Cognitive functions in drivers with brain injure

Anticipation and adaption

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Abstract

The purpose of this thesis was to improve the understanding of what cognitive functions are important for driving performance, investigate the impact of impaired cognitive functions on drivers with brain injury, and study adaptation strategies relevant for driving performance after brain injury. Finally, the predictive value of a neuropsychological test battery was evaluated for driving performance.

Main results can be summarized in the following conclusions: (a) Cognitive functions in terms of attentional and dynamic working memory-related functions are relevant for driving performance. (b) Neuropsychological impairments in information processing speed, divided and focused attention, requiring working memory, are associated to limitations in driving performance. In addition, qualitative aspects of driving problems especially impaired anticipatory attention appeared to constrain driving performance. (c) A neuropsychological test battery assessing speed of information processing and attention in terms of working memory predicted driving performance. In addition, cognitive factors are relevant for interpretation of driving problems qualitatively. (d) Driving speed adjustment and anticipatory attention were adaptive strategies for driving after brain injury. Interest in driving, motivation for driving safely, and driving experience appeared also relevant for driving after brain injury. (e) Collaboration between medical, neuropsychological and driving expertise is recommended for a total evaluation of driving performance after brain injury.

Anticipatory attention was considered a working memory based attentional system, directing the processing resources flexibly and appropriately between the different information processing components. Thus, anticipatory attention demonstrated qualitatively that working memory is a prominent function in a real driving context.

Keywords: Brain injury, cognitive impairment, anticipatory attention, driving.

PREFACE

This thesis is based on the following studies, which will be referred to in the text by their Roman numerals.

(I)   Lundqvist, A., Alinder, J., Alm, H., Gerdle, B., Levander, S. and Rönnberg, J. (1997). Neuropsychological aspects of driving after brain lesion: Simulator study and on-road driving. *Applied Neuropsychology, 4*, 220-230.

(II)   Lundqvist, A., Gerdle, B. and Rönnberg, J. (2000). Neuropsychological aspects of driving after stroke - in the simulator and on the road. *Applied Cognitive Psychology, 14*, 135-148.

(III)   Lundqvist, A. and Rönnberg, J.(2001). Driving problems and adaptive driving behavior after brain injury: A Qualitative Assessment. *Neuropsychological Rehabilitation, 11*, 171-185.

(IV)   Lundqvist, A. (in press). Four case studies: Neuropsychological aspects of driving characteristics. *Brain Injury*.

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CONTENTS

"Nicht Kunst und Wissenschaft alein,
Geduld will bei dem Werke sein".
(J.W. Goethe, Faust I, 1808)

INTRODUCTION

Driving a car is considered an activity of daily living, and the ability to drive is often required to live an efficient and independent life in the modern motorized society. For many people driving is also important for identity and self esteem. People continue to drive at high ages, and since the population grows older, the proportional number of older drivers is continuously increasing (OECD,1985; Schelin,1991).

Every year many people suffer from disease or trauma that cause cerebral lesions. In Europe and North America the incidence of cerebrovascular lesions is about 300 per 100.000 head of population per year (SBU, 1992). Consequently, in Sweden about 25.000 patients suffer from stroke every year. Ten to twelve thousand persons get permanent impairments. The incidence of Traumatic Brain Injury (TBI) patients who are admitted to hospital is 200-350 per 100.000 head of population per year in Europe and North America (Johansson, Rönnkvist, & Fugl-Meyer, 1991; Rosenthal et al., 1999; SoS, 1993). In Sweden about 20.000 patients are admitted to hospital every year due to TBI *and* commotio cerebri; about 10 % of them might become disabled. Since most of the patients suffering from TBI are relatively young and will live for many years to come, the number will accumulate over time. In addition, there are people with congenital cerebral lesions, residual conditions after infections and early dementia with impairments of higher mental functions.

Driving after brain injury is a complex issue and requires careful consideration. When deciding about a patient's driving capacity, it is essential to weigh the patient's legal rights and his need for autonomy in relation to the requirement of public safety. Driving can be even more important to the person who has difficulties to walk because it helps him/her to maintain mobility and independence. If a person is dissuaded from driving his/her life might change considerably with regard to convenience and social life. The person is obliged to use other means of transportation. Then, at least for older

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people, the risk of accident being an unprotected road user increases (Hakamies-Blomqvist, Johansson & Lundberg 1996).

In rehabilitation of patients with brain injury the rehabilitation team often has to evaluate whether the patient has regained sufficient motor, perceptual and cognitive functions to return to driving. Cognitive functions refer to the processes involved in thinking (Kolb & Whishaw, 1998) that is, encoding, internal processing and response selection. Patients and relatives often wonder whether the patient can resume driving. Therefore, evaluation of the ability to maneuver a vehicle and drive in traffic is an important issue. However, for most of the brain-injured patients the question of driving is not considered. Most of the patients resume to drive without any medical-legal consideration (Brouwer, Van Zomeren & Van Wolffelaar, 1990). There is sparse information about the number of brain injured drivers who continue to drive despite their cognitive impairments. Van Zomeren, Brouwer and Minderhoud (1987) estimated that about fifty per cent of patients with acquired brain damage still have a driving license although not all of them actually drive.

To acquire a first-time driving license in Sweden the individual must present a valid health and vision certificate, manage theoretical tests of traffic rules and regulations. In addition (s)he must show appropriate driving skills operating the car in an on-road test. In most countries the criteria for assessing medical fitness to drive after brain injury are vague. Some countries require a medical examination before a driver's license can be renewed after brain damage, but in Sweden there is no obligation for re-licensing after brain injury. According to the Swedish law for driving license regulations, a physician is responsible for reporting to the County administration authority if (s)he finds a patient *obviously* unfit to drive (Körkortslagen, 1998). Official directives for evaluating fitness to drive after brain damage concern poor visual acuity, homonymous hemianopsia or lower quadrant defect. Other disabilities, which preclude driving, are epilepsy and alcoholic abuse. Besides, significant impairment in visuo-spatial, attentional, psychomotor functions and memory dysfunction will prohibit driving (VVFS, 1996; VVFS, 1998a). However, the regulations do not describe *how* these functions are to be measured. Neither are the *degrees* of impairment described that will prohibit

driving.

Driving a car requires a set of complex skills, abilities, judgement and over-learned motor and cognitive functions. Although driving to a great extent is automatized it never becomes entirely routine. Traffic behavior demands information processing speed, flexibility and executive function in order to cope with complex traffic situations. Relevant information for driving is mainly visual (Simms, 1985; cf. Sivak, 1996). Consequently, attention and complex visual processing are of major importance for driving.

Motor impairment can generally be compensated by appropriate ergonomic applications to the vehicle, but expert advice is required on this. Vision conditions are clearly stated by medical rules. Less concern is given to the potential effects of cognitive impairment when driving is resumed after brain damage. What kind of cognitive criteria that are needed for driving and how these are evaluated, is to a great extent still ambiguous although human performance is the crucial factor for traffic safety (Simms, 1985).

Cognitive impairments can be manifested in attentional problems and in inefficient information processing. The brain-damaged patient may have difficulty in selecting among numerous simultaneous inputs, which is an important demand in complex traffic situations, and, an anticipatory behavioral deficit is a significant problem for many patients suffering from brain injury (Freedman, Bleiberg, & Freedland, 1987). Thus, the patient may have difficulty in planning his/her actions in a particular situation.

Sometimes the patient may not have a visible dysfunction, i.e. he can talk and walk. Nevertheless, (s)he may show an impulsive behavior and distraction by irrelevant stimuli. Cognitive impairments may remain for a long time or become persistent, and consequently it is a relevant issue in the context of road traffic safety.

There has been a variety of approaches for identifying which patient can drive and which can not. Different procedures have been used: (1) neuropsychological assessment, (2) simulator driving, (3) off-road assessment, and (4) on-road evaluation. To predict fitness to drive and to generalize to patients suffering from brain injury and to all traffic situations has been difficult.

A systematic multidimensional approach is required to make justified assessments for evaluating whether the brain-injured patient has regained sufficient cognitive ability to drive. There are many neuropsychological tests to measure an individual's cognitive capacity, but what relevance the results may have for his driving capacity is unclear. Several studies show relationships between neuropsychological assessment results and driving evaluation outcome (cf. Schanke & Sundet, 2000), while other studies have shown more conflicting relationships depending on various patient samples, design of study, and time since injury (for a review see Van Zomeren et al., 1987; Christie, 1996; Korner-Bitensky et al., 1998).

According to the literature adult people with acquired brain injury perform worse in neuropsycological tests measuring speed of information processing and executive functions compared to control subjects (Brouwer & Withaar, 1997). The same functions are supposed to be required to manage complex traffic situations. For example, in an intersection different pieces of information must be processed more or less simultaneously within a very short time, and action must be decided and executed promptly. Still, there are no studies showing that patients with brain injury as a group are more prone to accidents, compared to other road users (Van Zomeren et al., 1987). This is probably due to various compensatory mechanisms used by the brain-injured person (Brouwer et al., 1990; Brouwer & Ponds, 1994).

The question of how to evaluate disturbance in cognitive functions and its effect on driving performance depends on what functions are affected, to what extent they are affected, and what possibility the patient has to compensate for the impairments. In evaluating fitness to drive, the emphasis is on functions rather than on medical diagnoses and localization of lesion, although it is sometimes appropriate to consider which injury mechanisms and cerebral localization constrain specific functions.

The World Health Organization has established an international classification of functioning and disability (ICIDH-2, 2000), which is a conceptual framework for description of human functional states related to health conditions and with focus on three dimensions: (1) Body functions and structure including the brain and its functions. The body dimension relates to impairments when problems in body function or

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structure occur. (2) Activity at the individual level. Activity limitations are difficulties an individual has in performing (executing) an activity. (3) Participation in society. Participation restrictions are problems the individual has in involvement in various life situations. *Functioning* is the umbrella term for the positive aspects of the dimensions while *disability* is the umbrella term for problems in the dimensions, e.g. disturbed performance in driving activity. To meet with a brain injury will generally imply some kind of disability. Cognitive impairments may cause activity limitations in terms of difficulty to drive, and participation restrictions. To continue driving facilitates independence and thus, participation in society. Therefore, evaluation of a patient's fitness to drive ought to be a part of the rehabilitation issue.

Rehabilitation is the process of all medical, psychological, social and vocational efforts to reduce disability for an individual. The goal is to support the patient to reach a functional level consistent with his/her conditions and needs despite the residual impairment (DeLisa, Currie & Martin,1998; ICIDH-2, 2000). Consequently, the effect of successful rehabilitation is supposed to be a sense of wellbeing and health for the individual, although in a new life situation with changed functioning conditions (Gerdle & Elert, 1999).

This thesis is about neuropsychological aspects of driving performance. It has the following structure and contents. Models of driving behavior are initially introduced. Then central concepts and issues related to driving performance, and brain injury are defined. With this as a background, analyses are made of which cognitive functions are relevant for driving performance, whether brain injury has an impact on driving performance, and to which extent a neuropsychological test battery can predict driving performance. In addition, driving problems and adaptive strategies in a brain-injured patient group are studied in terms of qualitative characteristics. Finally, four case studies illustrate the concordance and discrepancy between neuropsychological assessment and driving evaluation, pointing to the advantage of collaboration between neuropsychological and driving expertise in promoting the overall assessment of driving performance after brain injury.

MODELS OF DRIVING BEHAVIOR

In the literature, there are several conceptions describing driving activity, for instance, driving skill, performance, capacity, behavior, competence and fitness to drive. Driving performance and capacity refer to what a driver is capable to do, while driving behavior refers to what the driver actually does on the road (Evans, 1991; Näätänen & Summala, 1976 & Summala, 1997). Driving skill is the automatized ability to manage the car technically, that is, steering, gearing, braking and keeping the car on the road. Driving competence and fitness to drive refer to the total abilities, motivational and attitudinal factors required for driving in traffic, operationally defined as the practical fitness to drive judged by on-road assessment.

Throughout this thesis, *driving performance* is used as a composite outcome of driving skill, driving behavior and fitness to drive. However, in Study I 'risk awareness', and in Study II 'driving skill' are used for the intended meaning of driving performance. Driving performance is operationalized by the outcome of a driving test evaluated by a driving expert on one driving occasion. However, driving performance assessed by means of a driving test does not necessarily describe driving safety. An experienced driving inspector includes parameters related to both driving skill per se and consideration to other road users as well as the complexity of the traffic situation. From a societal point of view driving safety is generally studied by accident involvement. However, from the individual's point of view accidents are very rare and might also be due to factors outside the actual driving performance. Thus, in order to study driving performance from the individual's point of view one has to go beyond accident rate data and allow for study of the interplay between cognitive and motivational factors, and driving experience.

Driving performance demands automatized perceptual-motor skills, adequate judgements of traffic situations and an ability to attend to dangerous situations. The driver is seen as an active decision-maker and an information seeker (Alm, 1989). That is, he is able to adjust to the current traffic situation, to take responsibility as a road user, and to show consideration to other road users. Given appropriate automatized perceptual-motor skills, careful attention, controlled decision-making and executive

behavior, driving performance will probably be carried out without problems (Summala, 1997).

Information processing model

The information processing model refers to perception, decision-making, response selection and execution in a sequence of stages in which the information is successively transformed and used (Eysenck & Keane, 1995; Wickens, 1992). According to the theory of Shiffrin and Schneider (1977) the conception of automaticity has influenced conceptualizations of driving behavior. During driving *automatized* and *controlled* processing is continuously changing depending on the traffic situation and the driver's driving skill. The novice driver must concentrate very hard on elementary driving components, excluding all intrusive stimuli. By practising, (s)he acquires automaticity in both attention and acting so as to combine automatized driving tasks like steering, accelerating, shifting and braking, with controlled visual search, reading traffic signs and listening to the radio. Thus, the automatized driving is based on fast, effortless processing (Shiffrin & Schneider, 1977) in contrast to driving in complex traffic situations requiring controlled processing which is slow and effortful.

Automatized processing does not require consistent situational conditions (Fisk & Schneider, 1984). For instance, braking and steering can become automatized despite differences in the attended environment. And, higher-order consistency can be utilized for automatized processing (Fisk, Oransky & Skedsvold, 1988). For example, consistent routine driving along the same route may result in automaticity with regard to route selection, independent of transient variations in traffic conditions and weather.

Thus, on the one hand, driving must allow for automaticity in the highly routine traffic environment. On the other hand, the general complex driving environment and driving speed also force the experienced driver to shift from automatized to controlled processing for efficient visual search and information processing. Consequently, situational factors trigger a shift in attention from automatized to controlled processing.

The information processing models have not considered motivational and attitudinal

factors that influence driving performance. It is, however, well known that drivers sometimes consciously choose to break speed limits due to time pressure, sensation seeking or lack of social responsibility. Hence, they are directed by motives for their driving and attitudes to driving safety. Therefore, a driving performance model must include (1) cognitive functioning, (2) driving experience, and (3) motivational factors.

Hierarchical control models

Three-level hierarchical model

Michon (1979, 1985) presented the hierarchical structure model of driving with three interdependent levels of decision-making, suggesting concurrent dynamic activity at the strategic, tactical and operational levels of control. The *strategic level* concerns decisions about planning to make the driving safe and to use the car selectively and carefully. The driver judges, decides and makes plans for the most appropriate route, considering weather, time and personal condition before he starts the driving. Decisions at the strategic level concern mainly risk estimates and avoiding risks before the driver sits behind the wheel.

The *tactical level* concerns activities and decisions during driving in the real traffic. For example, the driver receives information from the ongoing traffic. S(he) considers and makes decisions about speed and distance when overtaking. Tactical aspects of driving involve judgement of traffic situations and anticipatory risk avoidance behavior (Van Wolffelaar, Brouwer, & Van Zomeren, 1990; Van Zomeren et al., 1988). It requires awareness of environmental demands and self-control. To a great extent, decisions at the tactical level demand cognitive control, especially attention combined with information processing speed, which makes it possible to select among possible solutions and to have a goal-directed behavior.

The *operational level* consists of on-line decisions of immediate control actions, which are elementary driving tasks based on automatized, over-learned perceptual-motor functions like steering, accelerating, shifting, braking.

Time is central in differentiating the levels. At the strategic level, decisions are not

really restricted by time, while at the tactical and even more so at the operational level, decisions are to be taken immediately. Due to the extreme time pressure there is no time to compensate for impaired functions at the operational level. Compensatory behavior must be carried out at the tactical and strategic levels.

Skill-rule-knowledge model

Rasmussen (1983, 1986) differentiated between skill-based, rule-based and knowledge-based behavior in his hierarchical model 'skills, rules and knowledge model' (Table 1). This model is, to some extent, similar to Shiffrin's and Schneider's (1977) model in which a distinction between automatized and controlled processing is made. Whether driving is skilled or a novice and whether traffic situations are familiar or unfamiliar, will influence if a driver is using skill-based, rule-based or a knowledge-based level of control. At the skill-based level traffic information is connected automatically to a response, which can be carried out without control, e.g. turning left at a traffic light on routine when driving to work. If there is no automatized response available, or if there are competing responses, the processing is moved to the next, rule-based level, where it is processed and executed. In Sweden, it is recently prescribed that drivers have to stop and let pedestrians cross the road. To change a previous automatized driving behavior, i.e. from passing a pedestrian crossing to compulsory stopping, requires a rule-based controlled response. However, if there is no appropriate rule, a problem must be processed at the knowledge-based level for finding a solution, e.g. finding out how to drive to a new destination. Generally, driving will be performed according to the three cells along the diagonal from the upper left to the lower right cell in Table 1.

Behavior at all levels may become automatized in highly familiar situations and if the driver has a sufficient driving experience. For instance, it is suggested that the experienced driver can rely on automatized processing in a familiar, although complex, intersection provided nothing unexpected happens, whereas the novice driver must utilize controlled processing relying on knowledge while gearing and using the clutch. Safety is thus dependent on the choice of correct level in certain situations and for

given circumstances, and problems will occur when the driver is processing at the wrong level.

Table 1. *Classification of selected driving tasks by Michon's control hierarchy and Rasmussen's skill-rule-knowledge framework* (adapted from A.R. Hale et al., 1990. Figure 1.p.1383) in Ranney, 1994.

