a freeway (about 70 km multi-lane beltway with on and off ramps, overpasses and two and three lane traffic in each direction) with different levels of traffic intensity. The pace car was programmed to brake at several randomly selected intervals during a trial. The mobile phone conversation was not varied when driving and talking (hands-free, the call was already started when the measurement started). The results showed that talking using the mobile phone. The brakeness were (1) by 29 ms: from 928 ms to 957 ms (phone conversation) is the low traffic density condition and by 179 ms from 933 ms to 1,112 ms in the high traffic density condition.

Using a hand-held phone, de Waard et al. (2001) investigated the effects on driving of answering and searching for a telephone number on an alphabetically ordered list clipped on the dashboard. The results showed that lateral position standard deviation increased from 0.22 m in the normal driving task to 0.29 m when the phone task was added. The amplitude of the steering wheel movements increased from normal driving and the standard deviation almost doubled. Crossing the lane marking with two wheels tripled when the driver looked up a number in the “phone book”.

Parkes and Hoolmejeer (2001) used rural road driving in a simulator with mobile phone conversations (answering numerical and verbal memory as well as arithmetic and verbal reasoning). They found that their participants reacted to a stop signal in 1.370 s without phone conversation and in 1.421 s when they were having a phone call. However, this small difference was associated with a different deceleration pattern to reach a speed limit. When the drivers phoned, they did not adapt their speed to the speed limit as quickly as when they did not phone. A most important and striking effect was that when drivers were phoning they became much less aware of the traffic environment and the traffic situation.

Salvucci and Macura (2002) found that for participants who drove in a simulator and used a phone including dialling, the mean lateral deviation increased from normal driving (of about 0.37 m) to menu and manual phoning (of about 0.49 m). Using the voice-controlled mode did not significantly change the mean lateral deviation from the no-phone condition although there was a slight difference favouring the no phone condition.

Fuse et al. (2003) investigated the effects of different phone tasks on driving performance, (1) driving, (2) making a phone call and looking at the phone while driving, (3) picking up the phone from the front passenger seat and looking at the phone, (4) picking up the phone from the passenger seat without looking at it, (5) picking up the phone from a bag on the front seat and looking at the bag and phone and (6) picking up the phone from a bag without looking. The researchers measured the time from presentation of an extra light mounted on the windshield until the participant pressed the braking pedal. They found that looking at the phone when picking it up delayed braking reaction time by about 600 ms. The number of participants was small and the results would have to be validated in other studies, but the problems are fundamental to all research on mobile phones and driving.

In summary, simulator studies indicate that using a mobile phone when driving decreases visual awareness, increases reaction times to braking (30-600 ms) and delays speed adaptation. It also increases the frequency and amplitude of steering and accelerator movements. This results in greater lateral acceleration and standard deviations of lateral position on the road. A typical increase in standard deviation of lateral position would be about 0.3 m to about 0.4 m. This means that in 32% of the cases the driver is more than 0.4 m from the main track on the road that he normally follows. When the driver does not use a phone he is more than 0.4 m from the main track in only 9% of the cases. Generally speaking, heavier traffic increases these disturbances of driving (e.g., prolongs braking reaction time with about 150 ms compared to low traffic) even though there seems to be some possibilities to mobilise extra effort to compensate for the extra load of heavy traffic driving in some situations. Headway distance increases when phoning, but the increase is not big enough to compensate for the increased reaction time caused by using a mobile phone.

5 Field and test track studies

5.1 Information input components

In line with contemporary psychological research, Miura (1995) found that the more complex the driving on a road the more narrowing of the driver’s visual field. Wikman et al. (1999) also addressed the issue of allocation of visual attention. They investigated the effects of IT equipment, learning and driver experience on driver attention. A total of 47 participants drove 126 km (about 3 h with a coffee brake) including city streets and roads of different standards. After about 1.5 h a cassette player task was introduced and shortly after this a mobile phone task. On the motorway, a participant was asked to take a hand-held mobile phone and dial his or her home phone number. After this he or she was asked to dial two other numbers dictated to him or her by the experimenter in the car. A radio task followed before the mobile phone task with the dialling of the three numbers repeated again.
The results showed that glances related to the extra task were longer for the radio task, 1,020 ms (to search for a radio station with soft music with the radio initially set so that the task would take time) than for the mobile phone task of 960 ms. The glances for the mobile phone task was longer than for the cassette task of 910 ms. All the differences were statistically significant. For experienced drivers, the standard deviation of glance length was smaller than for novice drivers. There were a greater number of long in-car glance durations (greater than 1,700 ms) for novices than for experienced drivers and more glances for experienced drivers than for novices. There were no in-car glances longer than 3,000 ms for experienced drivers, but 29% of the novices’ glances were longer than 3000 ms. However, the novices also had a greater number of very short glances than the experienced drivers.

Novices left the main attention scheme of driving for longer periods of time than experienced drivers. When the novices left the main task for more than about 2,250 ms, their average lateral displacement on the road increased drastically and was much greater than the displacement of experienced drivers. The study gives a very valuable insight into the differences between experienced and inexperienced drivers. The mobile phone calls were made on the motorway and it would have been interesting also to know about behaviour in city traffic.

Recarte and Nunes (2000) studied visual search characteristics of drivers who drove 84 km on highways and roads. While driving, the participants performed two verbal tasks and two spatial imagery tasks. In comparison with the mobile phone conversations used in most studies of mobile phoning and driving, these tasks correspond to complex and engaging conversations. The results showed that compared with ordinary driving the visual functional field size decreased horizontally and vertically and in particular when the drivers were performing spatial imagery complex tasks. Compared with ordinary driving, fixations were longer during the spatial imagery complex task. When a verbal task was performed, the fixations were shorter than in the spatial imagery complex condition. When performing a mental task, the gaze direction rose. The glance frequency at mirrors and speedometer decreased during the spatial imagery task. Again, this shows that the energetic resources needed by mobile phone conversations may not only detract resources from the processing of sensory information, but also change the input of sensory information. This would be particularly evident when a conversation involves any kind of spatial representations.

Harbluk et al. (2002) had 21 participants drive on a 4 km stretch of a busy 4-lane city road on which each driver drove a total of 8 km north and back for each condition. The posted speed limit was 50 km/h. The drivers’ workload was increased by having them talk on a mobile phone that was mounted on the dashboard with a pillar mounted microphone and a speaker mounted under the dashboard. The phone was completely hands-free. The experimenter sat next to the driver in the front seat and a research assistant called from the base and gave the driver simple addition problems (e.g., 6+4-9) or difficult ones (e.g., 47+38). The eye recording equipment included a eye tracking system connected to a video camera. The results showed that the drivers made significantly fewer saccades (high-speed eye movements facilitating the exploration of the visual field) per time unit as the phone task increased in complexity. The simple task was not significantly different from just driving.

The visual field search was measured through dividing the visual field (on the video recording) into central (15% of the windscreen area) and the left and right periphery areas. The results showed that, the central area was given on the average 79% of the time when the participant only drove the car. When the driver was solving simple problems the time increased to 81% and when he or she solved complex problems the time increased to 83%. The time spent on watching at mirrors and instruments decreased when complexity increased from the driving only condition over the simple to the difficult task. Thus, the findings illustrate a visual “tunnel effect” of the extra load on the driver. Tokunaga et al. (2003) reported, in a rather preliminary and tentative report, that mental workload increased while the drivers had a phone conversation. The driver’s experience with mobile phones had no effect on reaction time.

Patten, Kircher et al. (2004) had 40 participants, who drove on a motorway route of about 74 km long. A within-subject design was used where all participants used hands-free and hand-held phones and were engaged in simple and complex conversations. A secondary task, the peripheral detection task, was used to gauge the varying levels of cognitive workload in the different conditions. Patten et al. found that the effect of the conversation per se, and its relative complexity, greatly increased reaction times. That is, the level of complexity of the conversation affected reaction times; when the conversation’s complexity was increased, the drivers’ reaction times were also increased. Moreover, despite the use of a relatively sensitive measure of cognitive workload, no significant difference was found between the hands free telephone mode and the hand-held mode of use. This underlines earlier results and suggests that the widely held, Isyam belief, in the safety benefits of hands free conversations, may well be folly. A hands free conversation should not necessarily be characterised as a relatively risk-free undertaking when combined with driving.
et al. 1991; Patten et al. 2004; Tokunaga et al. 2001). To illustrate, Tokunaga et al. (2001) measured subjective workload and showed that receiving a call and operating the phone and having a simple conversation demanded more effort than just driving. The complex conversation was judged significantly more demanding than the other conditions. In the complex condition, the older drivers gave lower average workload ratings than the younger drivers. This shows that drivers are aware of the mental load added when using a mobile phone. But do they have sufficient knowledge about the effects on driving?

Ahn and Nilsson (1985) investigated the perceived risks of using a mobile phone concerning navigation, interaction with other traffic, operating the vehicle, driving speed and rule following. Of the 1156 respondents 47% thought that using the phone while driving affects traffic safety, but 62% thought that safety was affected. We will return to studies on risk perception, mobile phones and driving later in this paper.

5.3 Psychomotor output components

Parkes et al. (1993) had 18 participants employed at a research institute drive on a motorway. The telephone conversations involved the drivers in mental arithmetic and memory problems. There were no effects on driver behaviour in terms of speed, lane change or accelerator operations. The study does not report any numbers on these parameters. The increase in subjective workload reported can be assumed to explain that these driving parameters did not change. Despite the extra energetic resources taxed by the mobile phone call, there were enough resources available for extra mobilization of effort by these drivers.

Hancock et al. (1999) used a test track to investigate the effects of keeping an unknown seven digit phone number in memory, while driving a car. The drivers were tested on the memory of the number while driving and also at the end of a rest loop. In one condition, the participants received a mobile phone call (a digit appeared on the screen and the participants had to respond whether the digit was the first digit of the memorised number or not) while driving towards an intersection with a traffic light. The drivers were asked to drive at 20 mph or 30 mph. The driving performance was measured through the participants’ brake response times to the change of a traffic signal. The participants worked under reward penalty patterns (e.g., braking in front of the red stop light gave the same reward, US$ 1.00 as the penalty for missing it—a false call braking cost US$ 0.50). There was no distracting traffic and the test track was the same every time the drivers approached the intersection. The results showed that brake response time increased from 61 ms to 930 ms when there was a phone call. The stopping time increased from 2.500 ms to 4.300 ms when there was a distracter. However, the stopping distance decreased when there was a phone call. This means that the drivers started braking later and compensated for this with a very intense braking reaction. When the speed was higher the response time was faster (average of 680 ms) than when the speed was low (average of 780 ms). However, in comparison with the low speed condition, the faster reaction time in the high speed condition was not fast enough to keep the same distance travelled until the onset of the brakes. If a driver brakes suddenly and very hard this can cause problems for him/her self (e.g., skidding) and for following cars (with drivers not able to react in time). Although, the researchers assume that the drivers worked under rather heavy workload, this can be questioned when compared to other studies and average real traffic conditions with higher speeds, more complex tasks, and/or more traffic.

Reed and Green (1999) who also studied the effects of placing a phone call while driving, this time on a motorway found that their drivers made slightly more frequent, but much larger steering corrections than when they did not phone. The effect of this was larger standard deviations of lateral position on the road. Lembre et al. (1999) investigated detection and braking ability in response to a lead car that started to decelerate, while the drivers were continuously dialling series of numbers on a mobile phone. The researchers found that at a speed of 80 km/h, the detection time was impaired by about 500 ms and the time-to-collision by about 1000 ms. The result was about the same when the drivers performed a memory and addition task.

Brookhuis et al. (1991) investigated the effects of using a mobile phone while driving in a study with 1 h of driving every working day during 3 weeks. The drivers had no experience with mobile phones before the investigation started. They drove on a quite rural road, a busy ring road and in a town. The phone was either hard-held or hands-free and the communication consisted of solving a paced serial addition task. The driving took place in real traffic and the participants were asked to follow a lead car that occasionally braked so that the brake reaction time of a participant could be measured. The standard deviations of lateral position varied between 0.19 m and 0.24 m. When phoning on a rural road there was a significant decrease in standard deviation. However, the reaction time of speed decrease in response to a change of speed of the lead car increased by 600 ms when the telephone signalled that there was a phone call to be answered. This difference was highly significant. The reaction time to the brake signal of the car in front was delayed by 130 ms, which did not exhibit statistical significance. Considering the fact that only 12 drivers participated in the study, the latter result is likely to reflect poor power of the statistical test. Steering wheel movements were “violent before the actual contact was made” (Brookhuis et al. 1991, p. 312) for the hard-held phone and increased for those receiving a phone call. Mental workload was measured through heart rate and subjective measures and indicated higher workload while phoning compared to just driving. The
participants showed strong learning effects concerning the results on the telephone problems. It would have been interesting to follow the development of driving and telephone handling skills over the three week long experiment. Unfortunately, the article does not offer this information.

Harbluk et al. (2002) investigated the braking performance of their drivers while driving, driving with easy addition and difficult addition respectively. They found that the more complex the situation the greater the frequency of hard braking episodes. It was found that participants who changed their gaze pattern most as a result of the phone task also tended to brake harder. It should be noted that solving problems is sometimes associated with certain gaze patterns (looking up to the left), in particular if the solution is mediated through spatial information processes (Kinsbourne 1974).

In summary, field and test track studies have shown that glances away from the driving scene vary more and are longer for novice drivers than for experienced drivers, with a greater number of long-in-car glances (greater than 1,700 ms) for the novices. No experienced driver spent more than 3,000 ms on a glance in a car, while novices had 29% of their in-car glances longer than 3,000 ms. There was a clear visual "tunnel effect" as a result of a difficult phone conversation and a decreasing frequency of saccades. Lowering the speed in response to a lead car changing speeds was satisfactory when using the phone, but if a speed change coincided with a telephone signal, a reaction delay of 500-600 ms appeared. Reaction time to a braking signal of a car in front of the driver increased the reaction time by about 130 ms when the driver used a mobile phone. There were more frequent and greater steering manoeuvres as well as longer fixations when phoning and driving compared to just driving.

6 Epidemiological studies

This section will first present some epidemiological studies with analyses of real accidents sampled from accident protocols and statistics. Following this, we will comment on the limitations of such studies in terms of conclusions about causes and risks. Following this, we will present some epidemiological studies in which the researchers have applied statistical control to reach more conclusive results concerning causal relationships.

Wierwille and Tijerina (1996) studied an accident database and if the driver was dividing her or his attention when the accident happened. Specifically, the driver could attend to something in the car (e.g., a tape cassette that was dropped on the floor) or outside the car not directly related to the immediate control of the car. Of a total of 189,464 accident narratives from 1989 they found 14,372 narratives that contained words related to what the driver was attending to or did in the car. The study included data from 1992 and included accidents in which (1) a driver’s vision was directed away from the forward scene and/or (2) the visual allocation process was judged to be the primary cause of the accident. This resulted in 2,816 relevant citations and of these 1,562 indicated that the driver had had his or her attention in the vehicle and 661 attention towards something outside the vehicle (e.g., searching for a street number). The remaining 593 cases had an unspecified notation, e.g., the driver looked somewhere else (and ran through the red light). Wierwille and Tijerina (1996) listed a number of conclusions based on the 1989 and 1992 data including the following (partly phrased somewhat differently here): (1) Visual allocation into the vehicle is a contributing causal factor in numerous accidents, (2) Introduction of additional items (e.g., mobile phones) while the vehicle is in motion can be expected to cause increases in accident rates and (3) Driver interaction and need for immediate attention with the following objects in the vehicle cannot be expected to cause increases in accident rates and (4) Driver interaction and need for immediate attention with the following objects in the vehicle cannot be expected to cause increases in accident rates and (5) Driver interaction and need for immediate attention with the following objects in the vehicle cannot be expected to cause increases in accident rates.