Task oriented control levels

		Strategic level	Tactical level	Operational level
Psychological control levels	Knowledge	Navigating in unfamiliar area	Controlling skid	Novice on first lesson
	Rule	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
	Skill	Route used for daily commute	Negotiating familiar intersection	Vehicle handling on curves

The hierarchical models provide differentiation but also integration of various components of the driving task and demands of control for driving performance. However, in real driving it may be impossible to separate the tactical and operational control levels, because there is a continuous and immediate interface between these levels. One advantage of the hierarchical models is that motivational factors and compensatory behavior are suggested to also influence driving performance. The driver's goal, attitudes and motives for driving will influence strategic and tactical decisions. Consequently, the driver's allocation of attention depends on changes in the traffic situation, driving performance, and the driver's motives for driving.

Motivational models of driving

The motivational driving models concern risk taking as an important issue of traffic safety. The models consider a global approach to driving emphasizing the transient situation-specific variability in the driving activity, to a great extent controlled by *motivational factors* (Evans, 1991; Fuller, 1984; Näätänen & Summala, 1976; Summala 1985, 1988, 1997 & Wilde, 1982, 1995). The driver aims at reaching a balance between perceived level of risk and a subjectively acceptable level of risk taking. Thus, these models focus on what the driver actually does, rather than on driving capacity.

In this context, Summala (1997) is relevant because he emphasizes the relation between cognitive workload and motivation. According to Summala (ibid.), the driver is adjusting his behavior from moment to moment to modify and minimize risks. Sudden traffic changes or extended complexity of the traffic environment can make it difficult to keep within the safety margin. Then, the driver will regard the situation as overloaded and risky. The feeling of *uncertainty* will trigger attention shift into controlled monitoring. For example, if the traffic becomes dense the demands on the driving task increase. Then, there is less time for action. And consequently, the driver has to put more cognitive effort (attention and concentration) into the driving task or use some compensatory adjustment to cope with his/her feeling of uncertainty. Thus, motivational factors are important determinants for choice of driving behavior, directing safety margins and allocating attention (Summala, 1997).

The motivational models were previously criticized for lacking details concerning mechanisms or details of motives and situation-factors influencing driving (Eysenck, 1982; Michon, 1985). However, Summala (1997) has gradually introduced different functional decision levels: the high-level pre-trip decisions and low-level on-line decisions, which can easily be controlled by sudden changes in the environment that trigger attention shift to controlled monitoring.

To summarize, on-road decisions change from moment to moment mediated by subjective workload, effort and uncertainty. In addition, the driver has also made some self-assessment of how capable (s)he is which also directs driving decisions. Safety-

oriented aspects of driving are related to the driver's knowledge about risks. However, knowledge is not necessarily transformed into driving behavior if feedback does not confirm the knowledge.

Generic error-modeling system (GEMS)

Reason (1987, 1990, 1994) made a combination of information processing model and hierarchical control theory considering the individual's intentions and motivation as a cause for error. Automatized versus controlled processing is interpreted within the context of Rasmussen's three-level control hierarchy. In addition, Reason's generic error-modeling system (GEMS) is in agreement with motivational models in that the driver's subjective uncertainty is viewed as a mechanism that triggers a shift in allocation of attentional resources between the different levels. Once the attentional control system detects a problem, the control will shift from skill-based to rule-based level. Consequently a change from automatized to controlled processing occurs.

Reason's model makes a difference between *error* and *mistake*. *Error* is due to a discrepancy between a planned and executed action, that is, the driver does not do what he intended to do. Errors are likely to occur when responses have become automatized like in familiar routine situations i.e., at the skill-based level. Errors can be slips or lapses. *Slips* are due to an intended action being wrongly executed. They are related to the psychomotor components of driving at the operational level of control. Often an automatized action takes over from the intended one and causes the slip of action. For example, the driver fails to turn or brake appropriately in a given situation. *Lapses* are errors of omission, that is, the action was *not* carried out either because of memory or attentional omission. Perceptual errors are, to a great extent, lapses of attention, which may cause inappropriate tactical decisions. The driver, for instance, misperceives the speed of an oncoming vehicle. Lapses of attention, which are also related to skill-based or automatized behavior, are assumed to be relevant to road accidents (Reason et al., 1990).

Mistake is a failure due to a discrepancy between a faulty plan to manage a task and

the appropriate plan. Mistakes occur when the driver makes a wrong planning or judgement at either the rule- or knowledge-based levels. The mistakes may be due to failures of interpretation or comprehension of the current situation, or applying inappropriate rules, for instance, entering a highway in opposite direction. Mistakes may also be due to insufficient knowledge about how the system works.

Individuals are often unaware that they have made a mistake and, therefore, detection in time is relatively rare, as regards mistakes, (Reason, 1990), while errors, which depend on faulty response selection, are easier to detect.

Summary comments

The driving models have emphasized different aspects of driving demands. They describe demands on driving performance in general, but do not predict differences among individual drivers. Gradually, all models have incorporated a hierarchical control structure, which has combined automatized components and controlled processing at different levels of control. Certainly, motivational factors and uncertainty in unfamiliar and ambiguous situations will direct a switch from passive noticing of the traffic environment to active goal-directed controlled processing leading to tactical decisions. However, intention to drive safely is not a guarantee for safe driving.

In modern cognitive psychology there is a lively discussion concerning the architecture for attention. One issue concerns the difference between (a) stimulus-driven, automatized, pre-attentive processing, and (b) goal-driven controlled processing, functioning through some central executive. There are multiple systems operating in parallel and interactively, including also expectations, motivation and the importance of an event, that is, the influence of a feed-forward system (Duncan, 1996; Eysenck & Keane, 2000; Tipper & Weaver, 1998). There is also neuropsychological evidence for an executive system, which is closely connected to attention. When a skill is acquired and processing becomes automatized, the executive function is still required to coordinate action and to determine strategy (Gopher, 1996) as the situational conditions change. For instance, to merge into the traffic waiting for the appropriate order re-

quires executive control.

Cognitive functions control decisions at different control levels. Thus, it is important to study what cognitive functions, especially attention, are used for driving performance at the operative and tactical levels, and in the interaction between these two levels. The brain-injured patient may have impaired cognitive functions, which cause inefficient allocation of attention in different traffic situations. Changed functioning may also evoke uncertainty in complex driving situations and, consequently, uncertainty about driving performance. Neuropsychological tests assess cognitive functions related to operational and, to some extent, to tactical driving aspects. The neuropsychological tests used in the studies presented below were chosen on the basis of empirical results from studies already carried out on the research topic (see Christie, 1996; Van Zomeren et al., 1987) and on theoretical considerations for driving performance (see Ranney, 1994). Focus was on dynamic information processing and attention, which in this thesis, were hypothesized to be as important to measure and capture as are more evident basic and medically verifiable perceptual and visuo-spatial functions. The reasons are that the dynamic tests stand a better chance of measuring rapid, transient and relatively subtle functions.

The present test battery (see Appendix I.) was considered to assess lower visuo-motor speed functions and reaction time in a non-distracting condition, but higher cognitive functions, like complex cognitive processing and executive functions, were emphasized. Complex cognitive functions were, for instance, divided attention and working memory. Simulator driving and on-road driving tests assess operational and tactical aspects. However, there is relevant information in the on-road driving evaluation, which is not possible to capture by a *quantitative* assessment. Therefore we also found it necessary to use a *qualitative* approach to cover aspects of driving performance more comprehensively.

In conclusion, driving demands different cognitive functions to meet with requirements at both operative and tactical control levels. Brain injury may change cognitive functioning and thus has an impact on driving performance. This thesis is focused on the relationship between cognitive functions and driving performance, and aspects in-

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fluencing driving after brain injury. Neuropsychological tests, which assess cognitive functions, can be used to study relevant functions for driving performance in general and especially after brain injury. In addition, the neuropsychological assessment can measure individual differences of relevant cognitive functions. Thus, one question, which is important to study, is whether cognitive impairments have an impact on processing at different levels of control. These considerations have guided the studies included in the thesis.

BRAIN INJURY

In adults, brain injury is generally caused by traumatic brain injury (TBI) or stroke. The lesion is due to damaged brain tissue including damaged neural connections between cortical, sub-cortical and limbic regions. Neural connection systems include the ascending reticular activating system, in which numerous neurotransmitter systems originate in the brainstem and in the basal forebrain and then terminate in the cortex (Filley, 1995). A brain injury may be diagnosed by neuroradiology or by clinical symptoms (Eysenck & Keane, 2000; Risberg, 2000).

Widespread neural tracts, the frontal lobes and posterior regions are involved in the attentional systems (Posner, 1995). Thus, deficits in attention are often residual symptoms of damage in cortical regions or/and in reciprocal connections between brain regions. The frontal cortex is engaged in selective attention, shifts and allocation of attention, in sustained attention and in controlling inhibitory and facilitatory mechanisms (Parasuraman, 1998). Accordingly, frontal brain injury generally affects attention in various ways (Lezak, 1995; Stuss & Benson, 1986; Stuss et al., 1999).

Generally, perceptual and visuo-spatial impairments are consequences of right hemisphere lesion, while left hemisphere lesions often affect verbal functions. In this thesis focus is not on basic perceptual or language impairments. Instead, focus is on cognitive impairments that are common for most brain injuries but often concealed and difficult to capture in a medical clinical examination (Johansson et al., 1996).

Physical violence to the head can impair brain functions seriously. In severe TBI there may be local contusions of cortical gray matter and axonal damage (white matter

shearing) in sub-cortical regions and in the brain stem. Cortical frontotemporal regions are especially vulnerable to closed head injury (Levin, 1992; Ommaya, 1979). Frontal as well as diffuse brain injuries may impair attentional functions and executive functions including executive inhibition (Brouwer, in press; Parasuraman, 1998; Shallice & Burgess, 1993; Stuss et al., 1999). The frontal lobe is even more important as task demands increase (Stuss, Eskes & Foster, 1994) requiring working memory, which might be affected by frontal lesions (Stuss et al., 1994).

Dual task performance and, especially, inhibition of automatized processes are dependent on prefrontal cortex and the anterior cingulate (Posner & Raichle, 1996). Distractibility (i.e. interference) has been related to injury in the right frontal hemisphere, and if a brain lesion is located in the left frontal lobe response inhibition may be impaired (Stuss et al., 1999). This may cause impaired flexibility in complex attentional tasks and, especially, motor control (Norman & Shallice, 1986; Shallice 1988; Stuss et al., 1999). It is in accordance with neuropsychological observations of impaired executive functions, already described by Luria (1966) and Lezak (1995).

In addition, the attentional impairment is to a great extent related to a non-specific processing slowness (Stuss et al., 1999; Van Zomeren & Brouwer, 1992), which is shown in task-paced processing under time pressure (Brooks, 1984; Brouwer & Withaar, 1997), such as divided attention, decision-making, and response selection. Also focused attention is affected by slowness. Patients need more time in a distracting task dealing with response interference (Stuss et al., 1985; Van Zomeren, Brouwer, & Deelman, 1984). Certainly, severity of the injury and complexity of the task also play a significant role (Stuss et al., 1999; Van Zomeren & Brouwer, 1994). The more bits of information there are to be processed, the greater is the difference between patient groups and controls due to decision-making and information processing slowness (Gronwall & Sampson, 1974; Van Zomeren & Brouwer, 1994).

Stroke is an age-related disease (SBU, 1992; Wolf, Kannel, & McGee, 1986). Among patients suffering from stroke 75% were estimated to have residual cognitive dysfunction (Bonita, Anderson, & North, 1987). Certain aspects of attentional function might be impaired after stroke. The right hemisphere is supposed to direct attention to

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the left hemispace (Filley, 1995; Heilman, Watson & Valenstein, 1994). Thus, right hemisphere lesion can cause hemispatial neglect. Also, speed of information processing, effortful processing under time pressure, and flexibility might be affected.

However, slowed cognitive processing, impairment in selective attention and sensitivity to time pressure can also result in decreased performance in healthy elderly people (Cerella, 1990; Salthouse, 1996; Van Gorp & Mahler, 1990). Thus, cognitive impairment is probably risk factors for older drivers (Johansson, 1997) and strongly related to driving accidents among old people (see Brouwer, in press; Hakamies-Blomqvist, 1996; Lundberg et al., 1998).

In sum, brain injury affecting frontal cortex and/or its interconnections with other brain regions may impair the ability to focus on selected information or divide and shift attention between several visual inputs. Accordingly, impaired attention and concentration are by and large the most common neuropsychological problems associated with brain damage (Lezak, 1995) and are likely to affect driving performance.

Brain injury and driving

Processing slowness is known to be significant after brain injury (Van Zomeren & Brouwer, 1994). Since driving to a great extent is dependent on speed, that is to detect information, process it and select response in time, the slowness may have an impact on driving performance (see Alm, 1989; Ranney, 1994). Nevertheless, many brain-injured patients continue to drive. According to a study by Fisk, Owsley and Pulley (1997) thirty per cent of patients resumed driving after stroke. In another study, Shore, Gurhold and Robbins (1980) showed that the relicensing rate was 50% for cognitively impaired patients. Relicensing for very severe TBI patients was also about 50% according to Brouwer and Withaar (1997).

Brain injured patients are generally impaired in operational driving skills when evaluated by driving experts (ibid.). Wilson & Smith (1983) found that stroke patients had tactical difficulty in negotiating traffic, poor awareness of other vehicles, difficulty in driving the car in reverse, problems with making complex decisions in an emergency situation, and difficulty in keeping the vehicle on the proper side of the road.

Most common driving errors are lapses of attention (Reason et al., 1990). That is, when attention is preoccupied by irrelevant stimuli.

Research is done on the relationship between cognitive functioning and driving performance. Korteling and Kaptein (1996) showed that perceptual speed and time estimation were related to driving performance, and Brooke et al., (1992) showed that brain injured patients, who failed a driving test had visuo-spatial impairments, very slow attention and were easily distracted, compared to those patients who managed a driving test. Lundberg et al., (1998) showed that cognitive impairment is an important causal factor in crashes of older drivers, and Withaar (2000) came to the conclusion that for older individuals neuropsychological outcome differentiated pass/fail driving evaluation. Relationship can be established between neuropsychological test scores and driving performance measures. However, Withaar argued, that within a cognitive impaired group it is still difficult to separate the unfit subjects from subjects who are fit to drive by neuropsychological test scores. One reason can be that premorbid driving performance and compensatory mechanisms also influence to which extent driving performance is affected by the brain lesion, and as Brouwer & Withaar (1997) stress, many brain-injured patients are good drivers, especially if they have had much driving experience.

Attention has become a research topic by the demands of watch keeping tasks in complex man-machine research. In various activities, like in driving, the individual is met with an enormous amount of external stimuli. In addition, (s)he must continuously cope with his/her internal state, which is influenced by motivation and emotion. Thus, selection and control of processing is necessary for handling the redundancy of information to avoid overload of the processing system. In conclusion, attentional processes are crucial for driving (Withaar, 2000). Therefore, a review of the concept is presented in the next session.

ATTENTION

"Everyone knows what attention is.
It is the taking possession by the mind
in clear and vivid form of one out of what seem
several simultaneous objects or trains of thought".
(William James, 1890)

Attention refers to several aspects of human processing. It is a prerequisite for survival and plays an important role for behavior in daily life, like driving a car. It is necessary for cognition and execution, and for all kinds of information processing. Attention serves the purpose of maintaining goal-directed behavior despite a distracting environment, controlling accuracy and speed of processing, and controlling action promptly and over time as well (LaBerge, 1995; Parasuraman, 1998).

Multiple external stimuli reach the sense organs continuously. The individual has to select what is relevant for efficient information processing and goal-directed behavior, and filter out irrelevant information. The description of attention first expressed by William James (1890) was similar to focused attention. Besides focused attention the individual has to divide attention in situations containing many stimuli, for example, attend to several objects in a traffic environment. Impaired attention and faulty concentration may reduce cognitive strategies and processing speed, although basic cognitive functions are relatively intact (Stuss, et al., 1985; Stuss et al., 1989).

Attention is an active system engaging widespread anatomical and physiological brain systems (Posner, 1995). It can not be described by a single definition, nor can it be related to focal cerebral structures, or to a general brain function (Allport 1989; Mesulam 1981; Posner & Petersen 1990; Parasuraman, 1998). It is the outcome of interacting with extended parts of the brain. Neural areas are involved carrying out different functions, which can be described in terms of attention. Frontal midline cerebral areas, the anterior cingulate gyrus, plays a crucial role in the attentional control or executive attention, while a posterior system is responsible for automatic orientation of attention (Posner, 1995; Posner & DiGirolamo, 1998). In addition, the basal ganglia are involved in switching attention between different sets of processing. The basal ganglia are the source of dopamine input to the anterior frontal areas. Consequently,

subcortical cerebral nuclei and frontal structures have close connections (ibid.).

Attention and memory are closely connected in the context of information processing, particularly in working memory (Baddeley, 1990). Information will be kept in working memory for a very short time, which can also be discussed in terms of attention (Van Zomeren & Brouwer, 1992). Lateral frontal cerebral areas are involved in holding information temporarily and thus also involved in working memory. Close relationship between executive function and temporary storage is the core suggestion in the theory of working memory (Baddeley, 1986). Consequently, close cerebral connections within frontal cortex, i.e. between the anterior cingulate and lateral areas, are relevant for working memory through both inhibitory and facilitating mechanisms.

There are no neuropsychological tests of pure attention. A specific test may be described by some investigators as a test of working memory, short-term memory and information processing, and by others as a test of attention. Each neuropsychological test will assess several aspects of attention. While tested, the subject has to be alert, attend to the task selectively, process the task and sometimes sustain attention over time. Consequently, it is impossible to make a test that taps only one aspect of attention in its pure form.

Automatized processing

When a task is thoroughly practised it may be performed automatically, which means it can operate outside control. Automatized processing has few capacity limitations and it is more robust against disturbances compared to controlled processing. It occurs when an appropriate stimulus is present and triggers the initiation of a complete stimulus-response chain. However, one problem with automatized processing is its lack of flexibility. It is difficult to modify an automatized processing sequence once it has been over-learned (Shiffrin & Schneider, 1977). As Eysenck (1982) pointed out, automatized processing is functioning rapidly and in parallel but suffers from inflexibility. The connectionist models consider information processing entirely parallel and requiring no control system. Processing is supposed to be performed through inter-

activation of units at different complexity levels (Quinlan, 1991).