Murray et al. (2001) investigated accidents that had driver inattention as one contributing factor and the specific coding of distraction by children aged 2 to 4 years. Of the 10,166 accidents in Texas 1990, that were related to driver inattention, 121 accidents involved children in the moving car that triggered the accident. Of these 121 accidents 57% involved distraction from the 2-4 year old passenger. However, the study does not give information about how many trips that were made with children aged 2-4 in total and with children of other ages etc or in how many trips the driver was distracted without an accident happening. Instead of attempting to collect this type of information, the authors computed the odds (ratios of frequencies) that an accident with inattention as a contributing factor would have a child below 12 in the car. They compute the odds and compare it with the odds that any passenger would be in the car when the accident with inattention occurred. However, the comparison of these odds does not tell us the complete causal story of the risks as long as the odds are not adjusted for exposures in real traffic.

Violanti and Marshall (1996) compared a group of 100 randomly selected drivers involved in recorded accidents over a 2 year period with a group of randomly selected drivers not involved in recorded accidents the last 10 years. The researchers used the median time per month each driver had used his or her mobile telephone (through records of the billings) to match the groups. The researchers reported that of those who had been in an accident 13% used cellular phones while driving and of those who had not, 9% used phones. However, the samples were small so no statistical difference between these numbers could be found. Cher et al. (1999) criticize an epidemiological study of mobile phones and fatal collisions by Violanti (1990). Violante based his conclusions on five fatalities from a total of 1,548 incidents. His findings cannot be interpreted as causally valid and Cher et al. raise some important points concerning data treatment and conclusions in epidemiological studies.
In addition, it is important to keep in mind that designs with sampling and analyses of accidents cannot normally be used for drawing conclusions about causal relationships. Even if the difference between 15% and 9% in the Violanti and Marshall study had been significant, the percentages represent different measures of the exposure to the dependent variable of accidents; here, the exposure on the road is assumed to grow proportionally with the total number of mobile phones in use.

The study by Redelmeier and Tibshirani (1997) is the by far most well-known, carefully designed, most cited, discussed and criticized epidemiological study of mobile phones and accidents. The study involved 669 drivers in Toronto who had mobile phones and who were involved in a nonfatal accident. The drivers' mobile telephone calls were monitored and categorized as to mobile phone or not. That is, P(T) = (accident | mobile phone) and P(NT) = (accident | not mobile phone). But to get P(T) and P(NT) we need a sample from the whole population of drivers, not the accident samples used by, for example, Violanti and Marshall that only involved drivers with mobile phones.

To compensate for the problem of sampling on the dependent variable, Violanti and Marshall (1996) used a frequentist method for estimating the variances and the sample size of the study. The authors used a logit model to estimate the odds of an accident in relation to mobile phone use. The authors reported a statistically significant association between the variables of using a cellular phone (more or less than 50 min per month) and having a traffic accident. The ratio between the frequency of accidents for drivers talking more than 50 min on the phone and the frequency for drivers talking less than 50 min was 5.59. This does not mean that if one restricts talking over a phone to less than 50 min, the risk of having an accident will decrease 5.59 times. But, it means that there is a positive association between the variables for the selected 200 drivers and that no definite conclusions about the absolute strength of the causal relation can be drawn that is valid for all drivers.

In 1997, the US National Highway Traffic Safety Administration (NHTSA, 1997) issued a report on the investigation of the safety implications of mobile phones in cars. In particular, the report analysed police crash report data related to mobile phones (North Carolina 1989, 1992-94 and half of 1995). The results showed that the number of reports that contain a reference to a mobile phone was rather small as was shown by Wierwille and Tijerina (1996), for example, 522/127 328 (0.4%) in 1995. The report gives numbers of mobile phones used in the USA as well as the number of reports with mobile phones for the years of 1989, 1992, 1993, 1994 and 1995. The authors use these data to predict the number of reports with mobile phones mentioned as a contributing factor and find that the number of mobile phone related crashes increase with the number of mobile phones in use in the USA. This is one attempt to overcome the problems with samples drawn on the dependent variable of accidents; here, the exposure on the road is assumed to grow proportionally with the total number of mobile phones in use.

Stevens and Minton (2001) studied police reports of fatal accidents in England. They found that of the 7,740 accident during 1989 to 1995, a total of 101 were classified as "distraction" cases (about 2%). Among these, "interaction with passengers" (26%) and "manipulation of car radio/cassette player" (19%) had the highest frequencies of fatal "distraction" accidents. Mobile phone had only a few classifications (3%). For vehicles in general traffic about 38% carried at least one passenger. In the sample of fatal accidents 34% involved cars with at least one passenger. Of the fatal accidents classified as "distraction" 47% involved a car with one or more passengers. Because, passenger distraction cannot explain the other 53% of the accidents, the proportion (number of "passenger interaction" accidents)/(number of "distraction" accidents) 26% underestimates the true risk of passenger interaction in relation to other true risks when there is a passenger in the car. But there was no information available about the other risks, such as mobile phoning, so they could therefore not be checked in the same way as the passenger interaction because of lack of exposure data.

Sagberg (1995) used estimated exposures in traffic and computed the relative risk as the proportion of multi vehicle accidents in presence of a mobile phone call.
divided by the estimated exposure of driving while phoning. His conclusions gave an estimate of the risk of an accident as about twice as high when a telephone is used compared when it is not used. There were no differences between hand-held and hands-free phones. Although, the logic of Sagberg’s work is without objection his study, like that of Redelmeier and Tibshirani (1997) also has some uncertainties concerning absolute numbers. However, at this moment, it is reasonable to assume that the use of a mobile phone when driving increases the risk of an incident/accident two to four times compared to just driving.

7 Mobile phones, driving and risk perception

Perceived risks are important because drivers adjust their driving in response to how risky they perceive the primary and/or a secondary task. If the secondary task is perceived as risky, a driver may slow down, select a longer headway distance etc. Using a mobile phone in a car follows a decision motivated by its benefits that may be exaggerated compared to its risks that may be underestimated (Svenson 1992, 1996). Unfortunately, we know from empirical studies that drivers sometimes seem too optimistic about their own risks and driving skills (Svenson 1980).

In USA National Highway Transportation Safety Administration (NHTSA 1997) presented an overview of how, when and why drivers use mobile phones on the road partly based on some of the studies covered in this section. Smith (1988) asked drivers to judge the magnitude of (subjectively perceived) risk of different activities while driving (1 = not at all to 10 extremely dangerous) and the results were the following: Reading a map (7.7), Writing something down (7.0), Dialing the mobile telephone (5.2), Looking at street numbers to locate an address (4.6), Drinking coffee or other beverages (4.4), Getting change from pocket or purse to pay tolls (4.3), Lighting a cigarette (4.1). Using a dictating machine (3.8), Putting the handset back to its cradle (2.7), Turning the car radio (2.4), Conversing with other people in the car (2.3), Adjusting the car heater or air conditioner (2.3), Picking up the handset (2.1), Conversing on the mobile telephone (2.0), Hearing the mobile telephone ring (1.6). It is interesting to note that conversing on the mobile phone is judged to be the next to the least risky activity, while dialing the phone is considered a highly risky activity. This indicates that drivers seem to understand the disturbing effects of handling a phone and placing a call but that they do not understand the magnitude of the disturbing effects of talking over a phone or waiting for a call.

Mikkonen and Backman (1988) reported that inexperienced car phone users found mobile phoning seriously affecting driving and increasing risk, while more experienced phone users responded that the effects are minor. In an international survey of the view of organisations related to transportation, (Petcas and Bluet 1989) found that two thirds of those who responded considered the use of a mobile phone in a car while driving potentially hazardous and particularly risky when the phone was a hand-held device. In Great Britain, a NOP poll (Stevens and Paulo 1997), with a sample drawn from all adults, indicated that 92% felt it unsafe for drivers to use hand-held phones while driving and 55% felt that hands-free phones are unsafe for use while driving. Considering the “are we all better drivers effect” (Svenson 1980), these numbers can be expected to decrease for risk estimates concerning own driving safety.

In a study of university undergraduates in the USA (Dukes et al. 2001) about what causes aggression in traffic (assumed to increase risks), there was no effect of mobile phone use on anger over another’s driving, which leads to the interesting question whether this can be generalised to other populations and countries as well. Petica (1995, p. 1718) gives another view and argues that in real traffic (in France), the use of a mobile phone can be associated with arrogance showing up in more risky driving. In Finland, Lumbe et al. (2001) reported the results from surveys about what people thought about what the governments should do concerning mobile phones. Over 48% of the respondents wanted the government to ban hand-held mobile phones while driving and 27% wanted a ban of all mobile phones while driving. Again, this is an indication that people do not understand the effects of a mobile phone conversation on driving, but that they do realise that motor actions interfere with driving.

8 Age, mobile phones and driving

Generally speaking, when people get older cognitive and motor processes become slower on the average. However there are exceptions for processes within a person’s own expertise and other well learned automated processes. The decrease in speed of cognitive and motor processes, due to ageing, are compensated for by greater experience, better judgment, decision making skills and self-insight; thus posing no great problem when driving a car. To exemplify, an older driver may prefer not to answer a mobile phone in a demanding traffic situation, while a younger driver may answer and take the risk of divided attention, an older person may drive more slowly and the younger person faster etc. However, when the effects of age on driving have been investigated, there has been no room for a participant ignoring or delaying a phone call. Therefore, drivers’ mobile phone habits were not controlled for in the studies reported below.

Using an advanced driving simulator, Nilsson and Aha (1991b) investigated young and old drivers when they were phoning and driving and found that older drivers’ lateral position was more affected (greater standard deviation of target line) than young drivers’ position. The older experienced drivers’ mean brake reaction time to a signal was about 400 ms longer than
younger drivers' reaction time in both the control and in the phone condition.

In Alm and Nilsson (1995), the simulator drivers reacted to a complex traffic situation. This increased the effect on braking reaction time in relation to a less complex situation. In the earlier 1991 study, a telephone task increased the time with 385 ms for young drivers (from about 950 ms) and with 439 ms for drivers above 60 (from about 1,530 ms). In the 1995 study the corresponding increases were 175 ms (from about 1,600 ms) and 1,021 ms (from about 1,900 ms). Thus, increased complexity of the traffic environment tended to increase the braking time more for the older drivers than for the average younger driver. However, the variance of the braking reaction times for older drivers varied considerably, meaning that age alone could not explain the results. These increases were similar to those found on the road by Tokunaga et al. (2001).

McKnight and McNichot (1993) investigated reaction to traffic situations (e.g., slowing down if a lead car slowed down, reacting to a pedestrian stepping out in the street) and found that all phone conversations in particular an intense conversation requiring more central processing caused more problems for the older driver. However, the older participants were less distracted than the younger ones by using the radio (which presumably was a familiar task to them), than by having a conversation over the phone. McCauley et al. (2002) found that older participants' reaction times to changes in a traffic scene (although longer) were less influenced by a causal phone conversation than younger participants. Reed and Green (1999) found that older drivers were more affected than younger drivers by making a phone call in terms of lateral position control in both a laboratory simulator and in a field condition.

Another example of the effects of the age variable can be found in a study by Reed and Green (1999) who published an interesting comparison between simulator (MacAdam et al. 1993) and field conditions with the same 12 participant drivers making mobile phone calls on a modified (Motorola SCN2085) hand-held mobile phone. First, the authors showed that lane keeping correlated in two conditions, but that lane keeping was less precise in the simulator than on the road. The standard deviation of lane position in the normal on-the-road condition without a phone was 0.165 m and the corresponding number in the simulator was about twice as big or 0.356 m. For normal driving, mean lateral speed was 0.050 m/s on the road and 0.138 m/s in the simulator. In the phone condition the corresponding numbers were 0.069 m/s and 0.353 m/s. That is, the difference was more than four times as big in the simulator compared to road conditions.

Second, the effect of making a phone call on lateral position was greater for older drivers than for younger drivers. The greater effect on lateral speed for the older drivers in comparison with the younger drivers was exaggerated in the simulator. Third, speed was monitored quite similarly in the simulator and on-the-road conditions. Fourth, adding a phone call to driving increased the standard deviation of speed from 1.22 in the simulator to 3.00 km/h on the road and no effects of gender or age were significant. The authors draw the conclusion that the simulator (both daylight and night driving versions) showed good validity for speed and for the effects of phoning on driving. Validation studies like the Reed and Green study are not abundant but certainly very important.

Tokunaga et al. (2001) studied driver reaction time and mental effort in 31 participants who drove on a motorway in Japan. The mobile phone was of a hands-free type mounted on the dashboard with an external microphone. There was a lead car (driving about 90 km/h) and an experimental car following. The reaction time of the participant driver was measured as the interval between the onset of the emergency lights on the lead car until the driver pressed a button mounted on the steering wheel.

While driving, a phone call reached the participant driver who had to answer the call through pressing a button. When having a simple (uncontrolled) talk about the driving conditions and navigation or more complex (mental arithmetic) conversation, the emergency lights of the lead car came on and the participant's reaction time was measured. The results showed that the reaction time for the younger subgroup (n = 19, average age = 23.95) of the participants was on average 645 ms and for the older subgroup (n = 10, average age = 62.75) 615 ms when they just drove on the highway. When the participants had a simple conversation the corresponding average reaction times were 850 ms (an increase of 205 ms for the younger group) and 820 ms (increase of 135 ms for the older group). The complex conversation condition gave the reaction times of 970 ms (increase of 325 ms for the younger group) and 990 ms (increase of 305 ms for the older group) respectively. To summarize, Tokunaga et al. (2001) found that older drivers had longer reaction times than younger drivers, but they could not find any interaction between age and message complexity on driver reaction time. The above reaction times for the complex conversation are in the same range as those reported on the test track of Hancock et al. (1999).

9 Discussion

Most of the present paper has focused on the disturbing effects of mobile phones when driving. However, there are also advantages of mobile telephones in the transport system. The benefits of mobile telephones may be viewed from different perspectives; individual benefits and socio-economic or community benefits (Lissy et al. 2000). Some of the societal benefits include faster accident reporting and also more detailed information on accident sites etc., thus improving medical assistance and survival rates. The possibility of real-time reporting of abhorrent behaviour such as suspected drunk driving
also aids apprehension by the police. Some of these benefits are, however, possible to obtain without having the phone switched on whilst driving. Other socio-economic benefits are those of productivity, for e.g., business-related calls. This kind of benefit must be put into a context of a business-related call becoming possible which would not have otherwise been possible. From the individual perspective, being contactable gives peace of mind, may reduce the number and duration of trips and expands possibilities of being 'productive' on a more personal level i.e., private phone calls etc. (Lissy et al. 2009). Other benefits may be that a driver can receive route-guidance information over the phone whilst driving thus supporting the driver and reducing unnecessary detours, reducing an exaggerated visual search for road signs, driver insecurity and stress. When discussing mobile phones and traffic it is important to keep in mind that the disadvantages should be always be compared with the advantages in each particular situation.

The empirical research covered in the present review was performed mainly with a driving performance perspective. The research includes laboratory studies, simulator studies, field and test track studies and epidemiological studies. These methods have their advantages and disadvantages. Haigney and Westernman (2001) presented a critical review of methods used in research on mobile phones and driving. In particular, they emphasised the problems of ecological validity when drawing conclusions from laboratory and simulator studies to every day driving and planning. Experimental laboratory and simulator studies investigating the effects of mobile phones and driving have the advantage of greater control of "driving" conditions and they are performed in order to obtain indisputable results that also generalise to driving in real traffic.