Controlled processing

Controlled processing on the other hand has limited capacity and it can be used flexibly in changing circumstances (Shiffrin & Schneider, 1977). It is needed in novel situations, in tasks that are not routine, that is, when the subject cannot rely on experience. In addition, controlled processing is temporary, and operates relatively slowly often in a serial fashion (Eysenck, 1982), and it is sensitive both to interference by automatized processing and to time pressure.

Anything which minimizes interference in different stages of processing, e.g. between stimuli, within internal processing and between responses, facilitates attention (Wickens, 1984, 1991). If two tasks require different processing resources there is little interference between them, and vice versa. For example, visual search time increases the more similar the goal stimulus is to present distractors, and, accordingly, to dissimilarity between distractors. Consequently, search time is maximal when distractors are dissimilar but in some way resemble the goal stimulus. (Duncan & Humphreys, 1989, 1992). Thus, using different codes of processing, (e.g. spatial or verbal), and different memory structures, (e.g. verbal or visual), facilitates processing (Wickens, 1991).

Focused attention

Focused attention, or concentration, is the ability to inhibit processing of intrusive information, that is, to focus on the relevant stimuli despite presence of distracting stimuli (Van Zomeren & Brouwer, 1990; Eysenck & Keane, 2000). Focused attention is effortful because irrelevant stimuli must continuously be selectively excluded. Distraction reduces the *speed* of executing the current task, because it takes time to deal with the conflict between the task response and the intrusive stimuli. If there is a strong association between a competing stimulus and the response, the intrusion becomes strong and focusing becomes very effortful. Disturbance in focusing may occur

when automatized responses come in conflict with the current task, e.g. when a new response is required by a stimulus, which has an earlier response very strongly connected to it. Such a conflicting stimulus-response bond is generally the result of earlier practice in a similar context. One example is when there is a temporary construction work on the daily route that demands the driver to change his routine noticing of the road into focused attention.

Theories of focused attention have been concerned about a 'bottleneck' in processing (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1964). The discussion has been concerned about whether the selection in processing is located early or late in the information processing system. Later studies on visual search uncovered that task demands influence focused attention, and the processing speed depends on similarity between the attended stimulus and the distractors, similarity between the distractors, and conjunction of features (Duncan & Humphrey, 1989, 1992; Treisman, 1988, 1993). Recent models of focused attention suggest differentiated attentional systems (Posner & Petersen, 1990; Posner, 1995; Stuss et al., 1999). One anterior attentional system controls stimulus selection and allocating resources, and one stimulus-driven posterior attentional system is involved in allocating attention to the visual space.

Focused attention has been studied presenting two or more stimuli at the same time thus measuring how efficiently the individual can select specific information and ignore other information. Cherry (1953) studied the classical 'cocktail party phenomenon', that is, following one person talking while ignoring all other people talking in the room. Visual focused attention is operationalized by visual search. It has been tested for instance in cancellation tests (Bourdon-Wiersma test), the Trail Making Test (Reitan 1958), the K test (Levander, 1988) and Color Word Test, (Stroop, 1935) where a target stimulus has to be found in a field of distractor stimuli (se Appendix I).

However, driving is carried out in environments, which comprise multiple distractors and multiple stimuli that must be attended to. Thus, driving requires that the driver can divide his attention simultaneously between various objects, events and people in the traffic situation.

Divided attention/information processing

Divided attention can be defined as the ability to attend to or perform two tasks at the same time (Eysenck & Keane, 2000) and it is often used synonymously with information processing. It points out how two or more elements are processed concurrently, but it also reveals limitations of the human information processing capacity (Van Zomeren & Brouwer, 1990). The limited capacity is due to the confined capacity of working memory, which includes a modality-free controlling central executive system and at least two subsidiary slave systems (Baddeley, 1990). Working memory controls processing speed and how strategies are used to divide the available capacity over subtasks of information. When the system is overloaded, the dividing strategy can allocate available processing capacity to the most relevant component of information and in that way restrict negative effects. Thus, *time* and *strategies* are critical factors in the limitations of divided attention.

Divided attention is required in doing two tasks simultaneously, called a *dual task*. The task demands can be to attend to two or more objects and tasks simultaneously, or combining two operations within a task that is needed in many daily activities, such as driving. Combining tasks may lead to a decline in performance in one or both of the tasks (dual-task interference). How successful two tasks can be performed depends on task difficulty (demands), the similarity between the tasks (Allport, Antonis, & Reynolds, 1972), but also experience and training. Practice facilitates dual task performance by way of strategies, which reduce the demands on attention and on cognitive capacity. All this leads to a more efficient functioning, which can rely on fewer controlled functions. It is well known that it is easy to perform an over-learned skill compared to the effort in initial learning, which demands full attention (see Eysenck & Keane, 2000). As mentioned above, the novice driver needs all attention for the driving task while the experienced driver may talk with a passenger and cast an eye at a shop-window during driving.

Models of divided attention have stressed principles similar to those for focused attention: similarities of different kind influence demands on divided attention and make processing difficult (ibid.). Divided attention will be facilitated if the stimuli belong to

different modalities, if processing is made at different stages, if processing capitalizes different memory systems, and if different responses are required (Wickens, 1984, 1991). Although it is well known that practice facilitates dual task performance, there are different suggestions about the major influence of practice: whether it improves performance by automaticity, i.e. reduces the cognitive capacity demands, by rapid alternation of attention, or by developing strategies to minimize task interference. Present models of information processing suggest some central capacity, which can be used flexibly to serve the demands on divided attention (Norman & Shallice, 1986; Baddeley, 1986; 2000).

Divided attention can be operationalized by combining two tasks into one test, or by combining two sources of information, both relevant to the same task. For example, Paced Auditory Serial Addition Test (PASAT), Trail Making Test B (TMT B) (Lezak, 1995) and Simultaneous Capacity test (Levander, 1988) are tests assessing divided attention (see Appendix I). Working memory is influencing the performance in that it is loaded with double tasks, temporarily storing one element while adding another in the processing.

Supervisory attentional control

To allocate processing capacity requires strategy and flexibility in which a *supervisory controlling system* is involved (Baddeley, 1986, 2000; Norman & Shallice, 1986). An inefficient control strategy may impair performance even when processing capacity (e.g. language and memory) is relatively normal as is the case with patients having a certain frontal lesion. On the other hand, a very efficient control strategy may, to some extent, compensate for capacity limitations. It is assumed that a central executive controls attention and executive functions like planning, programming, regulation, and verification of goal-directed behavior (Lezak, 1995; Luria, 1966, 1980), which direct complex information processing and dual task performance.

Shallice (1982, 1988) and Norman and Shallice (1986) developed an information-processing model in which a supervisory attentional system (SAS) executes controlled processing and selection of schemata, composed of internal routine programs and or-

ganized plans, which are activated in any cognitive activity. These are easily triggered and effective in the performance of well-trained tasks. A schema initiates action when appropriate triggering conditions exist, for instance red light indicating to stop the car. Once a schema is selected, it remains active until the task is carried out or is inhibited by a competitive schema, or by higher-level supervisory control. Any conflict or competition between schemata is resolved through contention scheduling that adjusts schema activation and coordinates different schemata through facilitation and inhibition.

In sum, automatized processing are directed by schemata and attentional control is not required during the time a schema is running, only when there is a *switch* from one schema to another. Then, the supervisory control can direct attention on the task in focus through contention scheduling. High-level schemata represent an overall intention, for instance, to go to a certain place, while low-level schemas correspond to the actions involved in accomplishing that intention, that is, taking the car to go there. Optimal performance requires very frequent shifts between the presence and absence of attentional control. The SAS is required in novel or difficult tasks, in troubleshooting, or when a strong habitual response is to be overcome.

For instance, in the Stroop Color Word Test (CWT) (Lezak, 1995) the subject is asked to name the color of the ink in which a color word (e.g. red, blue) is printed. The color word is incongruent with the ink color. In processing the test it is required to ward off distraction of one visual processing and to give priority to the processing of another. Word meaning dominates the color processing of words because reading the short words are based on highly automatized processing, thus, distraction reduces the speed of executing the non-automatized task. The strong response interference taps the supervisory control.

Sustained attention

Another important aspect of attention is sustained attention, which has been investigated under the concept of 'vigilance' (Parasuraman, 1998; Posner, 1990). Sustained attention refers to how performance can be maintained and performed in a similar

manner over an extended period of time (Van Zomeren & Brouwer, 1990). Variability of individual performance in a sustained attention task is measured with lapses of attention, time-on-task effects, and intra-individual variability. Lapses of attention are usually response omissions in a continuous task, or extremely long reaction time in a continuous reaction time task. The lapses are related to declined alertness in a physiological way, which is apparent for instance, during long driving distance at night. Sustained attention is outside the scope of this thesis, because it has not been possible to study attention and driving over an extended space of time.

Skill

Skill is the efficiency of using a capacity (Welford, 1983), that is to carry out a task competently, smoothly, and fast. Performance changes both quantitatively and qualitatively when someone is acquiring a skill. The more skilled the individual is, the less controlled processing is required to carry out the task. A distinction between perceptual-motor skills and cognitive skills is often made. However, all skills are cognitive in the sense that a goal is set and performance must be organized, and all skills involve some form of motor output (Matthews, et al., 2000).

Models of skill acquisition describe the development from the effortful and uncertain performance of the novice to the fluency of the expert. As a skill is acquired there is a change in the type of knowledge that serves the performance. Ackerman´s model (1988) contains three different phases of skill acquisition: (1) declarative, (2) associative, and (3) autonomous. The initial declarative phase demands declarative knowledge like reasoning and declarative memory. The associative phase demands more task-specific associations, which are organized in schemata initiated by supervisory control. In the autonomous phase performance is fluent, stimulus-driven and based on procedural memory. During the autonomous phase, the activity can be mainly performed without distraction from other sources of information, thus leading to better dual-task performance.

Anderson (1982, 1983, 1995) presented his ACT, (Adaptive Control of Thought)

theory of skill acquisition. The early stages rely on declarative knowledge, which is based on explicit rules for carrying out the activity. Then, when the task is practised the declarative knowledge is replaced by special-purpose productions, which are routines for encoding and responding to task stimuli leading to procedural knowledge. In the skilled person, the productions comprise rules covering various inputs, which the person will meet, leading to appropriate performance in different circumstances. Thus, the procedural knowledge allows skill performance for generalization to several contexts.

In sum, driving is an activity relying on both cognitive and motor functions in that the driver processes incoming data, and executes motor responses. Daily driving is to a great extent based on procedural knowledge in the form of schemata. Skilled drivers recognize chunks of meaningful patterns in the environment, and cognitive and motor schemata can operate very much in parallel during skilled driving. Speed and precision of reaction and psychomotor functions are demands for applying the driving task, and how successful the skill development is depends on the individual's ability to proceduralize the components of the driving task.

However, the procedural condition is subjected to lapses of attention and slips of action when the automatized schemata are insufficient in a situation, which suddenly becomes ambiguous and uncertain. Accidents are often a result of lapses of attention, because the driver does not use his optimal ability or capacity. That is what Näätänen & Summala (1974, quoted by Summala, 1997) argued when they pointed out the relevance of observing current driving behavior rather than maximal level of competence in evaluating driving performance.

In conclusion, there are various aspects of attention which serve information processing, activity performance and skill. Task demands in terms of complexity and interference between different stages of processing influence how efficiently the task will be accomplished. Although practice improves task performance, if task demands exceed processing capacity the supervisory controlling system will take charge of attention allocation to serve the current demands. In fact, the driver continuously meets with alternating well-known simple situations *and* complex unfamiliar traffic situa-

tions. Thus, (s)he must all the time alternate between automatized and controlled processing.

Attention and driving

"...there is enough attention.
But, it is spent unjustly on
non-driving tasks".
(Brouwer,in press)

Driving is thus suggested to combine automatized and controlled processing as in any psycho-motor complex skill (Brouwer, in press; Michon, 1985; Summala, 1997). At the operative level of control driving is mainly automatized using elementary driving skill, which has become automatized through long training and practice. It is related to perceptual-motor functions and it is used in familiar situations where the driver can rely on schemas that are triggered in an automatized manner. At this level processing is fast and effortless. The automatized driving activities can be combined with visual search, reading traffic signs, listening to the radio and talking to a passenger.

However, in daily driving the driver has to divide attention continuously to several objects and course of events in the environment. This is crucial if something unexpected occurs. At the tactical level of control the driver has to judge risks of road conditions and judge behavior of other road users. When overtaking he has to control backwards and forwards, make judgements about distance of oncoming vehicles and speed of his own and other vehicles. Thus, when the situation demands, the driver has to focus attention on the relevant events and avoid distraction of irrelevant objects. And then, in the next moment he has to switch to divided attention on multiple input again.

Therefore, automatized and controlled processing is continuously changing during driving depending on the situation and the driver's experience. Situational factors can trigger a shift in attention from automatized to controlled processing. For instance, routine driving in a familiar environment is functioning through chunks of automatized

schemata. But now and then the traffic demands a shift of attention to controlled processing to make decisions. The more complex the situation is, the more controlled processing is needed, and thus supervisory control is applied. Sometimes the driver has to cope with critical situations, where a comprehensive cognitive effort is required. Then, the supervisory attentional system takes charge of the controlled processing for judgement of new events and selects appropriate schemata to modify and execute decisions according to feedback from the environment, (Shallice, 1988).

The brain-injured driver might have various cognitive impairments, which can affect his/her driving performance. Focus in this thesis is on subtle cognitive functions, which are required for information-processing speed, attentional shift and for reacting to events in the driving environment. The neuropsychological tests are supposed to measure dynamic attentional functions, which also require executive control. The driver might have well learned automatized driving schemata due to long experience which, to some extent, can compensate for cognitive impairments. In addition, (s)he might be motivated to drive safely. Thus, there is a complex relationship between different factors comprising driving performance, and it is important to study how driving performance is influenced by cognitive functions, adapting strategies, and whether the driver's performance is affected by brain injury.

PURPOSES OF THE THESIS

The general purpose of this thesis is to improve the understanding of what cognitive functions are important for driving performance and to investigate the impact of brain injury on driving performance. This was done in four studies, which were specifically designed to provide information regarding the following issues:

I. Which cognitive functions are relevant for driving at the conceptual level (Studies I and II)?

II. What impact does acquired traumatic brain injury, subarachnoidal haemorrhage and cerebral infarction have on patients compared to a control group? Thus, does brain injury result in impaired driving performance (Studies I and II)?

III. Which empirical neuropsychological variables are associated with limitation of driving performance? Thus, the objective is to evaluate the *predictive validity* of a neuropsychological test battery for driving performance (Studies I and II).

IV. In what way are driving problems manifested in a group of brain-injured patients? One purpose of Study III is to do a thorough study of qualitative dimensions regarding driving problems.

V. What adaptive aspects are important to maintain driving despite brain injury? Description of qualitative aspects of adaptive strategies following brain injury is the second objective of Study III.

VI. Four cases in Study IV illustrate the relevance of cognitive factors for interpretation of driving problems but also the importance of a driving test to show compensatory capacity in some drivers with brain injury. Thus, collaboration between neuropsychological and driving expertise can profound the total evaluation of driving performance after brain injury.

GENERAL METHODS

This dissertation combined quantitative and qualitative research methods. Methods were chosen given the practical conditions at the time of the studies. A controlled be-tween-group design with a multi-factorial quantitative approach was used in Study I and Study II. The data were collected by means of test results, rating scales and ques-tionnaires. Focus was on application of neuropsychological tests rather than on ex-perimentation. The aim was to study relationships between cognitive functions and a complex activity, i.e. driving performance.

A qualitative research approach was used in Studies III and IV in which the data were collected by open-ended interviews but also with neuropsychological tests and rating scales. The qualitative approach was used to discover and describe content and meaning underlying the quantitative empirical findings. An overview of the methods used in the studies is presented in Table 2.

Table 2. *Overview of the methods used in the four studies.*

Methods	Study I	Study II	Study III	Study IV
Neuropsychological tests	X	X	X	X
Rating scales	X	X	X	X
Questionnaires	X	X		
Interviews			X	X

The subjects were informed about the purpose of the studies and that participation was voluntary. It was agreed that the driving test outcome would not cause any nega-tive consequences for the subjects participating in Studies I and II. Thus, subjects, who failed the driving test, nevertheless continued driving. These persons, however, re-ceived an oral dissuasion from driving but not a prohibition. Subjects in Studies III and IV were volunteers but also referred for driving assessment. Consequently, the out-come of the assessment led to real consequences.

The studies were approved by and carried out in agreement with the Medical Ethical and Scientific Board of the Medical Faculty, University of Linköping, Sweden.

Subjects

Study I

Twenty-nine patients (mean age was 44.1 years, SD = 11.7) were sampled from 145 patients between 23 and 60 years of age with the diagnosis subarachnoidal haemorrhage or traumatic brain injury who were registered at the Neurosurgical Department at the University Hospital, Linköping University, during 1990-1993. Inclusion criteria for medically defined brain injury are described in detail in the paper. Six patients refused to participate because they did not want to leave work or had moved far away. Sixteen patients (55%) suffered from traumatic brain injury. Thirteen patients (45%) suffered from subarachnoidal haemorrhage. The patients were in a chronic stage and socially well recovered after cerebral lesion. They were examined on average 3.7 years after suffering the injury. Twenty-nine control subjects were employed persons selected from different medical departments and the transportation department of the University Hospital, from a local factory, and from the local government. Matching variables were: age, gender, education, and driving experience (present annual driving mileage).

Study II

The patient group comprised a consecutive sample of 30 stroke patients (mean age was 68.3 years, SD = 4.8) from 92 patients (60 - 75 years of age), who were treated at the Neurological Department at the University Hospital of Linköping, Sweden, during 1995. The inclusion criteria are described in detail in the paper. Five patients refused to participate due to health conditions. Four patients (13%) had had an intracerebral haemorrhage while 26 patients (87%) had a cerebral infarction. The patients were in a sub-acute stage, examined on average 8.6 months after illness. Prior to the study the patients had undergone a neurological examination, including visual field

examination, which was documented in medical records. For seven patients visual field was not clearly documented in the medical casebooks. However, due to the permission to drive it was assumed that they did not suffer from a limited visual field. Possible neglect was not explicitly examined, but neglect would typically be combined with other serious impairments, which would have been uncovered. Hemi-inattention was assessed by the neuropsychological tests. The control group was selected from four retirement organizations. Again, matching variables were: age, gender, education, and driving experience (pre-morbid annual driving mileage).