There are a few attempts to validate the generalisation of experimental laboratory and simulator settings used for investigating mobile phones. To exemplify, Graham and Carter (2001) validated their tracking task through calibrating the difficulty of it in terms of subjective effort needed so that it corresponded with the effort of driving a car on the road. Another example of a validation study of a simulator was presented by Reed and Green (1999), who published an interesting comparison between a simulator (MacAdam et al. 1992) and field conditions with the same 12 participant drivers making mobile phone calls in both contexts. The authors showed that lane keeping correlated in the two conditions, but that lane keeping was less precise in the simulator than on the road and the effects of phoning was exaggerated in the simulator. Arguments for the extent to which results in simulators generalise to real traffic can also be found in comparisons across different investigations using simulators or test tracks/real traffic contexts. In general, most modern simulator studies seem to be at least as sensitive as and studies when some effects of mobile phones are studied, such as lane keeping and reaction time measures.

Even though validation may be lacking in many cases, some fundamental fact in the areas of, e.g., human vision, attention and motor reactions are applicable in all situations. Other findings, such as the priorities given to driving and talking respectively do not necessarily generalise from the laboratory to on the road driving conditions. Quite often, the participants are told to answer the telephone, but especially older or expert drivers might ordinarily prefer to defer or avoid answering a phone call in real traffic high workload situations. That attention priorities are different in the simulator than on the road is also illustrated by the more frequent inadvertent road-departure incidents in simulators. Note, however, that the problem of generalising priorities to real traffic conditions cannot be avoided in test track and real traffic investigations either.

Epidemiological studies use real traffic data. There are both problems of collecting data, for example from police reports that may not have uniform and relevant recording categories and of interpreting data, such as, covariances found in accident analyses. Epidemiological studies have been mainly post hoc, studies, such as, incident and accident analyses. Although, for example, analyses of accidents often seem close to real-life facts with a high degree of "face validity", there are problems when attempting to draw valid causal conclusions and in particular when attempting to establish the statistical significance of causal relationships and to estimate them quantitatively. The discrepancy between subjective intuitive interpretations of causal relations in data (intuitive interpretations have a tendency to rely on covariances) and scientific conclusions about causal relationships is a problem. This is because accident data brought to the public and the political eye, may lead to a focus on less important factors and the neglect of more important causal factors.

In summary, using a mobile phone when driving, among other things, disturbs driving through a diminished field of attention, longer detection times to, e.g., changes in dynamic traffic conditions, longer braking reaction-times to brake lights of preceding vehicles and greater lateral deviations on the road. Contrary to what people assume hand-held phones have not been shown to impair driving quality more than hands-free phones. Instead, in contrast with public opinion, the content of a conversation is more important as determining the degree of distraction, complex conversations disturb driving much more than simple conversations. The
distracting effects of mobile phoning while driving are estimated to increase the risk of having an accident in traffic two to four times. Based on the frontline of mobile phone research cited in this paper, banning handheld phones only, would have relatively small effects on safety. Hopefully, future research will provide more detailed knowledge about the differences between handheld and hands-free mobile phones and their specific effects on driving and traffic safety.

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Using mobile telephones: cognitive workload and attention resource allocation

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Abstract

Driver distraction is recognized as being one of the central causes of road traffic incidents and mobile telephones are tangible devices (among many other electronic devices) that can distract the driver through changes in workload. Forty participants completed a motorway route characterized by a low level of road complexity in the form of vehicle handling and information processing. A peripheral detection task (PDT) was employed to gauge mental workload. We compared effects of conversation type (simple versus complex) and telephone mode (hands-free versus hand-held) to baseline conditions. The participants’ reaction times increased significantly when conversing but no benefit of hands-free units over handheld units on rural roads/motorways were found. Thus, in regard to mobile telephones, the content of the conversation was far more important for driving and driver distraction than the type of telephone when driving on a motorway or similar type of road. The more difficult and complex the conversation, the greater the possible negative effect on driver distraction.

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Keywords: Mobile telephones; Hands-free and handheld; Attention resource allocation; Workload

1. Introduction

With the era of the information society upon us, people are given ever-increasing opportunities to send and receive information. However, there are limits to man’s attention, motor and perceptual resources. One recent example of an introduced communication tool is the mobile telephone, also referred to as a cellular telephone or cell phone. The present study will address the use of mobile telephones when driving. In particular, we want to explore mobile phones usage and their effect on cognitive workload and attention resource allocation needed for safe driving.

Evidence from studies of perceptual workload and visuo-cortical processing suggests that perceptual workload can modulate attention focus early in visuo-cortical processing (Handy et al., 2001). Furthermore, Handy et al. (2001) results also suggest that increasing the workload of the foveal targets decreases the amount of residual attention capacity available for allocation to task-irrelevant parafoveal locations. The parafoveal, or peripheral stimuli detection capacity, is important for the driver of a vehicle. If the driver feels a serious decrease of his/her attention capacity for driving the car, then he or she can reduce their vehicle’s speed in a conscious or subconscious compensatory behaviour to the reallocation of their mental resources. Therefore, driving speed and perceptual stimulus detection capacity are important indicators of how mobile phone conversations may affect traffic safety when driving.

McKnight and McKnight (1993) studied conversation complexity and the effects on driver distraction in a low-fidelity driving simulator. Their results indicated that in simulated hands-free telephoning conversations, levels of complexity affected driver distraction. McKnight and McKnight also introduced elements of comparison between different situations such as tuning a radio and placing a call with detection rates that were relatively small but statistically significant. Different levels of secondary tasks and driving situations (e.g. primary task) complexity and their impact on the driver are important elements to be distinguished when considering the impact of ‘secondary tasks’ such as telephoning on driver distraction.
1.1. Purpose

For a decade or so, mobile telephones have been a focal point for traffic safety concerns from researchers and laymen. These traffic safety concerns have, however, had different loci of concern. A wide spread belief has existed, in particular by laymen, that driver distraction caused by mobile telephones lies in the mode of telephone, i.e. hands-free or handheld units. In fact, several OECD countries have even introduced legislation banning the use of handheld mobile telephone units when driving.

Driver distraction is recognized as being one of the central causes of road traffic incidents and mobile telephones are tangible devices (among many other electronic devices) that can distract the driver (Treat et al., 1979; Englund et al., 1998; Harblak et al., 2000; Ahn and Nilsson, 1995; De Waard, 1996; Zaidel et al., 1978; Martens and Van Wijnsum, 2000; see also NHTSA, 2000). Mobile telephone ownership and use has increased dramatically in recent years; from initially being large, cumbersome, expensive devices with exclusivity akin to ownership, to being small, lightweight, inexpensive devices that now have universal ownership. The concern with driver distraction is of course the links to road traffic accidents. Where the causes of road traffic accidents may be many, driver distraction may only be one factor in the chain of many events leading to an accident. Moreover, the loci of the driver distraction may also vary greatly. However, in this study, our focus is on the driver distraction aspect of the competition over mental attention resources where the cognitive or mental workload is high.

The term ‘driver distraction’ would imply that the drivers do things that are not primarily relevant to the driving task (driving safely) and that this disturbs attention needed when driving safely. Consider the fact that humans have the ability of doing more than one thing at a time (e.g. walk and talk at the same time), then the problem of driver distraction for traffic safety must lie in the limitations of human attention resources and how the attention is allocated (prioritized) by the humans in their management of the different tasks, whether they are primary-task related (driving) or not. The allocation of mental resources, attention, is hinged to the different levels of driver (mental) workload (Wickens and Hollands, 2000; De Waard, 1996). Workload is defined as the amount of information processing resources (and limits thereof) used for task performance (Wickens and Hollands, 2000; De Waard, 1996). The purpose of this study was, therefore, to explore the ability of drivers to cope with different levels of cognitive or mental workload that were introduced as secondary tasks and their effect on attention resource allocation. Moreover, the differences between hands-free and handheld mobile telephone units were also explored.

1.2. Scope

The scope of this study is restricted to a real traffic environment on public motorways and using two mobile telephone modes, hands-free and handheld. The hands-free unit had a separate microphone and loudspeaker and the handheld unit was simply held in the driver’s hand while driving. The telephone conversations, per se, were examined and tasks such as dialing and other manual tasks were not included. The conversations were divided into two categories, simple and complex.

2. Method

To evaluate the workload of the participants whilst driving in a real-life field study, we used a secondary task methodology. Here, this means that the participants were asked to perform a high response-frequency parallel task (e.g. peripheral detection task (PDT) method) throughout the entire test route that was not relevant to the primary task of driving. The secondary task acts as an indirect indicator of mental workload. Secondary tasking, as a measure of cognitive workload, has been employed by a number of research groups within transportation research (e.g. Van Wijnsum et al., 1999; Crundall et al., 1999). Driving a vehicle is normally dominated by visual perception demands on attention, that is, ‘successfully’ driving a vehicle in traffic requires large amounts of mental resources (Hills, 1980). This is due to the fact that most of the information for safe driving needs to be gleaned from the driver’s immediate physical environment—assuming that the driver is qualified and experienced. Other sources of information may be auditory, haptic or even olfactory, but to a lesser degree. Additional mental processes that need attention and may reduce attention capacity for driving come from perceptual interpretation, cognition, long-term memory processes, decision selection and decision execution (Wickens and Hollands, 2000). Driving’s close dependency on visual perception suggests that a visual secondary task would be appropriate because according to the multiple task theory (Wickens and Hollands, 2000), any increase or decrease of the visual demand will be more sensitive to changes in workload than to changes through other senses. Attention resources are multiple and in some sense multimodal tasks will only seriously compete for attention resources if the task draws on the same source, e.g. two separate visual tasks. Thus, when two tasks require attention from the same source, the human performance becomes more impeded than two tasks requiring different modes, e.g. visual and auditory (Wickens and Hollands, 2000; Harms and Patten, 2001). The peripheral detection task is a secondary visual task that has shown great sensitivity to mental workload level of drivers (Martens and Van Wijnsum, 1999; Olsson, 2000; Harms and Patten, 2001; Burns et al., 2000).

The route chosen for this field study was characterized by a low level of road complexity in the form of vehicle handling and information processing according to the taxonomy of complexity by Fastenmeier (1995) and van Benda et al. (1983). The road was a motorway section of the E4
(European inter-urban highway no. 4) with a maximum allowed speed of 110 km/h. The total distance used for this study was circa 74 km. The participants started travelling northbound from the city of Linköping to Norrköping (ca.
37 km). The participants turned off the motorway at an appropriate intersection on the E4 and drove the 37 km back to Linköping. The total driving time, including stops for the NASA raw task load index (NASA-TLX) evaluations was approximately 1 h. The NASA-TLX evaluations will be reported in a forthcoming study. (See Hart and Staveland (1988) and Byers et al. (1989) more details of the NASA-TLX and NASA-RTLX respectively.)

An acclimatisation section at the beginning of the route was ca. 7 km, with various speed limits used to make the drivers familiar with the experimental car. This extra-experimental section is not included in the total distance of 74 km, neither was any data from this section included in the data analyses.

The main reason for selecting a motorway section with a low/flow classification, according to the taxonomy by Fastenmeier (1995) and van Benda et al. (1983), was to reduce the amount of ‘noise’ in the experimental data that might otherwise occur. That is, the motorway route chosen would have a low level of interactions with other road-users whom we experimentally would have no control over. Moreover, the data generated would also reflect a best-case scenario from a driver workload/distraction and a traffic safety perspective. Any additional complexity would exacerbate driver workload and thereby even traffic safety risks.

A taxonomic approach to describe information processing demands of traffic situations was proposed by Fastenmeier (1995) as mentioned above. Fastenmeier performed a detailed analysis of the classification scheme for traffic situations developed by van Benda et al. (1983). Fastenmeier highlights the following characteristics of traffic situations as crucial for complexity: the demands they put on drivers’ information processing and/or vehicle handling capabilities. According to this approach, from a driver’s perspective, traffic situations can be subdivided into the following four groups:

1. High demands on information processing and high demands on vehicle handling: Typical examples from this group of situations are “driving within city centres” and complex intersections with road signs where the driver has to give right of way. In this paper, the authors term these route sections as having a “high-high” complexity.

2. High demands on information processing and low demands on vehicle handling: Typical examples from this group of situations occur at intersections regulated by road signs and where the driver has the right of way. Other examples are entering or leaving a highway/motorway. These road sections are termed by the authors as having medium complexity.

3. Low demands on information processing and high demands on vehicle handling: Typical examples from this group of situations occur on older, curvy rural roads or at intersections that are regulated by traffic lights. These road sections are also termed by the authors as having medium complexity.

4. Low demands on information processing and low demands on vehicle handling: Low demands result from all those situations in urban and rural areas and on motorways where ‘free driving’, i.e., without interactions with other traffic participants, is possible. In this paper, the authors refer to these route sections as having a “low-low” complexity.

Definitions of the two telephone modes: Handheld—when a mobile telephone is held in the user’s hand and positioned close to the ear. Hands-free—having a device consisting of a separate microphone and a separate loudspeaker connected to the mobile phone so that it is possible to talk on the phone without using a hand to hold it. However, depressing a button on the telephone itself will activate the telephone.

2.1. Materials and equipment

An instrumented vehicle was used in this study: a Volvo 850S, 2.5 l engine, manual gearbox and the model year 1996. The Volvo, an estate (or station wagon) version was, for the driver, apparently quite ordinary. The driver could not see any of the video cameras; they were concealed and also very small. All of the data collection equipment is in the boot of the Volvo. The sensors, etc., in the car are collected at a rate of 5 Hz and stored in an onboard laptop computer. The vehicle’s cruise control was disabled.

The peripheral detection task equipment was built by Volvo Technical Development Corp.; the mobile telephones were a Nokia, model 6150 with a CARK 91 hands-free unit; the GSR and HRV instruments were from TEMEC (VITA-PORT II).

The PDT equipment had been modified from the most recent PDT study at the Swedish National Road and Transport Research Institute (VTI) together with Volvo Development Corp. The PDT equipment comprised of a display with six red, light emitting diodes (LED) set in a display panel, a modified micro-switch with increased depression-feedback and a computer unit for control, calibration of settings and data logging.

One diode at a time is illuminated, the selection of which is random. In the present study, the interval between illuminations of the LED signal was between 3 and 5 s, also at random within that range. The period of illumination is a maximum of 2 s unless the participant extinguishes the LED signal by depressing the micro-switch.

The light signals from the LED are reflected up onto the windscreen in the form of a head-up display. Prior to experimental trials, the stimulus intensity was adjusted to the individual participants and ambient lighting conditions (sun or
clouds), to make sure that stimulus onsets could be detected while the driver looked out on the road scene. The LED reflections would appear approximately 6.5–21.8° left of the center of the steering wheel and approximately 3.8–5.3° elevated over the car console. The participants' performance was recorded in the form of PDT correct hit rate and their reaction times in milliseconds (ms).

2.2. Participants

The participants selected for this study were professional drivers (taxi drivers, couriers) with at least 3 years of holding a higher classification of drivers license. The age group requirements were from 21 to 60 years age and an annual mileage of at least 15,000 km. Professional drivers were selected because they have an established experience of driving and also usage of information technology (IT) systems in their vehicles, e.g. logistical systems, communication radios and/or mobile telephones. The participants were reimbursed for their participation with 100 € each. Forty participants completed the route. Eight were female and 32 were male. The mean age was 39.6 years and the mean annual mileage was 43,100 km.

2.3. Procedure and design

All the participants were instructed about the experiment and signed informed-consent forms regarding their liability and responsibilities when driving. Video footage consent forms were secured post-experimentally.