Neuropsychological assessment, self-ratings and questionnaires were administered individually. The subjects had a valid driving license, but eight patients had not yet resumed driving after their stroke.

Study III

The subjects were a heterogeneous group of 22 brain-injured patients, who were treated at the Rehabilitation Department of the University Hospital of Linköping, Sweden, at the time of the study. Diagnoses included three tumors, five traumatic brain injuries, nine infarctions and five cerebral haemorrhages. The patients were assessed on average twenty-three months after injury. All patients had a valid driving license, although two had not yet resumed driving.

Study IV

The subjects were four patients referred to the Rehabilitation Department of the University Hospital of Linköping, Sweden, for a neuropsychological assessment with the question whether they could resume driving after brain injury.

Case 1 was a retired professional driver suffering from a traumatic brain injury. Case 2 was a male assembler with a residual condition after a right frontal intracerebral infarction. Case 3 was a female storeman with a residual condition after a left thalamus infarction and a basilaris aneurysm, which was removed by surgery. Case 4 was an assistant nurse who suffered an intracerebral infarction laterally close to the right ventricle.

Interview in Study I and II

The interviews in Study I and in Study II were composed of ad hoc questionnaires that included topics such as driving experience in terms of frequency and annual driving mileage, driving habits, driving problems, and subjectively experienced cognitive impairments.

Neuropsychological assessment

The neuropsychological assessment was carried out by a trained psychology-student. Half of the subjects received the computerized tests first and then the paper-and-pen tests. The rest of the subjects were tested in inverted order. Each patient and his/her control were presented the tests in the same order. All subjects were tested during one single session, which took about 3,5 hours including breaks. The patients had a follow-up result discussion with a neuropsychologist, while the controls received their results by the examiner before they left the examination.

Since processing speed and selective attention are influenced by aging (Salthouse, 1996; Schaie 1996), the Stroop Color Word Test, assessing concentration, was included in the neuropsychological test battery in Study II. To limit the number of test variables Raven Progressive Matrices and Complex Figure Test (CFT) recall, which are not speed demanding, were excluded. In that way the test battery was selected which the analyses in Study II are based on. Otherwise the test batteries in Studies I and II are similar.

In Studies III and IV a reduced test battery was used. The tests are described in the individual papers. For a detailed description of the neuropsychological test battery see Appendix I.

Driving in simulator

The simulator used belongs to the Swedish Road and Transport Research Institute (VTI). The simulator car, design and route are described in the individual papers. For a detailed description see Appendix II. The driving design was similar in Study I and Study II. Each subject was given an opportunity to become familiar with the car, the road, the driving environment, and additional distracting tasks, by driving a 20-km rather easy and straight training route. The test route was 80 km and comparable to a country road with low-density traffic.

Two distracting tasks were: (1) a visual stimulus (square) appeared in the same position on the screen, i.e. when a red square appeared the subject was to break as fast as possible. (2) when the mobile telephone rang the subject was required to answer and respond to a modified Listening Span test (Baddeley et al., 1985). Twice the red square and the telephone task were combined.

Dependent measures were *speed*, *lateral position*, *time headway* (TTC) and *following distance* (DTC) in a car following condition, *reaction time* on visual stimuli, and *amount of words* recalled in the Listening Span test.

Driving on road

The on-road evaluation was based on the driving evaluation procedure used by the Swedish National Road Association (VVFS 1998b; VVFS 1999). For a detailed description of the on-road evaluation see Appendix III. In all four studies the same standardized driving route (Figure 1) was used comprising a distance of 25 km and involving a variety of driving situations regarding action and locality. Driving inspectors representing the official licensing authority (The Swedish National Road Administration) carried out the evaluations in the four studies. In Studies I and II the driving evaluations were conducted by two driving inspectors. The inspector was sitting beside the driver and made detailed observations of the driver's behavior. In eight cases two driving inspectors made evaluations concurrently and independently.
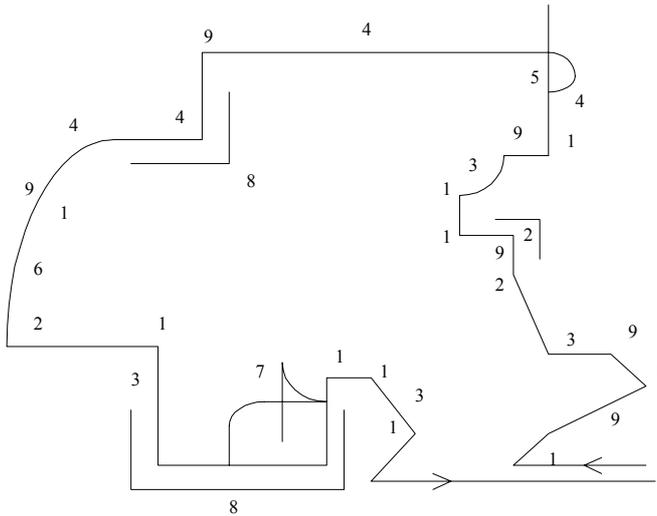
Evaluation	Condition	Evaluation
1	Traffic light	Attention
2	Roundabout or junction	Positioning, attention
3	Turning right crossing cycle path	Attention
4	Rural public road 50 km/hr, 70 km/hr	Speed, positioning
5	Prohibition to turn left	Attention, planning, positioning
6	Highway 90 km/hr	Speed
7	Residential area, turning in junction	Maneuvering, attention, speed
8	Distraction, talking with instructor	Attention
9	Participant given instruction, "Follow signs to … e.g., "city", "Stockholm"	Planning

Figure 1. On-road driving route: Conditions and examples of tasks evaluated.

The inter-rater reliability of the expert judgements was 0.96 ($p < 0.01$), which is in accordance with other inter-rater consistency (Klebelsberg, 1982). In Studies III and IV one driving inspector evaluated the driving performance on all occasions.

The inspectors provided instructions to the driver while directing him/her on the standard route of 25 kilometers. The test route started at the University Hospital and proceeded through busy city streets, a country road, a highway, and residential areas (see Figure 1).

The driving performance was evaluated on five driving criteria: *speed*, *maneuvering*, *vehicle position*, *traffic behavior* and *attention* (see Figure 2). Performance was scored between 1 and 5, where 1 and 2 implied unfit to drive, 3 indicated reasonable driving performance, and 5 was splendid. Based on these criteria, however not quantitatively, an overall-driving performance evaluation, that is, a pass/fail outcome was determined by the inspector. The overall-driving outcome is named risk awareness by The Swedish National Road Administration. After driving the inspector gave all subjects feedback on their driving which was highly appreciated by the drivers.

Risk awareness				
Speed	*Maneuvering*	*Position*	*Traffic behavior*	*Attention*
Situational dependent speed	Motor ability	Distinct position in Road lane	Planning, Following rules, Consideration	Attending to treacherous Situations
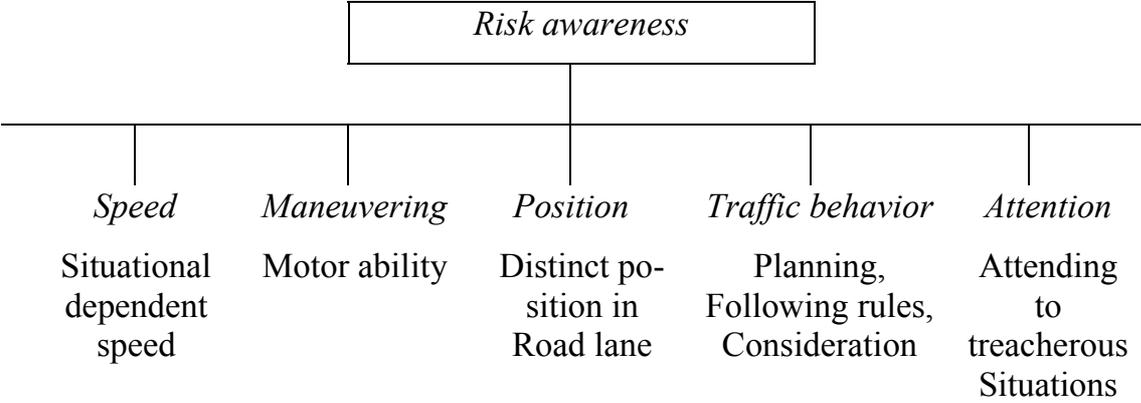
Figure 2. Evaluation variables according to the standards of The Swedish National Road Administration. The sub-variables comprise an overall-driving performance outcome named *risk awareness* by The Swedish National Road Administration.

Quantitative and qualitative methods

Understanding without explanation
is blind knowledge.
Explanation without understanding
is empty knowledge.
(after Ricoeur,1988)

Quantitative methods

For independent samples *t* tests were performed to evaluate group differences on the neuropsychological tests between patients and controls, as well as between subjects passing the driving test and subjects failing the driving test. Also the Chi-square test was used to compare groups concerning categorized variables. We chose conservative significance levels. Thus, where multiple *t* tests were used, $p \leq 0.01$ was considered significant. Where single tests were carried out or where the tests were planned in advance *p* equal to or less than 0.05 was regarded as being statistically significant. All variables were tested concerning normal distribution with a Kolmogorov-Smirnov test. When normal distribution was not acquired the data were tested with Mann-Whitneys U-test requiring the same result as with a *t* test. The statistical analyses were performed with SPSS PC software, version 6.1 (Norusis, 1993).

Factor analysis was used for explorative purposes to reduce the number of tests into a subset of conceptual factors. The factor scores were saved according to the regression method and were used to compare the patient and control groups and for the logistic regression analyses.

A stepwise logistic regression analysis of each factor on driving performance pointed out which factor was most predictive. Since the neuropsychological tests are inter-correlated, a stepwise logistic regression analysis was to prefer.

The neuropsychological test battery comprised 14 variables in Study I (the Raven PM loaded < 0.50 in all factors, so 13 variables are presented in the factor analysis) and 13 variables in Study II. There were 58 subjects in Study I and 60 subjects in Study II. There are some recommendations in the literature about relationship between subjects and variables for applying factor analysis and regression analysis. Knapp and

Campbell-Heider (1989) explored different studies recommending a ratio subjects/variables 2:1 to 30:1. The most common ratio used was 10:1. Another liberal rule was that the number of subjects should be twice as big as the number of variables. Other suggestions were to use the difference between subjects and variables instead of the ratio. Harris (1985) (see Knapp & Campbell-Heider, 1989) introduced the rule for factor analysis where the difference 'subjects minus variables' should be more or equal to 30.

In Study I, the difference between subjects and variables was 44, and in Study II the difference was 47. Thus, the ratio subjects/variables were 4:1 in both studies. Knapp and Campbell-Heider argued, that the traditional ratio of 10:1 is not just too stringent but also often impossible to fulfill because of design limitations in clinical studies.

Qualitative methods

The qualitative methods used aimed at describing and interpreting driving characteristics in an on-road context. The purpose of qualitative methods is to increase and deepen the information content, and identify new characteristics, which are not captured by quantitative methods. Descriptions should explore the relevant and the unique but still keep qualitative distinctions between different aspects of the phenomenon (Larsson 1993; Kvale, 1996).

Replication in qualitative research has to do with reinterpreting phenomena, and focus is on variety. Larsson (1993) describes five validity criteria. (1) The discourse criterion, whether statements and arguments withstand other alternative statements and arguments. It proves the validity of the results, interpretations and discussion. (2) The results shall prove inter-subjective agreement. (3) The correspondence criterion is about concordance between reality and interpretation. The interpretations are to be grounded in the empirical basic data to fulfill the criterion. (4) The consistency criterion has to do with the relation between the parts and the whole. There should be consistency between interpretation (the whole) and data (parts). And, (5) the pragmatic criterion refers to the practical value of the study (Howe & Eisenhart, 1990; Larsson,

1993).

STUDIES I-IV

"La théorie, c'est bon,
mais ça n'empêche pas d'exister".
(Jean-Martin Charcot)

This thesis is based on four studies. Studies I and II assess cognitive functioning and driving performance and aim at analyzing cognitive functions, neuropsychological impairments and the predictive validity of the neuropsychological test battery of driving performance. Study III describes driving problems and adaptive aspects of driving after brain injury. Finally, Study IV contains four cases to illustrate how neuropsychological test results and a driving test can be used in a complementary fashion to evaluate the total driving performance after brain injury.

Study I

The objective of Study I was to study cognitive functioning and driving performance and to analyze neuropsychological impairments and the predictive validity of a neuropsychological test battery for driving. All subjects went through the neuropsychological examination. Twenty-seven patients and 26 control subjects carried out the simulator driving. All subjects made the on-road test.

The *neuropsychological tests* showed significant differences between patients and controls in all tests, except for the Simple and Complex Reaction Time tests. The results, thus, showed impairments in cognitive functions, including attention, and in executive functions measured by performance on time-pressure information processing tests, for instance, divided attention, and performance on problem solving tests.

In the *simulator driving task* the patients were driving as well as the controls in predictable situations. However, they had a slightly slower reaction to unpredictable visual stimuli and a tendency towards larger safety margins in terms of time headway, giving them more time to act in relation to vehicle ahead. In addition, the patients had

40

significantly less recalled words on the Listening Span test while driving in the simulator.

In the *on-road driving test*, the traffic inspectors classified 41% of the patients and 10% of the controls as failing the overall-driving score pertaining to driving performance (Figure 3). The difference between the groups was present in all sub-scales, but only significantly so in the scales of attention ($t(56) = 2.75$, $p< 0.01$) and in the overall-driving score ($\chi^2(1) = 13.52$, $p< 0.01$).

There was a low correlation between neuropsychological measures and the individual on-road driving scores. In addition, there was low correspondence between the simulator scores and either the neuropsychological or the on-road test scores. Gender, age, education, medical diagnoses and residual neurological symptoms were not significantly correlated with the on-road test scores.

A factor analysis of the neuropsychological test battery resulted in four factors, which accounted for 75% of the variance. The factors were named: *executive capacity*, *cognitive capacity*, *automatized attentional capacity* and *simple perceptual-motor capacity*. In a stepwise logistic regression analysis with the four factors on driving performance the *cognitive capacity* factor, was significantly classifying 76% of the subjects correctly concerning driving performance (Model Chi-square(1) = 6.18, $p = 0.01$). Including additional factors did not increase the level of correct classification of driving performance. The test battery per se classified 78% correctly in the driving performance variable in a stepwise logistic regression analysis (Model Chi-square(1) = 9.3, $p< 0.01$) with the *Simultaneous Capacity test* being the best predicting variable. None of the neuropsychological tests were able to predict the outcome variables of the simulator driving.

Study II

The aim of Study II was to replicate the study of cognitive functioning, driving performance, and the validity of a neuropsychological test battery for driving.

The patients were not different compared to controls concerning modification of

pre-morbid driving style, in terms of adapting strategies to various traffic situations except for avoiding long-distance driving. Thirty-seven per cent of the patients avoided long-distance driving compared to 13% among the controls ($\chi^2(1) = 4.36$, $p < 0.05$). One third of the patients avoided driving in darkness and in rain prior to the stroke, and so did as many in the control group. The patients had reduced their annual driving mileage ($\chi^2(1) = 10.06$, $p < 0.01$) after stroke.

All subjects went through the neuropsychological examination. Twenty-three patients and twenty-eight controls participated in the simulator driving, while twenty-eight patients and thirty control subjects carried out the driving test. Drop-outs from individual tests, related to driving performance, are described in detail in the paper.

The *neuropsychological test* battery demonstrated significant differences between patients and controls in cognitive processing, including attention, measured by performance on time-pressured, complex information processing tests, for instance, divided attention and working memory.

Driving in the simulator the patients were driving as well as the controls in all conditions. However, the patients had significantly less recalled words on the Listening Span test while driving in the simulator.

In *on-road driving*, the traffic inspectors classified 50% of the patients and 20% of the controls as failing the overall-driving score pertaining to driving performance (Figure 3). The difference between the groups was present in the overall-driving score ($\chi^2(1) = 5.77$, $p < 0.05$), and in the sub-scales speed, maneuvering, lateral position and traffic behavior.

Again, none of the neuropsychological tests were able to predict the score of the outcome variables of simulator driving. Nor was it possible to predict the individual on-road driving measures by the simulator-driving variables. However, in a stepwise logistic regression of driving performance using the simulator variables as independent variables Complex Reaction Time for visual stimuli and Distance to Collision in unpredictable situations were significant variables (Model Chi-square(2) = 14.99, $p < 0.01$). This model overall classified 85% of the subjects correctly.

In a stepwise regression analysis of driving performance using the neuropsychologi-

cal test battery variables as independent variables, Complex Reaction Time was significant (Model Chi-square(1) = 15.76, *p*< 0.01). Using this model 83% of the subjects were classified overall correctly concerning driving performance.
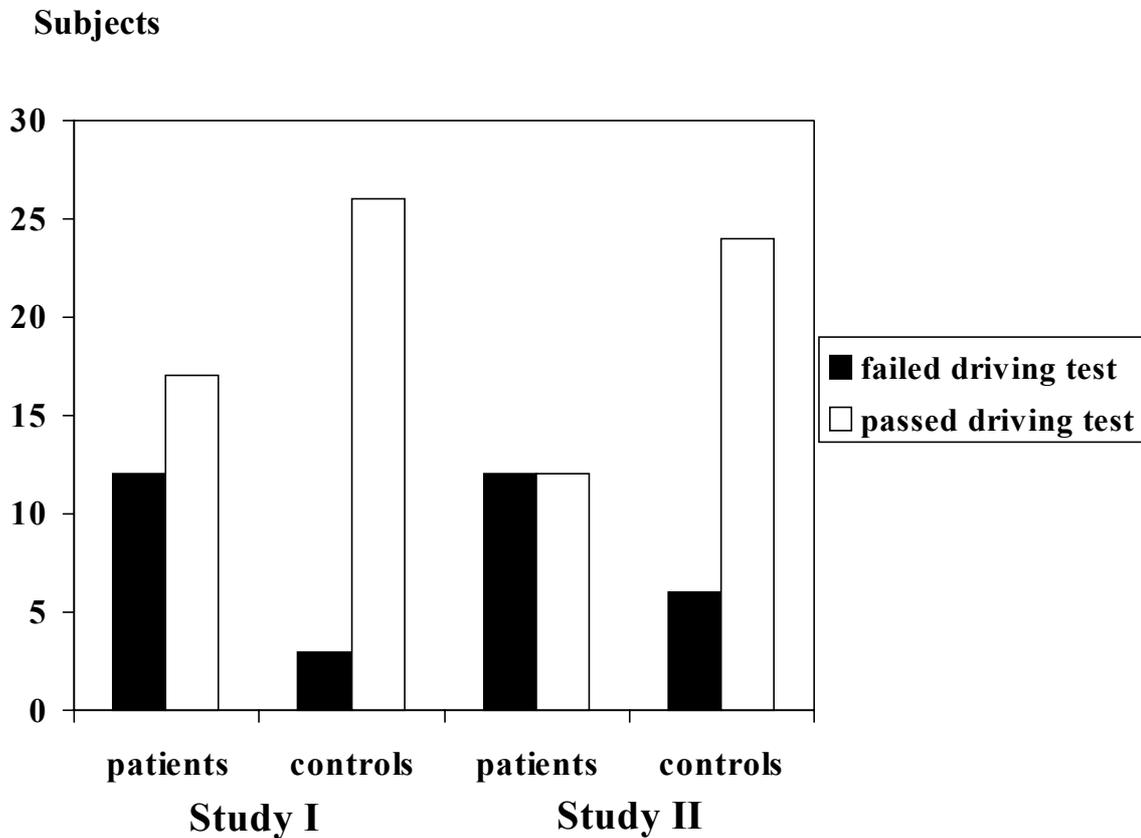
Subjects

Figure 3. Subjects passing and failing the driving test, Study I and II.