The participants were further instructed to drive, as they would 'usually' do, but to keep in mind their legal responsibilities regarding traffic violations. Training was also provided for the PDT and the mobile phone tasks prior to driving. All adjustments of seats, mirrors, coupe temperature and seat belts were done before leaving the VTI garage. Finally, the participants were instructed to prioritize the driving task first and respond to the light signals of the PDT diodes second.

Throughout the entire journey, a VTI technician was present in the test vehicle, sitting behind the driver. His role was to coordinate the phone calls, follow the design protocol, attach electronic markers to the vehicle data at predetermined points, to administer the NASA-RTLX subjective workload protocols and to deal with any problems. The participants were instructed to have no contact with the technicians during the driving tasks.

2.3.1. Peripheral detection task

The peripheral detection task was used in this study to evaluate the participants’ workload whilst driving. The PDT task required the participants to react to a light stimulus (the LED) that appeared in the participants' periphery (in respect to the main driving focal point—straight ahead) and the light stimulus is illuminated for 2 s. The participants reacted by depressing the micro-switch attached to the left index finger. The LED upon depression, subsequently extinguished. If the response is classified as 'correct' (response within 2 s), the reaction time was recorded in milliseconds (ms), otherwise the response was recorded as a late or missed response.

2.3.2. The mobile phone task

The participants were informed that they would receive an unspecified number of phone calls (eight phone calls in actual fact) during their drive. In one direction (outward or homeward), on the motorway to or from Norrköping, they were required to answer the mobile phone in either the handheld mode or the hands-free mode. The mobile phone was held in their right hand when using the handheld mode. The incoming call was 'opened' by pressing the 'accept call' button on the phone. The same participant would after completing one route, change telephone modes. The order of use was balanced. The hands-free unit required only a depression of the 'accept call' button on the telephone to 'open' the communication link. A microphone was attached to the roof above the driver's head for optimum sound quality and loudspeakers were also placed close to the driver’s seat.

2.3.3. Conversation task

The conversation task was divided into three distinct levels of conversation; complex, simple and no conversations. The conversation task that was classed as complex, involved responding to questions that involved single digit addition and memory tasks. The research assistant read aloud (from a protocol) two single-digit numbers (e.g. 2 and 3) to the participants (via the mobile telephone). The participants were required to add the numbers and reply with their (correct) answers (i.e. 2 + 3 = 5) conveyed verbally to the research assistant (their performance was recorded). After the first pair of numbers, only one single-digit number was read aloud to the participants (e.g. 4). This new number would then be added to the last number read out by the research assistant (in this case, 3). The correct answer (i.e. 3 + 4 = 7) would again be conveyed verbally to the research assistant. The process was repeated with one single-digit number at a time, for a minimum period of 1 min and 30 s. This task required abstract thinking (mental arithmetic) and memory. The simple conversation task required the participants to verbally repeat single digit numbers, which were read aloud to them by the research assistant (via the mobile telephone). The numbers were also read from a protocol.

The phone calls’ duration was approximately 2 min, whereas the actual telephone task was a minimum of 1.5 min.

2.3.4. Data preparation

The first and last 400 m of the motorway drive were excluded, because these sections were used to accelerate up to cruising speed and respectively for decelerating, before exiting the motorway. Data for some shorter sections on the motorway, where temporary road works were registered (which
led to a speed decrease and traffic environment changes) for some of the participants, were also excluded.

3. Results

We compared effects of conversation type (simple versus complex) and telephone mode (hands-free versus handheld) to baseline conditions, that is, just driving situations. From the PDT data, we found a significant effect of conversation type but no effect on telephone mode. That is, the participants' reaction times increased when conversing but no benefit of hands-free units or handheld units on rural roads/motorways were found. The solid line in Fig. 1 represents the PDT reaction times in milliseconds (ms). The pair wise t-test analysis of the PDT reaction times between the simple conversation–task condition and the complex conversation–task condition for the hands-free telephone mode was significant ($t = -7.414$; d.f. = 39; $P \leq 0.001$). The PDT reaction times between the simple conversation–task condition and the complex conversation–task condition for the handheld telephone mode was also significant ($t = -8.036$; d.f. = 39; $P \leq 0.001$). The difference in PDT reaction times between telephone modes (i.e. hands-free and handheld) was not significant. The increase in reaction times from the baseline condition to the simple conversation–task condition for hands-free was significant ($t = 4.637$; d.f. = 39; $P \leq 0.001$) as was the handheld condition ($t = 3.964$; d.f. = 39; $P \leq 0.001$). The increase in reaction times from the baseline condition to the complex conversation–task condition for hands-free was significant ($t = 11.898$; d.f. = 39; $P \leq 0.001$) as well as the handheld condition ($t = 12.029$; d.f. = 39; $P \leq 0.001$).

<table>
<thead>
<tr>
<th>Conversation type</th>
<th>Mode</th>
<th>PDT reaction times (ms)</th>
<th>Mean PDT reaction times across modes (ms)</th>
<th>Overall percentage increase in reaction time over conversation type from 'none' condition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple</td>
<td>HH</td>
<td>562***</td>
<td>656</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>HN</td>
<td>560***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex</td>
<td>HH</td>
<td>849***</td>
<td>945</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>HN</td>
<td>841***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HH: hands-free; HN: handheld; ***: significantly different ($P \leq 0.001$) from the 'none' condition.
However, a significant effect on mean speed (broken lines in Fig. 1) could be related to telephone mode (hands-free and handheld) in pair wise t-test analyses. With handheld units the mean speed dropped, whereas the mean speed for hands-free was significantly greater than the mean speed for handheld units in the simple conversation-task condition (t = 3.78; d.f. = 39; P = 0.001), as in Fig. 1. The difference in mean speed between handheld and hands-free mobile telephones in the complex conversation-task condition also was significant (t = 2.082; d.f. = 39; P = 0.04). Increases in mean speed from the baseline (no conversation condition) up to the mean speed for hands-free units in the simple and complex conversation-task conditions were not statistically significant. The decreases in mean speed from the baseline condition to the handheld simple (t = 3.009; d.f. = 39; P = 0.005) and complex (t = 2.22; d.f. = 39; P = 0.05) conversation–task conditions were both significant.

In Fig. 2, the PDT hit rate performance is expressed in percentage of correct responses, i.e. a PDT reaction time <2.0 s. Fig. 2 shows the hit rate the telephone tasks and without telephone tasks while driving the motorway test route. The correct mean PDT hit rate without a telephone task was 96% and the correct mean PDT hit rate with a telephone task was 85% (paired t-test; t = 5.982; d.f. = 39; P ≤ 0.001) (see Table 1).

Assuming that the driver detects a signal to stop (i.e. an impending traffic situation that could have a critical nature such as a large obstacle on the road ahead of them), the stopping distances are not greatly increased when engaging in the telephone tasks of this study, as seen in Tables 2 and 3. However, these reaction delays are calculated from the retardation in the detection of information (PDT reaction time). Also important for traffic safety is the percentage of misses, that is, when the participants failed to detect the visual information completely, as in Fig. 2. If this information had

![PDT hit rate](image)

**Table 2**

<table>
<thead>
<tr>
<th>Conversation type</th>
<th>'Thinking time/distance'</th>
<th>Braking distance (m)</th>
<th>Total stopping distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>17.9</td>
<td>75</td>
<td>92.9</td>
</tr>
<tr>
<td>Simple</td>
<td>20.1</td>
<td>75</td>
<td>95.1</td>
</tr>
<tr>
<td>Complex</td>
<td>25.9</td>
<td>75</td>
<td>100.9</td>
</tr>
</tbody>
</table>

'Thinking time/distance' is calculated by converting the PDT reaction time (ms) into m/s for the respective constant vehicle-velocities represented in distances (m) travelled while 'thinking'. The distances (m) for 'thinking time' and actual braking are added together to give the total stopping distance in meters.
been of a traffic safety-critical nature, then the impairment of attention caused by the telephone conversation would also thereby be critical in unfortunate circumstances. Moreover, the participants were aware that the PDT diodes would illuminate regularly and roughly where they could expect to see them. Visual information from the road scene that a driver would require could appear at anytime and from anywhere, even from behind, therefore, the traffic safety implications of the slowing or retardation of PDT reaction times has a greater significance than the absolute retardation in milliseconds.

‘Thinking time/distance’ is referring to the mental process of detection (“Is there something?”), perception (“There is something!”), cognition (“What is it?”), response selection (“What to do?”) and response execution (“Do!”). ‘Thinking time/distance’ is calculated by converting the PDT reaction time (ms) into meters per second (m/s) and then into distance (m) for the respective constant vehicle-velocities represented in distances (m) traveled while ‘thinking’. The distances (m) for ‘thinking time’ and actual braking (HM Stationary Office, 2001) are added together to give the total stopping distance in meters. In Table 2, the delay in ‘thinking time/distance’ between driving situations without a telephone task and with a simple conversation and a complex conversation task is 2.2 and 8.0 m respectively, at 110 km/h.

In Table 3, the delay in ‘thinking time’ between driving situations without a telephone task and with a simple conversation and a complex conversation task is 1.0 and 3.6 m, respectively, at 50 km/h.

The distances shown in Tables 2 and 3 are conditional to best possible situation scenarios, i.e. keen perception, best possible response selection, unfaltering response execution and optimal road friction. Anything less than the above will result in longer stopping distances.

The relationship between mean speed and the PDT reaction time data is important to establish. First, there was no significant relationship between mean speed and PDT reaction time for complex conversations. However, simple conversations produced significant relationships between mean speed and PDT reaction times. Figs. 3 and 4 illustrate the regression analysis between speed and PDT reaction times. The regression between speed and the PDT reaction time for hands-free telephones in simple conversations in Fig. 3 is statistically significant (ANOVA; $F = 4.711$; d.f. = 34 $P = 0.037$).

The samples used in the regression analysis were trimmed at the uppermost and lowest levels of distributions for the PDT data and the mean speed data. Two cases had no or only partially recorded values. A total of six
cases were thereby trimmed from the regression analysis data.

The analysis of variance in Fig. 4 for the regression between speed and the PDT reaction time for handheld telephones in simple conversations is also significant (ANOVA; $F = 11.183$, d.f. = 34; $P = 0.002$).

4. Discussion

The main findings of this study are that there is a significant effect of the task (conversation type) on the peripheral detection task performance (reaction time) but no effect of telephone modality (hands-free or handheld) on PDT performance. However, a significant effect of telephone modality was found on the dependent variable of mean speed. This is a very interesting finding because the PDT measure has been found to be a sensitive measure of cognitive workload as also found in Martens and Van Wijns (2000), Olson (2000), Harris and Patten (2001) and Burns et al. (2000). The mean speed for the handheld units was significantly lower than the baseline mean speed whilst the mean speed for the hands-free units was significantly greater than the handheld unit and also greater (but not significant) than the baseline mean speed in both the conversation conditions (simple and complex).

The PDT reaction times increased by 45% from the baseline condition to the complex conversation condition as shown in Table 1. When converted to theoretical stopping distances, as in Tables 2 and 3, certain traffic safety considerations become apparent. When travelling at 110 km/h, a vehicle moves at 30.5 m/s. An average motorway lane in Sweden is ca. 3.75 m wide. At a rate of 30 m/s, even small lapses in concentration may result in alarming situations for the driver, especially if unexpected situations occur such as a slow moving vehicle in front of the driver. If, however, the mean reaction time for complex telephone tasks had a delay of 261 ms, then this ‘system retardation’ of the human brain may have a snowball effect on the information detection, processing, analysis and the response execution. In this study, the mean PDT reaction time increased by 45% with complex conversations and thus the driver will also have (at least) 45% less time for detecting new information. In other words, the driver engaged in a complex conversation is appreciably less likely to detect changes in his/her traffic (road and vehicle) environment than when he/she is not distracted and can fully attend the primary (driving) task. Typically, this retardation of the driver’s information processing, in a road environment that has few ‘surprises’ (e.g. requiring a quick response) may well pass without any incident. However, in a complex road environment or in a situation requiring high levels of attention, this retardation in mental attention capacity will be much more apparent and may contribute to an incident.

The effect of telephone modality (hands-free and handheld) on mean speed in this study, as seen in Fig. 1, is difficult to explain and should, therefore, be followed-up by further research.

The participants’ workload level in this study imposed by driving and conversing, may have pushed towards a critical workload level for tackling multiple tasks, in the sense that they were not as sensitive to their self-imposed impediment, i.e. due to the increased workload and thereby their reduced capacity for performing a primary and a secondary task. Brought on in part by cognitive tunneling/capture and at the same time, in the case of the hands-free condition, a failure to compensate for the loss in attention resources for primary task activities (e.g. speed monitoring), the impediment’s
subsequent result was no mean speed reduction and as indicated by Harbluk and Noy (2002), a visual scanning pattern with reduced monitoring of instruments. Moreover, when the participants were divided into the conversation tasks they were forced to reorient their attention and in the case of the hands-free condition, to the detriment of the primary task of driving. Therefore, this increase in workload not only increased the PDT reaction times but would also appear to have fostered a tendency to reduced speed awareness with no compensatory speed reduction behaviour in the condition for hands-free telephone units.

When using the handheld telephone unit (in contrast to the hands-free unit), the participants were constantly reminded of the secondary task (i.e. the telephone conversation) in the context of the primary task of driving.

The mean speed (broken line in Fig. 1) in the condition for the handheld telephone unit for the simple and complex conversation tasks were significantly lower than the baseline condition (i.e. no conversation, only driving) indicating a compensatory response from the participants. Astute readers may point out that even when there was a compensatory behavioral response to reduce visual information input through reduced speed, the recorded mean speed reductions in the hands-free condition of this study were arguably not of a magnitude that would compensate for the reduction of attention to the primary task of driving safely, but what is important is the behavioral tendency of the drivers to compensate their increased workload level by reducing the vehicle’s speed and maintaining a primary task awareness.

As mentioned above, cognitive capture or cognitive tunneling would also appear to arise as a result of increased or high workload. A similar tendency for cognitive capture was noted by Martens and Van Wijnatten (2000). The cognitive capture may have been somewhat interrupted when using the handheld telephone unit because of the psychomotor reminders (e.g. an aching arm) coming from the participants hand and arm that supported the device. That is, when the participants used the handheld device they were reminded of their self-imposed impediment whereas when they used the hands-free device, they lacked any physical reminders despite the fact that in both telephone modes indicated a clear cognitive workload increase even with an induced conversation type that was ‘simple’. Furthermore, cues in the peripheral vision in humans are important sources of information for judgement of speed (Samuelsson and Nilsson, 1996). This would therefore suggest that a reduction of the functional field of vision due to increased workload will also influence the drivers’ ability to judge speed when under high mental workload. Another important function of the peripheral vision is that it also helps the driver by in part, directing or leading the visual scanning pattern.

Recent eye-tracking studies have shown a greater tendency to fixate or reduce the visual scanning process when driving unde: higher workload (see Harbluk and Noy, 2002).

5. Conclusion

PDT reaction times indicate the human response time to detection and reaction of new information. However, the PDT reaction time cannot without additional assumptions be directly transferred to traffic safety accident risk comparisons. What it does say is that when participants are exposed to an increase in workload, the brain cannot process and react to new information at the same rate as situation with less workload.

When driving on motorways and larger rural roads, the mobile telephone modality would appear to be of little consequence when solely considering the conversational aspect of telephoning. For more important for driver distraction, in regard to mobile telephones, is the content and the complexity of the conversation per se. Note that even simple conversations may distract the driver, however, the more difficult and complex the conversation, the greater the negative affect on the drivers’ ability to allocate or direct their attention between tasks while driving.

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