A factor analysis of the neuropsychological test battery resulted in three factors, which accounted for 73% of the variance. The factors were interpreted as: *attentional processing*, *executive processing* and *cognitive processing*. When driving performance was regressed on these three factors, the *cognitive processing* factor was again the most potent predictor, classifying 76% of the subjects correctly concerning driving performance (Model Chi-square(1) = 8.90, *p*< 0.01). Including the other factors increased the level of correct classification to 83% (Model Chi-square(3) = 18.35, *p*< 0.01). The cognitive processing factor was a significant predictor for group belonging,

as well as for driving performance. The *Color Word Test,* was the test that had the highest loading on the cognitive processing factor. The *Complex Reaction Time* test was the single most predictive *test* for driving performance in the whole battery. Neither gender, age, education, medical diagnosis nor residual neurological symptoms were significantly correlated with the on-road test scores.

Study III

Besides the quantitative assessment of driving performance in Studies I and II a *qualitative* approach was applied to make a more profound description of driving performance. Thus, the aim of Study III was to proceed from quantitative assessment of driving performance to qualitative description of driving problems and adaptive driving behavior among 22 brain-damaged patients. The data comprised 22 open-ended interviews by one informant from 22 driving occasions. The informant was a professional, certified driving inspector and he was interviewed immediately after each driving occasion.

The patients performed significantly lower on a minimal test battery (the Trail Making Test B, the Complex Reaction Time test, the K test, the Simultaneous Capacity test, and the Listening Span test) compared to a control group ($N = 59$). The control group, which was used in former Studies I and II was within the same age interval as the group of patients ($M = 56.4$, SD = 15.2). From the test results it was concluded that the patients suffered from moderate lesions, especially affecting controlled reaction speed and working memory.

Interview data were broken down into descriptive dimensions. The Swedish National Road Association uses an evaluation covering five evaluation areas: speed, maneuvering, lateral position, attention, and traffic behavior (VVFS 1998b; VVFS 1999). Manifestations of driving problems were found in all prescribed qualitative dimensions. In addition, three non-prescribed qualitative dimensions were found: *orientation*, *decision-making* and *confidence*. Adaptive aspects were: *anticipatory attention*, *slowing down speed*. In addition, pre-morbid *interest and motivation for driving safely*,

and *driving experience* were emphasized for maintaining driving performance after brain injury.

Examples of driving problems within the individual dimensions are described in detail in the paper. Driving problems related to the operative level of control concerned elementary driving skills like speed control, maneuvering and position.

"There was no speed adjustment keeping the same speed despite oncoming vehicle".

"He had problems with the clutch".

"He crossed through roundabouts without knowing that there was a vehicle beside the car, and driving course was unsteady, constantly staggering between the midline and the verge".

The tactical control level concerned attention, traffic behavior, orientation, confidence and decision-making.

"He is looking but the question is what he sees. Sometimes he obviously does not see the relevant things… looking but not perceiving. Passing just in front of another vehicle".

"She was stopping and standing without knowing where to go despite clear instructions. She asked a lot in obvious situations showing difficulties to plan her driving".

Besides driving speed adjustment, which in most cases was a reduced driving speed, pre-morbid interest and motivation for safe driving, and driving experience were qualitative aspects for appropriate driving performance after brain injury.

"He is interesting in driving issues. He asked and discussed traffic and traffic rules".

"He was not just concentrated on the driving but he also tried hard to drive safely. Something more than just learning to drive is required to have such a driving behavior".

Besides focused and divided attention, the interview data uncovered the importance of *anticipatory attention* as a central concept tied to the subjects' capacity and experience.

> *"Early attention provides early information that allows time and space to act, in order to avoid surprises in the traffic environment… all of this leading to a smooth driving behavior. If you provide yourself with time you also have alternatives of choice".*

Anticipatory attention was considered a controlling attentional function, directing the processing resources flexibly and appropriately between the different information processing components.

The overall information processing ability was analyzed into some of its constituent functions relevant for driving. It comprises both encoding, storage and retrieval of information and all components are integrated in a short time during processing. What represents speed of processing is the ability to quickly allocate the limited resources of working memory to encoding, storage and retrieval operations. And, the controlling attentional system, or central executive, is assumed to supervise and coordinate the interaction between the different components. During driving a monitoring search set is keeping traffic information in working memory while processing and preparing the driver to act appropriately in the future. The central executive is crucial for directing and executing the anticipatory attentional control necessary for efficient driving. In the interviews "reading" the traffic was considered such anticipatory attention.

According to the interview data anticipatory attention was a relevant adaptive ability that makes it possible to plan in advance and give time and space to act. Slowing down driving speed was considered having the same effect to give time for alternative actions. Also a premorbid interest in driving and motivation to drive safely were important for maintaining driving. Given cognitive impairments, motivation to drive safely can influence the driver to make strategic and tactical decisions. In addition, driving experience is supposed to improve driving performance. It was emphasized in the interviews that driving experience depends on *how* the individual can profit from

earlier traffic situations, how s(he) can utilize critical incidents for modifying his/her driving behavior. If the driver can take into account expected traffic events, which (s)he has learned from similar earlier situations, adaptive driving behavior will be facilitated.

Study IV

The purpose of Study IV was to demonstrate the relevance of cognitive factors for interpretation of driving problems. The study also demonstrates that the driving test is important to show compensatory capacity that is not revealed in the cognitive assessment in some drivers with brain injury. It comprised four cases. Data were taken from neuropsychological assessment and on-road driving.

Case 1 was a retired professional driver suffering from a traumatic brain injury. He showed impaired attention in the neuropsychological assessment as well as during driving on road. There were also several results indicating impaired executive inhibition, which may explain some of the shortcomings during driving. His impulsive behavior and impaired anticipatory attention were probably due to impaired working memory and executive dysfunction.

Case 2 was a male assembler with a residual condition after a right frontal intra-cerebral infarction. He showed considerable indications of a moderate hemi-inattention to the left on neuropsychological tests as well as during driving on road. Although the moderate hemi-inattention accounted for most of the driving failures, impaired executive inhibition and poor understanding of the traffic situation were present as well. His slow information processing, especially in complex traffic situations, indicated an impaired working memory.

Case 3 was a female storeman with a residual condition after a left thalamus infarction and a basilaris aneurysm, which was removed by surgery. The neuropsychological assessment showed a discrete hemi-inattention, which was unobserved in the medical examination. In addition, she had impaired divided attention and working memory capacity, which also was verified during the driving. She demonstrated impulsive re-

sponses on neuropsychological tests and impulsive driving behavior indicating impaired executive inhibition.

Case 4 was an assistant nurse who suffered an intracerebral infarction laterally close to the right ventricle. Although she had impaired divided attention, executive inhibition, working memory and visuo-spatial construction, she adapted her driving performance carefully and slowed down driving speed.

Two patients (cases 2 and 3) did not pass the driving test and the professional driver in case number one passed the driving test with hesitation.

Although driving is to a large extent automatized, controlled processing is required when the traffic situations are complex and the routine reactions are insufficient. Controlled processing is vulnerable to time pressure because one has to hold information temporarily in working memory with its limited capacity for encoding, temporary storage and retrieval operations. Difficulty with processing simultaneous and successive information might be revealed during driving. In the present study, all four patients showed executive inhibition impairments, three patients had impaired working memory and three patients showed impaired information processing and impulsive behavior during driving as well. Neuropsychological impairments were confirmed to a great extent by qualitative characteristics in the driving test.

Patients who are well aware of their dysfunction and have a long driving experience might adapt their driving behavior despite neuropsychological impairments, as the patient in case 4 did. Slowing down speed was probably a strategy for her to adjust to cognitive workload. Then she acquired time to anticipate events and to process information despite her mental slowness and impaired working memory.

Sometimes the driving inspector finds it difficult to interpret driving problems related to brain injury. A neuropsychological assessment is therefore relevant when evaluating driving shortcomings. Thus, collaboration between the neuropsychologist and the driving authorities can promote neuropsychological understanding and experience of driving expertise for a more confident total evaluation.

MAJOR RESULTS

Studies I and II showed that the predictor variables (neuropsychological test results) could predict the external criterion variable pertaining to driving performance. Thus, 78/83 % of the subjects could be correctly classified in terms of driving performance (i.e., pass/fail) respectively. The *cognitive factor* in Study I, containing PASAT, the Simultaneous Capacity test, the Listening Span test and the CFT recall, as well as the *cognitive factor* in Study II, containing PASAT, the CWT, the Listening Span test and the K test, were best in predicting driving performance. Thus, the results generally demonstrated that cognitive functions, in terms of divided and focused attention, and information processing speed, which require working memory, were significantly related to driving performance outcome, and that cognitive functioning is relevant for driving performance.

Study III showed that, among several cognitive demands for driving performance, attention stands out to be a critical function. The results highlight the importance of *anticipatory attention* as a working memory based attentional system. Anticipatory attention demonstrated qualitatively that working memory is a prominent function in a real driving context. Thus, impaired anticipatory attention came out strongly identifying driving problems, and sufficient anticipatory attention was a salient adaptive strategy besides adjustment of driving speed. In addition, interest in driving, motivation and interest for driving safety, and driving experience appeared relevant for driving quality after brain injury.

Study IV presented neuropsychological test results and driving evaluation results from four brain-injured patients. Driving problems and adaptive driving strategies were discussed from a neuropsychological perspective. The four case studies demonstrated the importance of *executive inhibition* and *anticipatory attention* for driving performance. In addition, anticipatory attention was discussed in terms of working memory. Adaptive driving strategies in terms of adjusted driving speed that provides time to anticipate events in the traffic environment and time to process information, despite cognitive slowness, was demonstrated in one of the cases. It was emphasized

in the paper, that collaboration between neuropsychological and driving expertise will promote and deepen the total assessment of driving performance.

EXTRA ANALYSES

In order to explore whether diagnosis, localization of injury, and driving experience correlated with driving performance some analyses, which are not presented in the papers, were carried out.

Studies I and II

In Study I, there was no difference between the patients suffering from traumatic brain injury and those, who suffered from subarachnoidal haemorrhage concerning driving performance ($\chi^2(1) = 0.221$, $p> 0.05$). All nine right-hemisphere injured patients passed the driving test, while two out of five left-hemisphere, and six out of twelve with bilateral brain injury passed the driving test. There was a significant difference between right and left hemisphere injured patients concerning driving performance (Fisher's Exact Test $p = 0.03$).

In concordance with Study I, there was a significant difference between right and left hemisphere injuries concerning driving performance (Fisher's Exact Test $p = 0.01$) in Study II. Four patients suffering from right hemisphere injury passed the driving test, while one out of nine patients with left hemisphere injury, and two out of five with bilateral injury passed the driving test. Some reservations must however be made, because, in one third of the patients localization of the lesion could not be verified from the medical casebooks.

Driving experience, in terms of annual mileage ($\chi^2(1) = 1.09$, $p> 0.05$) and frequency ($\chi^2(1) = 2.92$, $p> 0.05$), was not related to driving performance in Study I. However, in Study II, driving experience, in terms of mileage *last year* was significant for driving performance ($\chi^2(1) = 6.05$, $p = 0.01$). Eight of the 60 subjects had not resumed driving, therefore $N = 52$.

The subjects scored on average 5.3 on a scale ranging from $1 - 7$ ($N = 103$) con-

cerning how realistic the simulator driving was, and their qualitative opinions were that the simulator driving was monotonous, stiff, with loud motor sound, but also exciting and interesting.

Performance in time-pressure information processing tests (TMTB, Simultaneous Capacity test, Complex Reaction test and K test) were most strongly related to the on-road test scores with correlations in the order of 0.40 - 0.50 in Study II.

An analysis was made to find out whether the logistic regression model was valid for predicting driving performance in a population without brain injury. The model could classify 93% of the control subjects correctly (Model Chi-square(1) = 4.70, $p<$ 0.05) in Study I, and, in Study II it could classify 84% of the control subjects correctly (Model Chi- square(1) = 10.90, $p<$ 0.01). Thus, the generality of the conclusion when it comes to prediction of driving performance is independent of group. In addition, when control subjects in Study I and Study II were compared, the young controls performed significantly better in all neuropsychological tests compared to the older controls ($p<$ 0.01). However, concerning an overall-driving performance there was no significant difference between the young and old control subjects (Fisher's Exact Test $p =$ 0.47).

Sensitivity and specificity of the neuropsychological test battery were analyzed. Sensitivity concerns to what extent an instrument can identify true positive individuals, while specificity concerns to what extent the instrument can 'free' true negative individuals. In addition, there are false positive and false negative individuals. False positive individuals are those, who fail the assessment instrument, although they pass the outcome criterion. False negative individuals are those who pass the assessment instrument although they fail the outcome criterion.

We decided that failing at three of the four most sensitive tests (Study I: Simultaneous Capacity, PASAT, TMTB, Listening Span; Study II: Complex Reaction Time, K test, CWT and Simultaneous Capacity test) would indicate 80% sensitivity. From that decided sensitivity, specificity levels of 77% (in Study I) and 80% (in Study II) were attained. When classifying subjects corresponding to these sensitivity and specificity levels the distribution was as shown in Table 3:

Tabel 3. *Subjects classified corresponding to sensitivity and specificity (Study I: 80/77; Study II: 80/80) on driving performance and on the four most sensitive tests.*

Study I.	Minimal test battery				Study II.	Minimal test battery			
	-	+				-	+		
Driving performance −	12	3	15		Driving performance −	15	4	19	
Driving performance +	10	33	43		Driving performance +	7	28	35	
	22	36	58			22	32	54	

Note: in Study II, two patients were not driving, two patients and two controls did not complete the CWT test, and one patient did not complete the K test. Therefore, $N = 54$.

In Study I, twelve true positive and 33 true negative subjects were identified while ten subjects were classified as false positive and three were classified as false negative. That is, ten subjects would have been dissuaded from driving despite passing the driving test, using the four tests alone, and three subjects would have been allowed to drive despite failing the driving test.

In Study II, fifteen true positive and 28 true negative subjects were identified while seven subjects were classified false positive and four false negative. That is, seven subjects would have been dissuaded from driving although sufficient driving performance using the four tests alone and four subjects would have been allowed to drive despite failing the driving test.

A stepwise logistic model generated for the four tests was significantly associated with outcome on the road evaluation, classifying 78% of the subjects in Study I (Model Chi-square(1) = 9.27, $p< 0.01$) and 81 % in Study II (Model Chi-square(2) = 23.49, $p< 0.01$) correctly. In this analysis, the Simultaneous Capacity test in Study I and Complex Reaction Time and CWT in Study II were most significant.

A regression analysis of the total number of subjects in Study I and II was carried

out (see Appendix IV). It was shown that the neuropsychological test results predicted driving performance. Age was an additional potent factor underlying the neuropsychological test results and thus had an indirect impact on driving performance. Group belonging that is, whether the subject was a patient or a control, was less important. On the other hand, univariate comparisons have shown that significant differences exist between controls and patients for most of the neuropsychological variables. However, the neuropsychological test results had a stronger predictive validity on age than on group belonging. Given that neuropsychological tests, age and group were independent variables and driving performance the dependent (criterion) variable, group belonging was significant. The relationships can be illustrated in the path diagram below:

Age ⟶ Neuropsychological test result ⟶ Driving performance

Age ⟶ Neuropsychological test result ⟶ Driving performance
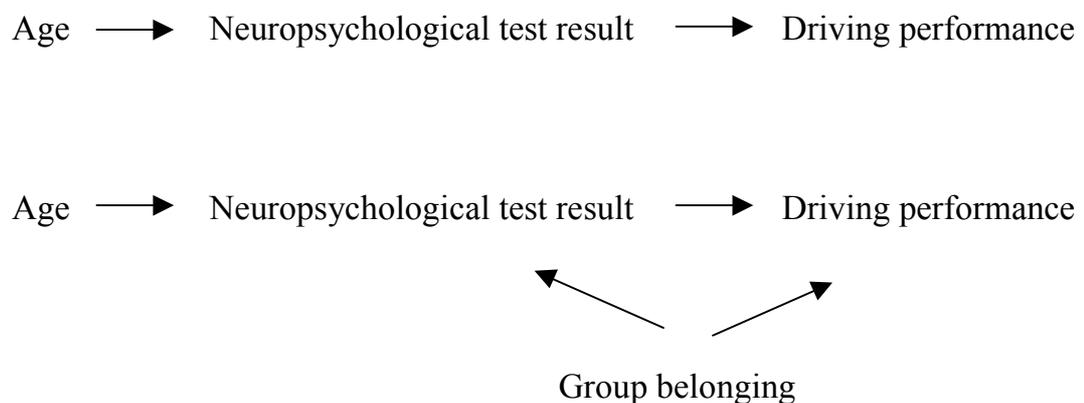
Group belonging

Figure 4. Relationship between neuropsychological tests, age and group belonging as independent variables and driving performance as dependent variable.

Visuo-spatial function, assessed by CFT copying and WAIS Block Design, was not significant for driving performance in Study I (Model Chi-square(2) = 3.37, $p = 0.19$), nor in Study II (Model Chi-square(2) = 4.00, $p = 0.14$).

Study III

Diagnosis was not related to driving performance ($\chi^2(3) = 2.695$, p> 0.05), nor whether the subject was a volunteer or referred to a driving evaluation (Fisher's Exact Test *p*> 0.05). The interview material in Study III contained ideas about what critical traffic situations appeared during the driving route. Critical traffic situations were: (1) turning left with meeting vehicles and/or cycle lane or pedestrian crossing, (2) complex situations leading to orientation problems due to too much information to process concurrently, (3) side road connecting to main road.

Summary of the extra analyses in Studies I, II and III

Patients (Studies I and II) had reduced annual mileage driving following brain injury. In Study II driving mileage during the last year was significant for driving performance. The cognitive factor in both studies predicted driving performance in the control groups. The Simultaneous Capacity test in Study I and the Complex Reaction Time test in Study II were the best predictors of driving performance. The Simultaneous Capacity test taps a number of both attentional and processing functions including divided attention speed, processing speed, and the Complex Reaction Time test requires divided attention speed and executive inhibition.

When a minimal test battery was administered, 88 of 112 subjects (79%) were classified correctly. Age was a potent factor underlying the neuropsychological test results.

Critical traffic events were complex situations (e.g. turning left in intersections with oncoming vehicles) demanding to process a great amount of information simultaneously.

DISCUSSION

The present findings show that a neuropsychological test battery assessing cognitive functions could classify 78-83% of the subjects correctly in terms of driving performance (i.e., pass/fail). Neuropsychological impairments in information processing speed, divided and focused attention, requiring working memory, are associated with limitations in driving performance, especially after brain injury. Qualitative aspects of the same cognitive core problems, such as impaired orientation, decision-making, confidence, and, especially, impaired anticipatory attention, appeared to constrain driving performance. Adaptive strategies in terms of adjustment of driving speed and anticipatory attention were salient for driving performance after brain injury. In addition, interest in driving, motivation for safe driving, and driving experience appeared relevant. Collaboration between medical, neuropsychological and driving expertise was demonstrated to promote a total evaluation of driving performance after brain injury.

The patients performed worse in overall driving compared to the control subjects. As expected, there was a clear difference in both Study I and Study II between the patient and control groups on most of the neuropsychological test performances. The results suggest that the patients had attentional deficits in a broader sense, impaired speed of cognitive processing, and limitations in the amount of information that could be handled concurrently.

To explore what concepts were underlying the neuropsychological test battery, factor analyses were carried out. Both studies produced factors, which were interpreted as: *attentional*, *cognitive* and *executive*. In addition, Study I produced one factor named *perceptual-motor*. The attentional factor in both studies comprised attention and motor speed, while the cognitive factors comprised cognitive capacity but also attention in terms of working memory. The cognitive factor could best predict the external criterion variable pertaining to driving performance. Thus, it can be suggested that the cognitive factor is composed of more significant components for driving performance and that it is superior to the attentional factor because it includes also some attentional aspects. It can therefore generally be suggested that cognitive functions, in

terms of focused and divided attention, and working memory are relevant for driving performance.

Automatized and controlled processing

The novice driver is dependent on knowledge-based controlled processing. At that level of control, selective attention and supervisory attentional control are required. As experience grows, driving components constitute routine programs, which form schemata, which are then organized into systems of schemata: a skill is acquired (cf. Shallice, 1982, 1988). According to the hierarchical models, the driver has more processing resources available for unexpected traffic events when (s)he can rely on skilled performance. If something unexpected happens, the supervisory system forces the processing to known rules or knowledge, which rely on semantic and episodic memory. For instance, adjustment of steering and speed as a reaction to a slippery road can be seen as a rule-based controlled behavior.

Thus, driving involves both automatized and controlled processing operating interactively (cf. Ranney, 1994). At the operational level, most processing is considered automatized with cognitive and motor schemata operating in parallel and generally with comprehensive capacity. The operational driving skills are on-line driving behavior but also control of the car requiring prompt reactions. It is directed by stimuli in the environment that are currently perceived and reacted to. Thus, fast perceptual reactions and motor speed are required at this level. The attentional and simple perceptual-motor factors produced by the factor analyses are to a great extent corresponding to the operational level.

In novel and unexpected traffic situations operational driving is insufficient. Then, cognitive workload and uncertainty will change allocation of attention from automatized noticing of the traffic environment to active searching and controlled processing to deal with the ambiguous and complex situation. Judgements and decisions are based on inferences from the current traffic context but also on past experience stored in long-term memory as knowledge. Whether the driver will change allocation of atten-

tion to controlled processing depends on his judgement of the complexity of the situation and his own ability to cope with that complexity. The controlled processing draws on limited capacity resources (cf. Eysenck & Keane 2000). The cognitive factor, which was most potent to predict driving performance in Studies I and II, is therefore supposed to have a significant impact on tactical driving.

It is generally claimed that in routine driving the experienced driver relies more on automatized processing of traffic input than the less experienced driver (cf. Ranney, 1994). However, when the workload threatens to be higher than the driver's capacity, even the experienced driver needs, immediately, to concentrate and allocate efforts to the most demanding part of the task, that is, to give priority to the most important task and exclude others. For instance, when driving on a dark, although familiar, road in rain weather, the driver must focus on the road lane, and on meeting vehicles and make adjustments to safety margins because of the poor visibility.

Thus, there is a momentary interaction between automatized and controlled processing. Given that driving is automatized, there should be no problems for the experienced driver to manage a second task concurrently, like talking in a mobile phone. However, it is well known that driving speed is generally reduced when the driver is occupied by a conversation (Alm & Nilsson, 1994; Brown, Tickner & Simmonds, 1969), and listening to the radio will generally be interrupted during overtaking.

There is also some doubt whether driving can be regarded that much as an automatized task as is generally emphasized. Groeger and Clegg (1997) scrutinized the automaticity and found that even simple components of the driving skill, for instance gear change, appeared incompatible with performing a second task. Neither practice nor specialized training generate automaticity. "What has been widely cited as an everyday example of an highly automatized task, when closely examined, actually shows few if any of the hallmarks of automaticity. Given this, we are very doubtful indeed that the performance of any more complex aspects of the driving task is likely to become automated" (Groeger & Clegg, 1997 p.145).

In line with this, it is interesting to evaluate to what extent the driver can use automatized driving skill after brain injury. In Study I there was no difference between pa-

tients and controls concerning operational driving components, like speed, maneuvering and position, which are considered mainly automatized. Conversely, in Study II automatized driving skill was significantly worse in the patient group compared to the controls. One explanation could be that the patients in Study I had a long driving practice post-injury, while the patients in Study II had less driving practice after onset of the illness. In Study IV, we could see that long pre-injury driving experience (cases 2 and 3) did not provide sufficient driving performance concerning speed, maneuvering and position to carry out the driving test without problems. In conclusion, driving experience per se is not sufficient for driving skill. Patients might need practice also for automatized driving components before they resume driving after brain injury.

It is important to find adaptive strategies when routine driving behavior is affected by brain injury. In the current studies we found that people modified their driving habits and driving style by strategic decisions as well as by tactical decisions when former driving capacity was not working. For instance, patients (Studies I and II) reduced their driving and avoided long-distance driving and driving in darkness and rainy weather after brain injury (cf. Brouwer et al., 1990). It was also shown that slowing down speed and attending to traffic events early were important adjusting strategies, which increased driving quality (Study III).

Attention

Attention plays a crucial role for information processing in the ability to cope with two simultaneous tasks. This capacity, that is, to keep two or more lines of processing going on as in solving two problems concurrently, or to remember one thing while doing another, is often affected by brain damage (Lezak, 1995). It was also the result of our studies (Studies I and II), which showed that the patients had reduced performance on tests requiring speed of information processing, especially in complex tasks, in which strategies to divide, allocate and shift attention were required. Performance on the TMTB, the Simultaneous Capacity test, the Listening Span test and the PASAT was significantly different between patients and controls.

To shift between automatized and controlled processing is indeed what is required

for driving. It was shown that the Simultaneous Capacity test, the TMTB and the Listening Span test, which demand processing of two tasks concurrently by switching attention between them, could separate the subjects, who passed the driving test from those who did not.

To monitor two or more sources of input puts increasing demands on short-term-memory. If switching attention per se requires more time, like in brain-damaged patients, there will be an extra load on working memory. Then the reduced capacity often results in slow and inflexible behavior. The reduced performance might depend on impairments in the supervisory attentional control, which directs attention between the processing components within working memory. Impaired *orientation* was one qualitative aspect of driving problems, that was uncovered (Study III). It was interpreted as a deficit in processing a sequence of information and missing the second part of the message. Thus, a reduced capacity of working memory was probably underlying impaired orientation.

Impaired attention accounts for a great part of driving failures (Reason et al., 1990). Study III presented examples of errors, for instance, lapses of attention and distraction. Although not expressed in quantitative terms, *errors* were: attending late to traffic light which led to hard braking, inattention to other vehicles in traffic junctions, and miscalculating distance to oncoming vehicles and vehicle ahead. *Mistakes*, that is, when the driver makes a plan but the plan is incorrect, were also demonstrated in Study III. For example, impaired orientation in an intersection, unawareness of correct direction in spite of clear instructions, impaired decision-making, that required other road users to solve the traffic situation, and entering highway in the opposite direction. Mistakes caused inconsistent and impulsive driving behavior when the driver discovered them. Generally, to cope with a mistake will cause significant cognitive workload, because when something goes wrong the driver has to attend to the on-line situation and concurrently identify the mistake, analyze what is wrong, and decide how to solve the situation. Errors and mistakes are often combined in a driving situation. For example, one professional driver (Study IV) missed to turn left in an intersection, which is supposed to be an error. After the inspector's reminder the driver made a

mistake when he suddenly turned into the first crossroad and reversed the car in a walk- and cycle-lane.

To summarize the discussion so far, attending to the right objects and the right events in the traffic environment means to pay attention to traffic signs, directions, and other road users. Shifting from focused to divided attention is done continuously. Thus, on the one hand the driver has to widen the attention and, on the other hand, focus on the essentials in the traffic, avoiding distraction. Figure 5 illustrates the influence of cognitive functions (i.e., executive function, different aspects of attention and perceptual-motor speed) on the completion of the driving tasks at the different levels of driving control.

Memory structures are in this context relevant underlying cognitive functions. Procedural memory provides routine driving programs, once driving schemata are activated. Semantic memory is stored in long-term memory and represents driving knowledge, while working memory is required when processing resources are directed between different information processing components, especially to serve anticipatory attention.

Controlled processing

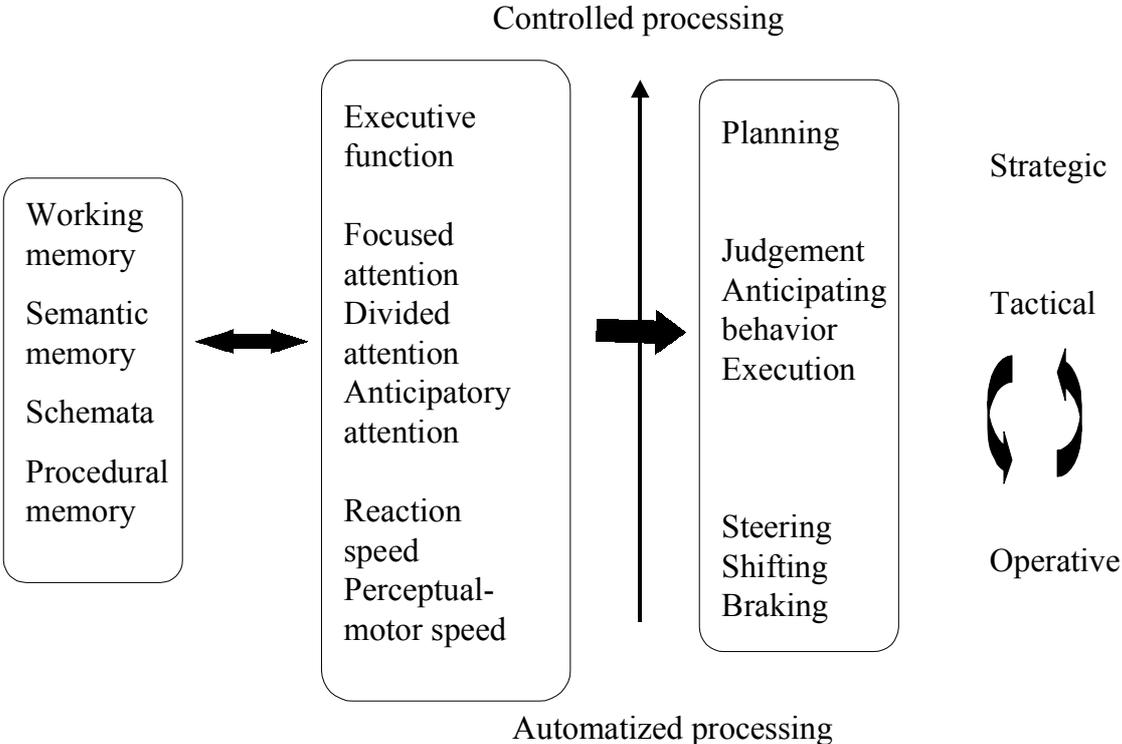| Working memory
Semantic memory
Schemata
Procedural memory | Executive function

Focused attention
Divided attention
Anticipatory attention

Reaction speed
Perceptual-motor speed | Planning

Judgement Anticipating behavior Execution

Steering Shifting Braking | Strategic

Tactical

Operative |

Automatized processing

Figure 5. Cognitive functions related to memory structures, driving variables and driving control levels

Anticipatory attention

"You may think that when you look,
you see, but looking is not enough.
You have to learn to see,
to see around corners,
to see right through…."
(Göran Tunström, 1998)

Another focus of the thesis was to describe manifestations of driving problems and adaptive driving strategies, respectively (Study III). For the purpose to explore and describe driving characteristics a qualitative approach was used. Besides problems in the prescribed dimensions *speed*, *maneuvering*, *road lane position*, *attention* and *traffic behavior,* and in the non-prescribed dimensions *orientation*, *decision-making* and *confidence*, Study III uncovered in qualitative terms the importance of *anticipatory attention* for driving behavior.

Impaired anticipatory attention was suggested to underlie several driving problems and was consistently emphasized among the drivers who failed the driving test. This is in accordance with Studies I and II, in which common driving mistakes were late planning, and short observation areas on intersections, which probably were due to impaired anticipatory attention. Late attention brings about surprises for the driver, leading to insufficient spatial and temporal safety margins and thus an impulsive driving behavior.

In Study III anticipatory attention was also a salient adaptive driving strategy among drivers who passed the driving test:

> *"Early attention provides early information. He*
> *was so early in attending. Getting problems, he*
> *solved them by being early in what he is doing,*
> *planning everything".*

If the driver can attend in advance approaching traffic lights, roundabouts, and speed and position of other road users, he gains safety margins in time and distance.

Thus, anticipatory attention facilitates decisions at the tactical level while an im-

paired anticipatory attention restricts the possibilities to make judgement of the ongoing traffic. If the driver manages to preview road conditions and traffic events, he may also reduce the need for cognitive effort to the driving task which will facilitate orientation, and decision-making and increase driving confidence. To anticipate the demands of a situation and prepare for acting in time are prerequisites for executive function. Thus, the executive function starts before there is any acting.

In the research domain of traffic psychology, and in the issue of driving after neurological deficits anticipatory risk behavior and risk avoidance are generally discussed (Brouwer et al., 1990; Van Zomeren et al., 1988). *Behavior* is what is observed in practice, but it does not describe the components of the cognitive process that precede anticipatory behavior. In addition, conceptions of information processing and divided attention describe speed and capacity, but do not deal with the components of the cognitive process.

In this thesis anticipatory attention is viewed as an intentional search set which keeps information in working memory for processing and acting. The main function of anticipatory attention is to continuously work at the edge of interplay between different control levels of driving. The driver continuously encounters information. The perceptions are encoded and temporarily stored within working memory where they are given conditions for valuing the content. Working memory directs what stimuli and information are selected, does some processing and takes action. This is in accordance with a recently updated model of working memory (Baddeley, 2000). Baddeley proposes an additional component in the working memory system that temporarily stores information into episodic representations. The 'episodic buffer' is episodic in the sense that it stores episodes and can integrate information from different sources in space and time.

Speed of processing is dependent on the encoding, the temporary storing and the ability to recognize previously acquired information, that is, driving schemata, which have become integrated as experience and stored in long-term memory. To switch attention flexibly between encoding, temporary storage and utilizing of the pre-planned schemata is the critical component in working memory. Inefficient encoding gives less

temporary storage capacity because more of the available resources must be allocated to the encoding per se. Speed may be at the expense of encoding and storage, and encoding, storage and speed may be at the expense of effort, which might cause extended fatigue for the driver. Impaired anticipatory attention is due to decreased capacity in encoding, temporary storage or retrieval. Consequently, impairment in working memory capacity probably reduces anticipation of successive information into an integrative and coherent context.

Figure 6 first illustrates that the driver's present interpretation of information, his/her judgement and decision-making are, on the one hand, dependent on retrieval from semantic and episodic memory. On the other hand, the driver has to anticipate future events to make appropriate judgements and decisions that are here described as "reading" the traffic. Thus, the *functioning of anticipatory attention is to process the present for serving the future by the help of the past.*

The second general feature illustrated in Figure 6 is about feedback and feed forward: present information processing is assumed to feed back information that will be integrated in experience and increase driving knowledge, and feed forward preparing action in the immediate future.

Past   Present   Immediate future

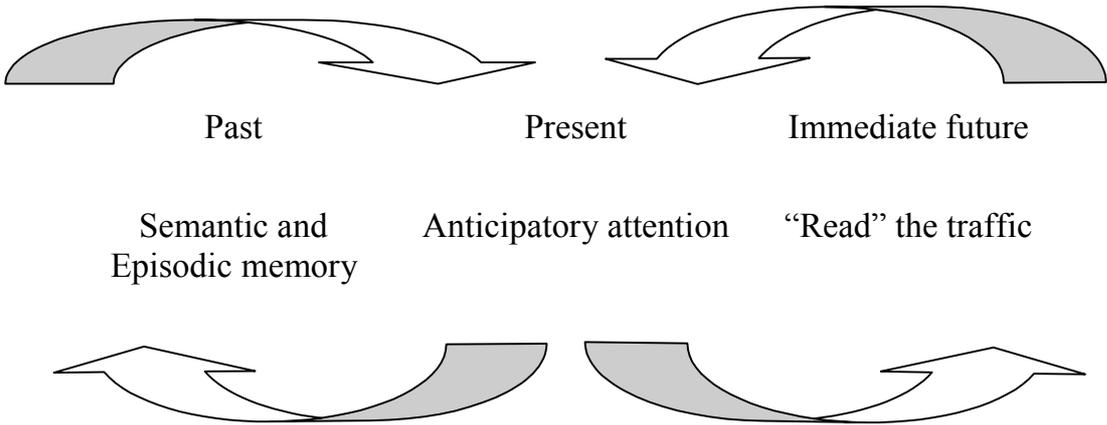Semantic and   Anticipatory attention   "Read" the traffic
Episodic memory

Figure 6. Continuation of past – present – future. Past experience and anticipatory attention provide the driver with a continuation through time.

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Reliability, validity and predictability of driving performance measurement

The results and conclusions could be evaluated from a variety of reliability and validity aspects. Are the test variables that are used responsible for the driving performance outcome, or can it be considered that some extraneous variables have influenced the results? Can the results be generalized to other populations and to general driving situations? How well can the various variables and tasks be applicable to driving performance and predict the outcome in a real situation, that is, their reliability, ecological validity and predictability (Cook & Campbell, 1979; Eysenck & Keane, 2000).

Reliability

Standardized methods assessing neuropsychological functions, simulator driving and driving on road were used to strengthen the reliability of results. Also, counterbalancing of the neuropsychological testing enhanced the reliability. In addition, experienced driving inspectors were used for the driving evaluation, applying blind evaluation so as to avoid reliability problems

The purpose of separating Study I and Study II was to make a replication of the study, that is, to test the model on a second brain-injured group suffering from another neurological disorder, with shorter time since onset of illness, and with a different age. The replicated results strengthen the reliability, validity and generality of the evaluated model.

Validity

Internal validity. There are some issues concerning the internal validity of the results. First, there is a difference between test application and the theoretical concepts they are supposed to represent. No neuropsychological test measures only one cognitive aspect. The theoretical concepts pertain to basic cognitive issues of human processing, while neuropsychological tests measure performance at a functional level that has a more comprehensive explanation of the outcome. The reason for using control groups was to test whether the neuropsychological tests actually capture the cognitive

impairments that they are supposed to do. In addition, the control groups showed how people without brain injury are performing on neuropsychological tests, simulator driving, and driving on-road. They also showed that the logistic regression model for the brain-injured groups was valid also for a population without brain injury.

The second question is whether factors related to the research design and instruments used could have influenced the results. To control for this problem, different aspects will be addressed.

One factor, which eventually influences the internal validity is that subjects are much more familiar with the driving activity compared to the simulator driving activity and neuropsychological testing. This might generally produce a more representative and better driving outcome and a generally lower simulator driving and neuropsychological test outcome. Thus, there will be some intrusion between the methods used. All subjects did not have equal level of theoretical driving knowledge and experience of equal complexity of daily driving environment. However, there was no difference between subjects passing and failing the driving test concerning daily driving environment. The patients in Study II had not driven continuously since the onset of their illness, although they were matched according to premorbid driving experience. As a consequence, driving experience, in terms of mileage *last year* was significant for driving performance in Study II.

Finally, one factor that might affect internal validity is that: being evaluated, whether it is neuropsychologically or concerning driving performance, might be more stressing for the patients. They are probably more motivated to do their best but might get more nervous compared to control subjects because the evaluation is more real for them. To neutralize the situation, we emphasized the voluntariness and that the outcome would not have any practical consequences for the participants (Studies I and II).

External validity. Another major aspect of validity concerns what designs were used for studying driving performance, how well the various variables and tasks represent the issue, and population validity.

The neuropsychological tests offer standardized quantitative data and reliable results. They mainly measure functions corresponding to the operational, and to some

extent, the tactical level of driving. However, driving is a multi-factor ability requiring aspects beyond functions measured by neuropsychological tests. The tests do not necessarily have ecological validity or face-validity for driving performance. One difference, which has an impact on the validity, is that between a *function* and a *competence* (Salthouse, 1990). It can be demonstrated that, despite a low level of cognitive function, a person may sometimes have a sufficient driving performance by using his total abilities reaching a certain level of competence. Neuropsychological tests aim at *reproducing* cognitive functions like reaction speed and divided attention. The test situation is relying entirely on information inherent in the current test. Contrary to the neuropsychological test situation, the driving test evaluates how the driver copes with traffic information to make specific decisions in that specific situation. Thus, driving performance is evaluated in an ecologically valid activity, which utilizes the subject's total abilities in adapting to the driving situation. In a *productive task* like driving there is a lot of task-support in cues from the environment (see Rönnberg & Bäckman, 1995).

However, the driving task demands processing of multiple stimuli simultaneously and the driver might be tempted to attend to irrelevant stimuli, which are minimal in the neuropsychological test situation. Assessing, for instance, attention by neuropsychological tests excludes a certain extent of additional intrusion but does not provide additional contextual support. A task analysis (Rönnberg & Bäckman 1995) might establish what demands are inherent in carrying out different tasks. Concerning neuropsychological tests a task analysis may describe duration of stimulus presentation, number of distractors and position of stimuli in simultaneous processing. An analysis of the driving task may describe what external cues are available, the variety of complexity and what possibilities there are to use experience and, thus, describe to what extent operational or tactical driving is required.

Another difference, which may also have an impact on the external validity, is the process of *decision-making* in neuropsychological tests and in driving activity. To make a decision the individual has to choose between a set of alternatives. The process includes an evaluation of relevant attributes for the choice but also of alternative

choice outcomes. Decision-making has to do with risky-riskless outcomes, single-attribute versus multi-attribute situations and single- or multi-stage processes (Eysenck, 1990). Neuropsychological test-decisions involve a low risk outcome, and compared to driving decisions they are single-attribute and single stage. Conversely, driving decisions are to a great extent risky, due to some uncertainty about the out-come, and there are multiple traffic attributes for integrating information into an over-all driving decision. For example, decision-making in an intersection during rush hour is a multi-attribute situation, which implies a multi-stage decision because the choice will lead to another choice, which will have implications for the next choice and so on.

Attention and information processing speed are assessed by two-dimensional tests, while in real driving anticipatory capacities are important for selecting information and making appropriate decisions in the complex three-dimensional environment (cf. Tipper, Lortie & Baylis, 1992).

Driving in a simulator is standardized providing quantitative data and reliable re-sults. It has some ecological and face validity relating to operational and tactical levels of driving, however not to the strategic level of control. Unexpected traffic situations can be built-in without dangerous consequences and the driver can be quite confident that there is no real collision risk. However, the validity of simulators depends on the design of the driving route and on the subject's motivation to drive as realistically as possible. It is generally verified that it is difficult for the driver to turn 90^0 in an inter-section when driving in a simulator. There is a difference in perception of the close environment when driving in a simulator compared to driving in real traffic (personal communication, Håkan Jansson, VTI). Consequently, it is ticklish to evaluate driving in intersections, which are suggested to be the most risky traffic situations in real traf-fic, at least for older drivers (cf. Brouwer & Ponds, 1994; Hakamies-Blomqvist, 1996). In Study I the simulator driving outcome was not able to predict individual on-road driving measures, nor overall-driving performance. However, in Study II, Complex Reaction Time for visual stimuli and Distance to Collision in unpredictable situations were significant variables for an overall-driving performance.

The simulator route in our studies was comparable to a country road with low-

density traffic. That design might have been too easy, partly explaining the lack of correlation between simulator driving variables and individual road driving variables. In addition, it seems that all subjects in our studies (Studies I and II) were driving very carefully probably due to inexperience and uncertainty, which may have increased their attention, concentration and cautiousness. However, the subjects rated the simulator as fairly realistic although monotonous, stiff, and with loud motor sound.

Driving in a simulator needs practice because it is a novel situation for most subjects. Tallman (1992) found great differences between a demented group and controls when driving in a simulator. She questioned whether the simulator actually functioned as a valid instrument of driving performance and argued, that the simulator was sensitive to dementia because it is a *novel* task rather than a genuine indicator of driving ability. Quigley and De Lisa (1983) argued that for older patients, simulator driving is not considered useful in evaluating driving performance. The elderly generally feel uncomfortable with the novel equipment and prefer being evaluated in a real car. Withaar and Van Wolffelar (1997) found that patients had difficulty in handling the simulator driving equipment and got simulator-sickness also when driving at low speed. This is also what was found in Study II: among the elderly subjects, seven subjects did not participate in the simulator driving because they thought it would be too effortful and stressful for them, and one subject interrupted the driving due to simulator nausea. Also in Study I, five subjects interrupted the simulator driving because they did not feel well. Hakamies-Blomqvist et al., (2001) found that, concerning elderly persons, the validity of the VTI simulator is good for experienced drivers but it is unsuitable for drivers who have driving difficulties. They concluded that the simulator is thus not well suited for test purposes. However, for younger patients the simulator can be successful in teaching defensive driving techniques. Galski, Ehle and Williams, (1997) argued that it is not evident what skills and abilities are required in simulator driving and that simulator evaluation can mainly be useful for evaluation of *overall* driving performance.

On-road evaluation has ecological and, of course, face validity as it is used to measure driving performance in real traffic. Driving tests are generally criticized for

being the *only* external 'golden standard'. Being a sample from *one driving occasion*, it is less reliable due to individual and situational variations. During one certain occasion the driver might perform differently compared to his/her real competence and, although standardized, it is impossible to make the driving conditions constant for all test occasions. Besides, extremely dangerous traffic situations are avoided because of safety considerations. However, in the present studies the driving inspectors maintained, that the driving route represented ordinary traffic environments containing maximal traffic demands. The driving route was standardized in a physical way but not equally familiar to everybody. Familiarity reduces the cognitive demands of the driving test. However, most of the subjects were familiar to the local area, and driving performance was not related to whether the subject was living in the local area or not.

Concerning the population validity question, the subjects represent a typical driver population with respect to age and gender, and the patients were sampled from common brain injured groups. However, the exclusion criteria (Studies I and II) represent some limitation if a generalization is to be made to brain-injured population as a whole. One can notice that the patients suffering from left hemisphere injury significantly failed the driving test compared to patients with right hemisphere lesion. However, it is difficult to draw any specific conclusion from this, because information on localization of the lesion was received from medical records, and for several patients localization of the lesion could not be verified. To make a reliable localization one has to make a systematic examination and find patients with a clear focal lesion considering also disconnection problems.

All subjects in Studies I and II were voluntary, and there was no difference between voluntary and referred subjects in Study III concerning driving performance. However, we do not know if the subjects differ from those who refused to participate in the studies.

Predictability

To evaluate the predictive validity of the neuropsychological test battery with regard to driving performance logistic regression analyses were performed in which the

categories were pass/fail the driving test. The predictive validity was described in that the neuropsychological test battery could classify an overall-driving outcome of 78% of the subjects correctly in Study I. Then, the model verification predicted the pass-fail driving outcome in 83% of the cases in Study II, implicating a substantial internal validity.

Although cognitive capacity appeared to be most predictive for driving performance, other determinants beside cognitive functions, including attention, influence individual differences in a complex activity like driving.

Additional factors, which restrict the predictive validity of the neuropsychological tests might be driving experience and adaptive abilities. The neuropsychological test situation is generally novel to the subject while driving is relying on well-practised *experience*. Early in practice, declarative knowledge and supervisory control direct driving. However, gradually driving schemata are organized as cognitive representations of knowledge, generalizations and expectations, which facilitate understanding and anticipation of what will happen in similar traffic situations. New knowledge is added to the existing experience, which forces the schemata to be triggered in an automatized manner. Then, the driver can rely to a great extent on his driving skill. Contextual cues also facilitate anticipation of traffic situations, reduce the attentional demands on the driving task, and make quick interventions possible. The experienced driver is supposed to know what situations require enhanced attention. By anticipatory attention the brain-injured patient may avoid or reduce time pressure, which is very vulnerable for him/her (Brouwer et al., 1990; Van Zomeren et al., 1988).

Driving experience in terms of annual driving mileage was one of the matching variables. As expected, amount of driving years was not related to driving performance in these subject groups with long driving experience. Driving experience in terms of annual driving mileage was not related to driving performance in Study I while in Study II driving mileage during *the last year* was significant. Driving experience can also be described in terms of driving *frequency*, which was not significant for driving performance. Thus, driving experience in terms of recent driving experience in the older subject group was related to driving performance outcome. This is in accordance

with Withaar (2000), who found that in a group of cognitively impaired older drivers, recent driving experience during the last year was significantly related to driving performance. The main explanation of lacking relationship in Study I might be that all patients had a long post-injury driving experience.

It is generally argued that driving practice and experience enhance driving skill and confidence, which will provide safe driving. Lajunen and Summala (1997) showed however that drivers who trust their driving performance might also drive faster and accept higher accelerations. They do not experience uncertainty. On the other hand, safety-oriented drivers recognize the risks of high speed and, therefore, use lower speeds. Thus, *motivational* factors are certainly important determinants of driving behavior. In Study III, the interview data showed that a pre-morbid interest in driving and motivation to drive safely were supposed to be important for facilitating driving despite brain injury. Given cognitive impairments, motivation to drive safely can influence the driver to make strategic decisions like avoiding driving in rush hours and darkness. Motivation to drive safely and an interest in the driving activity develop driving competence, in that the driver learns from various traffic situations, profits from feedback and thus, enhances driving confidence.

Driving experience, driving style and motivation to drive safely are interrelated in a complex way. However, having an appropriate judgement and insight in one's own cognitive functioning and driving performance are also important factors for safe driving and helps the driver to make strategic and tactical decisions. The patients in Study I reported generally more memory problems and cognitive slowness compared to the controls, which implies that they had some insight in their cognitive state. In Study II however, there was no difference between patients and controls concerning subjective evaluation of cognitive deficits.

To summarize, besides cognitive capacity, driving characteristics and demands, certain aspects of driving experience and motivation have an impact on how the driving task is carried out.

Given certain cognitive impairments, there is nevertheless a compensatory possibility for many brain-injured drivers by means of (1) well-practised cognitive functions

(Brouwer et al., 1990; Brouwer & Ponds, 1994) and (2) adaptive decisions at the strategic and tactical levels. *Adaptive behavior* is generally controlled behavior, like planning, programming and evaluation of goal-directed behavior (Shallice, 1982). Adaptation at the strategic level is for instance to reduce driving, to avoid situations that will tax impairment, like long-distance driving and driving in darkness and rain. Adaptation at the tactical level is to increase headway (Van Winsum, 1996) and adjust driving speed. Another adaptive tactical strategy is to concentrate on what is most relevant in the situation. For instance, driving in the simulator the patients (Studies I and II) managed the Listening Span test significantly worse compared to the control subjects. Besides less word span, the patients probably experienced the Listening Span workload too demanding and thus, excluded it, which in that situation was a tactical decision.

In this thesis, adaptive behavior means to modify existing ability to actual demands. Adaptive factors may influence functioning corresponding to an activity dimension (ICIDH-2). Given certain cognitive impairments, adaptive mechanisms may still facilitate driving performance, thus preventing activity limitations. According to interview data in Study III, adaptive means were to have an anticipatory attention, slowing down speed, having a pre-morbid interest and motivation for safe driving, and driving experience. That is, to adapt performance using existing resources and the same skills as before but in another way (cf. Dixon & Bäckman, 1995). *Anticipatory attention* was the prominent adapting factor for planning in advance, giving time to act.

The adaptive consequences may be successful or unsuccessful. Successful consequences of adaptation are functional behavior leading to anticipatory risk avoidance. Unsuccessful adjustment might be, for instance, if speed is reduced to an extent that hinders other traffic or when the driver has excessive attentional routines but is still not attentive.

Driving speed has an impact on what time is available to correct driving errors and it also influences the severity of an eventual accident (Brown, 1980; Deen & Godwin 1985; Johnson et al., 1981; Rothengatter, 1988). Driving speed might be an indication of driving style. It is well known that driving fast is associated with greater accident risk (French et al., 1993; Galin, 1981; Parker et al., 1994; Wasielewski, 1984; West et

al., 1993). Behind a high driving speed there might be a sensation-seeking disposition by the driver, time pressure and, for young people, pressure from the peer-group. Driving speed has the impact, that when driving demands become overloaded and the driver is unable to increase attention, the only practical adaptive decision is to slow down. Consequently, for brain-injured patients, who are sensitive to time pressure and overloaded situational demands, the only, and important, adaptive strategy is to slow down driving speed.

Another result suggesting adaptive behavior was, when control subjects in Study I and Study II were compared, the young controls performed significantly better in all neuropsychological tests compared to the older controls ($p < 0.01$). However, concerning an overall-driving performance there was no significant difference between the young and old control subjects. This confirms that older healthy individuals commonly adapt driving to decreased cognitive performance, probably by experience and cautiousness (cf. Withaar, 2000).

Besides already discussed factors, *age* is important to control for in studies concerning speed of processing. It decreases with increasing age, and the slowness is caused by a time reduction in both execution and simultaneity that affects cognitive functioning, also required in most driving situations (Salthouse 1996, Schaie 1996). In our studies (Studies I and II), older control subjects had reduced performance compared to younger control subjects on tests requiring speed of information processing. This occurred especially in complex tasks, in which strategies to divide, allocate and shift attention were required. Age appeared to be a potent factor underlying the neuropsychological results which verified the purpose to separate subjects in two studies according to age. The influence of age was shown in the extra partial least square regression carried out on all subjects in Study I and Study II altogether (Figure 4).

Age-related differences tend to emerge when individuals are required to select among intrusive inputs. For instance, in the CWT older subjects demonstrate greater interference effects than younger adults when color and word are incongruent (see West & Bell, 1997). Neuroimaging work has shown that the anterior attention system is activated during performance of the Stroop task (Bench et al., 1993; Carter, Mintum,

& Cohen, 1995) and that the prefrontal cortex appears to be sensitive to the effects of increasing age (West & Bell, 1997). The already slowed cognitive processing and attention in older people might be even more vulnerable after stroke.

We found that the CWT loaded highest in the cognitive factor, which determined driving performance among the older subjects. In addition, Complex Reaction Time, included in the neuropsychological test battery and in the simulator variables, predicted driving performance. In accordance with this it is often found that older drivers have impaired simultaneous attention and reaction speed in dual-tasks measured both in simulator and in real driving (see Hakamies-Blomqvist, 1996; Withaar, 2000). However, since stroke is an age-related disease it is difficult to separate what degree of impairment in cognitive functions and driving performance is due to brain injury, and what is due to age-related cognitive difficulties.

MAIN CONCLUSIONS

I. The neuropsychological test battery could be summarized by three underlying conceptual factors: attention, cognition and execution. The attentional factors comprised attention and motor speed. The cognitive factors comprised cognitive capacity but also attention in terms of working memory. The executive factor comprised executive function without time pressure.

The cognitive factor, and to some extent, the attentional factor predicted driving performance. Thus, cognitive functions in terms of attentional and dynamic working memory-related functions are relevant for driving performance.

II. The patients performed significantly worse on an over-all driving test compared to controls. The neuropsychological test battery separated patients and control groups. Thus, the tests captured cognitive impairments.

III. The neuropsychological test batteries could classify 78-83% of the subjects correctly on the overall-driving score pertaining to driving performance. Neuropsychological impairments in divided and focused attention, information processing speed requiring working memory, are all associated with limitations in driving performance. Neither medical examination nor assessment of cognitive

functions are sufficient to evaluate driving performance entirely (Johansson, 1997). There are additional individual factors that influence driving performance:

IV. Problems in terms of qualitative aspects like impaired orientation, decision-making, confidence, and especially impaired anticipatory attention appear to constrain driving performance.

V. Adaptive strategies like driving speed adjustment, and again anticipatory attention were qualitative aspects, which appeared relevant for driving after a brain injury. In addition, interest in driving and motivation for safe driving, and driving experience, in terms of considering previous traffic events, influence driving performance.

VI. Collaboration between medical, neuropsychological and driving expertise may be required for a total evaluation of driving performance after brain injury. There have been a variety of approaches for assessing driving performance. However, the sensitivity and specificity of various instruments indicate that a practical driving evaluation is required in order to make extended judgements, especially in ambiguous cases. In addition, in many cases the patient and his/her family would not accept a decision to withdraw a driving license without evaluation from an on-road test.

In sum, consecutive driving decisions are based on information components temporarily kept in working memory, driving schemata, which are activated from long-term memory, and execution. For all this, cognitive functions, especially anticipatory attention, motivation for safe driving, and experience are required. Adaptive strategies, which might be uncovered in a driving test, must be taken into consideration.

Future research should focus on: (1) development of neuropsychological tests assessing anticipatory attention, (2) identification of situational factors causing driving errors, and (3) identification of those consecutive driving decisions, which are sensitive to situational and transient factors, (4) development of a theoretical model to explain the findings.

CLINICAL IMPLICATIONS

The medical clinical examination for driving following brain injury aims at deciding whether the injury has caused body function or structure impairments that will seriously decrease necessary requirements for the activity of driving. Thus, the driving activity includes ability to drive in various conditions, that is, driving at operative, tactical as well as at strategic level.

Driving after brain injury is an activity of significant importance for the individual concerned, and suspension of driving always implies serious activity limitations and participation restrictions. From a justice of rights point of view it is important *not* to suspend patients from driving when they are capable to do so, or can be re-trained to drive. On the other hand, the society has an obvious interest to identify persons who represent a substantially increased risk in the traffic and to suspend their license.

The driving test is considered the 'golden standard' and it might be the best criterion of driving performance up to date. However, there is some uncertainty as to whether a driving test represents the person's driving performance entirely. It turned out that a certain amount of the control subjects did not pass the driving test (Studies I and II), and there are always patients who are able to compensate for their cognitive impairments.

A driving test shows how the driver can manage present traffic situations. However, one must be aware that the driving test is done on one occasion and it might be influenced by situational circumstances, like the driver's stress and nervousness, and traffic variations. In addition, some people might try hard to drive appropriately during the test but have another habitual driving style. It is always difficult to know what a patient's pre-morbid driving performance was like, and whether an insufficient driving performance is due to lack of routine, or due to cognitive impairments following the brain lesion. The purpose of the medical and neuropsychological examinations are to assess functions and abilities required for managing all kinds of situations, which might or might not appear during the driving occasion.

We can identify neuropsychological abilities of importance for the task of driving,

and we have shown that a test battery can predict the outcome of a driving test. However, at a certain sensitivity and specificity level, a total number of 24 subjects (Studies I and II) were classified incorrectly concerning driving performance. That means that the subjects either failed the neuropsychological test battery although they passed the driving test, or vice versa. It is a matter of balance between traffic safety and justice of rights for the individual when deciding about levels of sensitivity and specificity of such assessment instruments. From a clinical point of view a higher specificity at the expense of sensitivity is to be recommended.

Van Zomeren et al. (1987) recommended a change from assessing abilities assumed to predict driving to screening neuropsychological impairments that make patients unsafe drivers. Thus, it is important to have a comprehensive approach and not use strict cut-off limits of individual neuropsychological tests (cf. Brooke et al., 1992; Brouwer & Withaar, 1997; Korteling & Kaptain, 1996; Schanke & Sundet, 2000). To make a global assessment of cognitive functions, which are supposed to be relevant for driving performance, should include basic visuo-spatial function, focused and divided attention, and working memory capacity. The decision about resuming or suspending driving must also be based on considerations about the patient's adaptive strategies and awareness about cognitive impairments.

The neuropsychological test results are useful in discussions with the patient either to recommend a re-assessment, or to advise the patient to take a training program, or avoid driving permanently. The assessment has a pedagogical value for some patients in promoting awareness about impairments, while other patients doubt the relation between neuropsychological outcome and driving performance.

When the assessment raises doubt with respect to driving performance the patient is to be referred for a driving test, which may show sufficient or impaired anticipatory attention, judgement and executive functions. Therefore, the on-road test should be a part of the assessment procedure, especially in borderline cases. Lambert and Engum (1992) presented two subgroups for whom it is important to make a driving test. These are the elderly patients, for whom driving performance is often better than the neuropsychological test results would predict, and young patients suffering from TBI, who

are evaluated unfit to drive despite sufficient neuropsychological test performance.

It is also important to use a pedagogical approach to educate patients in adaptive aspects of safe driving, and offer practical education and re-training of driving routines. Driving experience, in terms of recent driving experience in the older subject group was related to driving performance. This implies consideration about how to train the brain-injured patients who might be capable to resume driving after practice. For those patients who are suspended from driving it is salient to compensate for their activity limitation by other transportation means to minimize participation restrictions and maintain independence.

To summarize, from a clinical perspective it is recommended that evaluation of driving performance and rehabilitation of drivers with brain damage must be based on teamwork of medical, neuropsychological, and driving expertise.

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APPENDIX

Appendix I: Neuropsychological tests

Trail Making Test B (TMTB) is a test of complex visual scanning with a motor component. It requires a capacity to perform a sequence mentally dealing with more than one stimulus concurrently (letters and numbers) and a flexibility in shifting the course of an ongoing activity. TMTB assesses multiple conceptual tracking, sequencing, and alternating divided attention. It is a sensitive test for brain injury but also for normal slowing due to aging (Lezak, 1995) although it does not explain whether the slowing depends on motor slowing, impaired coordination, visual scanning or conceptual difficulties.

Digit Symbol is a psychomotor performance test assessing perceptual speed. It requires perceptual organization, selective attention, and simultaneous processing and executive function. It is unaffected by intellectual ability, memory or learning. However, it is sensitive to brain dysfunction regardless of locus of lesion and to normal aging (Lezak, 1995).

Raven Progressive Matrices Set 1 (RPM) is a visuo-perceptual, abstract reasoning test. It requires to conceptualize spatial, design and numerical relationship, and to shift sets (Lezak, 1995).

Color Word Test (CWT) is a color-word interference test. It requires concentration and warding off distractors in naming the printed color of color words when printed in a different, conflicting color. It assesses orientation, selective attention and executive function, and is sensitive to subtle attentional deficits and slow information processing (Lezak, 1995).

Rey- Osterrieth Complex Figure Test (CFT) (a) copy: require perceptual organization (b) reproduction after three minutes is a visual memory test given sufficient visuo-perceptual function which is sensitive to visual memory defects (Lezak, 1995; Rey, 1941).

Block Design is a visuospatial construction test assessing visuospatial organization (Lezak, 1995). It is sensitive to especially right hemisphere brain injury.

Auditory-Verbal Learning Test (AVLT) (Rey, 1964) is an auditory-learning test, which assesses verbal learning function, verbal immediate memory span, short-term and long-term memory as well as learning strategy (Lezak, 1995).

Paced Auditory Serial Addition Test, Version B (PASAT) is an information processing test with complexity and speed demands. The task is to register auditory input (digits) presented at a rate of one digit per 1.6 second, respond verbally, inhibit encoding of ones own response while attending to the next sensory input. PASAT demands divided attention, stored memory elements, mental transformations, and responding. It has a processing component (adding digits) and a storage component (i.e. remembering the last presented digit). The performance of PASAT is not significantly correlated with either general intelligence or arithmetic (Gronwall & Wrightson, 1981) but there is a training effect between first and second administration. PASAT is sensitive to deficits in information processing ability (Lezak, 1995).

The Listening Span test is a working memory test which was modified from the one employed by Baddeley et al., (1985). It consists of simple three-word sentences presented word-by-word at a rate of one word per 0.6 sec in groups of three to six sentences. The task is to answer yes or no depending on whether or not the sentence is absurd. An example of an absurd sentence could be 'John drank grass', and an example of a sensible sentence is 'The pupil was late'. Only 2.0 seconds are allowed for the yes/no response before the next sentence appears. Then the subject is required to recall after each sequence of sentences the first or the last word, without knowing which in advance. Three sequences of sentences per span size were used, from span size three (i.e. three sentences) to span size six (i.e. six sentences). The examiner pushed a button to start the next sequence of sentences as soon as the subject had responded. There was no time limit for recall response although most of the subjects responded within 3 min. The score was the total number of words correctly recalled. The Listening Span test has a processing component (i.e. answer yes/no to the sentences) and a storage component (i.e. remembering the first or the last word respectively). The Listening Span test is sensitive to working memory impairment (Daneman & Carpenter, 1980).

Wisconsin Card Sorting Test (WCST) demands the ability of concept formation and

reasoning, abstract behavior and shift of set (Lezak, 1995). It assesses planning, organization which is required for executive function. The subvariable *percent of perseverative errors* shows problems in formulating concepts, profiting from correction and conceptual flexibility. It is often used to capture frontal brain injury in common and executive disorders including deficits in planning-organization (Lezak, 1995). *Total categories completed* are the total number of categories completed with 10 consecutive correct responses. *Total percent correct responses* is the total number of correct responses divided by total number of trials x 100. And, total percent perseverative errors are the total number of perseverative errors divided by total numbers of trials.

Finger Tapping is a manual dexterity function test (Levander, 1988).

Reaction Time tests (Levander, 1988) include simple reaction time on auditory and visual stimuli, reaction time on two choice visual stimuli, and reaction time on complex two choice visual stimuli combined with requirement of inhibition if the stimuli were presented with a concurrent auditory signal (Complex Reaction Time). The effects of brain damage upon RT are most clear observed on tasks demanding choice reactions involving speed of cognitive processing (Stuss et al. 1989).

K test is a focused attention test. The requirement is to attend to a computer screen and decide, as fast as possible and with a minimum of errors, whether the letter *k* is present or not among a set of distractors (squares or letters). The K test performance is built up by speed and accuracy into an overall-performance measure (Levander, 1988).

Simultaneous Capacity test is a computerized dual task dealing with two parts of information simultaneously and switching attention between them (Levander, 1988). It demands perceptual and cognitive processing speed. The test consists of one background task running continuously, requiring the subject to identify three consecutive odd digits in a continuous stream of digits at the rate of 1/second, and one foreground task requiring the subject to respond to messages by pressing one of ten numeric keys.

T-scores in the computerized test battery were an overall performance measure, taking both speed, accuracy and percentage of correct answers components into account. Evaluation was done according to sensory decision analysis principles (*d´* and beta). In the K test and in the Reaction Time tests the *T*-scores were based on speed

and accuracy. And in the Simultaneous Capacity test the *T*-scores were based on the sensitivity measure (d') of the background task and the percentage of correct responses (%) of the foreground task. The measurements were transformed into *Z*-values and expressed in *T*-scores with a mean =50 and SD =10. The *T*-scores were then used as raw data. Norm data are based on more than 300 subjects aged 17 to 55. Subjects are randomly selected students, conscripts and control subjects from various studies.

Appendix II: Simulator driving

The subjects got the instruction that, during driving, two distracting tasks would appear. A visual stimulus would appear and the mobile telephone would ring. The visual stimuli comprised of two different squares, one red and one yellow, measuring 4x4 cm. They would appear in the same position on the screen. The yellow square indicated the subject doing nothing. And when the red-square appeared the subject was to break as fast as possible. The visual stimuli were presented four times during driving.

When the mobile telephone rang the subjects answered by pushing a button on the telephone. Then they were listening to an instruction on the telephone and solved the task presented over the telephone. The message was a modified Listening Span test (Baddeley, Logie, Nimmo-Smith, and Brereton 1985) Twice the red-square and the telephone task were combined. After completing the test route the subjects answered a rating scale measuring the subject's workload (NASA-TLX, Hart & Staveland, 1988).

Dependent measures were *speed*, *lateral position*, *time headway* (TTC) and *following distance* (DTC) in a car following condition and *reaction time* on visual stimuli. In addition, the telephone task, the *Listening Span test* was supposed to measure information processing during driving. Time to Collision (TTC) is the time before a following vehicle collides with a leading vehicle if the speed of the vehicles remain constant. For two vehicles driving in the same direction at velocities $v1$ (leading vehicle) and $v2$ (following vehicle) and with a distance d between them, time-to-collision (TTC) is defined: TTC = $d/v2$-v1 which reflects the time in seconds before the following vehicle collides with the leading vehicle. Distance to Collision (DTC) reflects the distance, expressed in meters, between the two vehicles referred to above. The speed of the leading vehicle is determined by the speed of the following vehicle when entering the observational interval.

The time delay in the visual system of the VTI driving simulator is 40msec for a visual picture to move according to each wheel movement (Nilsson & Nåbo, 1995). A corresponding value for other simulators is 70-80 msec and more.

Appendix III: On-road driving

The on-road evaluation used by The Swedish National Road Association consists of different competence domains required in different traffic situations and in different traffic environments (Hans Mattsson personal communication). The conceptions used in the driving test are established standards that are comprehensible for the public. Moreover, they are based on professional consensus and experience (VVFS 1998b, 1999). The driver is suggested to show his competence during a driving test. The driving performance was evaluated on five driving criteria: *speed*, *maneuvering*, *vehicle position*, *traffic behavior* and *attention*.

Speed comprises to keep appropriate speed in relation to current traffic demands, to speed limits, and to one's own driving capacity.

Maneuvering includes steering, gearing, braking, and control of the vehicle.

Position is to place the vehicle adequately in the road lane, when changing lane, in intersections and in roundabouts.

Traffic behavior concerns planning the driving, following and applying traffic rules, adjusting to and showing consideration to other road users.

Attention is attending to events ahead, around, behind and in the vehicle in time, attending to road signs, directions and to other road users, resulting in acting when required.

Performance was scored between 1 and 5, where 2 implied unfit to drive, 3 indicated reasonable driving performance and 5 was splendid. Based on an overall-driving performance a pass/fail outcome was determined by the inspector.

According to the Swedish National Road Administration passing the driving test suggests a risk awareness implying that the driver controls all essentials during the test and that (s)he makes it with a certain extent of experience.

Appendix IV: Partial least square (PLS) regression

Methods

Regression analyses were made according to the *partial least square technique* (PLS) using SIMCA-P (version 8.0; Umetrics AB, Umeå Sweden). PLS finds the relationship between a matrix Y (dependent variables) and a matrix X. The VIP variable (variable influence on projection) gives information about the relevance of each X-variable and each Y-variable pooled over all dimensions and VIP >1.0 is considered as significant. In the present study two PLS regressions were made. In the first analysis age and group belonging (X-variables) was used to regress the neuropsychological variables (Y-variables). In the second analysis the neuropsychological variables together with age and group belonging (X variables) were used to regress driving performance (Y-variable). Thus, these analysis were made in order to understand the effects of age and group belonging. *Multiple linear regression* (MLR) could have been an alternative method for the regression but it assumes that the regressor variables are mathematically independent. If such multi-colinearity occur*s* among the X-variables, the calculated regression coefficients become unstable and their interpretability breaks down. Moreover MLR assumes that a high subject to variables ratio is present (5-10). Such an assumption do not exist for the PLS regression; in fact it can handle ratios lower than 1.0. PLS regression can also regress several Y variables simultaneously. These statistical tests were performed at the 5% significance level ($p \leq 0.05$, two-tailed).

Results

The first PLS regression:

Age and group belonging were used to regress the neuropsychological variables. Only age (VIP =1.20) but not group (VIP=0.75) was significant in this regression ($R^2 = 0.33$). On the other hand univariate comparisons have shown that significant differences exist between controls and patients for most of the neurpsychological variables. Thus the effect of age is stronger than that of group upon the neurpsychological variables.

The second PLS regression:

In the second regression the neurpsychological variables together with age and group were used as X-variables in the regression of driving performance (Table 1). Several of the neuropsychological variables were significant regressors (as expected) together with group belonging. Age was not a significant regressor (VIP<1.0) according to this analysis.

Table 1: *Regression of driving performance using the neurpsychological variables together with age and group as X-variables. For each variable is given VIP. VIP > 1.0 is significant (above the dotted line). The sign after VIP indicates the direction (negative or positive of the correlation). At the bottom row is given explained variance (R^2).*

Variables	Driving Performance (VIP)
Listening Span test	1.20+
WCST Percentage Correct	1.17+
Finger Tapping	1.12+
Simultaneous Capacity	1.09+
Group	1.09-
WCST Total Categories	1.06+
TMTB	1.06-
Reaction Time, Complex	1.03+
WCST Percentage Perseverative Errors	1.01-
Digit Symbol	1.00+
K Test	0.98+
PASAT 1.6	0.97+
Reaction Time, Simple	0.44+
Age	0.39-
R^2	0.171