Non-driving related tasks in highly automated driving –

Effects of task characteristics and drivers' self-regulation on take-over performance

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Executive Summary

The rise of automated driving will fundamentally change our mobility in the near future. This thesis specifically considers the stage of so called highly automated driving (Level 3, SAE International, 2014). At this level, a system carries out vehicle guidance in specific application areas, e.g. on highway roads. The driver can temporarily suspend from monitoring the driving task and might use the time by engaging in so called non-driving related tasks (NDR-tasks). However, the driver is still in charge to resume vehicle control when prompted by the system. This new role of the driver has to be critically examined from a human factors perspective.

The main aim of this thesis was to systematically investigate the impact of different NDR-tasks on driver behavior and take-over performance. Wickens' (2008) architecture of multiple resource theory was chosen as theoretical framework, with the building blocks of multiplicity (task interference due to resource overlap), mental workload (task demands), and aspects of executive control or self-regulation. Specific adaptations and extensions of the theory were discussed to account for the context of NDR-task interactions in highly automated driving.

Overall four driving simulator studies were carried out to investigate the role of these theoretical components. Study 1 showed that drivers focused NDR-task engagement on sections of highly automated compared to manual driving. In addition, drivers avoided task engagement prior to predictable take-over situations. These results indicate that self-regulatory behavior, as reported for manual driving, also takes place in the context of highly automated driving. Study 2 specifically addressed the impact of NDR-tasks' stimulus and response modalities on take-over performance. Results showed that particularly visual-manual tasks with high motoric load (including the need to get rid of a handheld object) had detrimental effects. However, drivers seemed to be aware of task specific distraction in take-over situations and strictly canceled visual-manual tasks compared to a low impairing auditory-vocal task. Study 3 revealed that also the mental demand of NDR-tasks should be considered for drivers' take-over performance. Finally, different human-machine-interfaces were developed and evaluated in Simulator Study 4. Concepts including an explicit pre-alert ("notification") clearly supported drivers' self-regulation and achieved high usability and acceptance ratings.

Overall, this thesis indicates that the architecture of multiple resource theory provides a useful framework for research in this field. Practical implications arise regarding the potential legal regulation of NDR-tasks as well as the design of elaborated human-machine-interfaces.

Zusammenfassung

In den nächsten Jahren wird die Fahrzeugautomatisierung stufenweise immer weiter zunehmen. Im Fokus dieser Arbeit steht das Hochautomatisierte Fahren (HAF), bei dem ein System in definierten Anwendungsbereichen, z.B. auf Autobahnen, die Fahraufgabe vollständig übernehmen kann (Level 3; SAE International, 2014). Der Fahrer muss das Verkehrsgeschehen nicht mehr überwachen, jedoch bereit sein, nach Aufforderung durch das System die Fahraufgabe wieder zu übernehmen. Bisherige Forschung legt nahe, dass Fahrer die freigewordene Zeit oftmals zur Beschäftigung mit sog. fahrfremden Tätigkeiten (FFTs) nutzen werden.

Die vorliegende Arbeit beschäftigt sich mit den Herausforderungen, die diese neue Rolle des Fahrers mit sich bringt. Der Fokus liegt auf dem Einfluss unterschiedlicher FFTs auf die Übernahmeleistung und der Frage, inwieweit Fahrer den Umgang mit FFTs an die situativen Bedingungen anpassen. Die Theorie der multiplen Ressourcen (Wickens, 2008) wurde dabei als Rahmenmodell gewählt und für den spezifischen Anwendungsfall von HAF-Systemen ausgelegt.

In vier Fahrsimulatorstudien wurden die unterschiedlichen Komponenten der Theorie untersucht. Studie 1 beschäftigte sich mit dem Aspekt der Ressourcenallokation (Selbstregulation). Die Ergebnisse zeigten, dass Fahrer die Beschäftigung mit einer prototypischen FFT an die Verfügbarkeit des HAF-Systems anpassten. Die Tätigkeit wurde bevorzugt im HAF und nicht im manuellen Fahrbetrieb durchgeführt und vor Übernahmesituationen wurden weniger Aufgaben neu begonnen. Studie 2 betrachtete den Aspekt der Interferenz zwischen FFT und Fahraufgabe. Die Modalitäten einer FFT wurden dazu systematisch variiert. Dabei zeigte sich, dass insbesondere visuell-manuelle Tätigkeiten mit hoher motorischer Beanspruchung (z.B. ein in der Hand gehaltenes Tablet) die Übernahme erschwerten. Fahrer schienen sich der Ablenkung bewusst zu sein und brachen diese Art von Aufgaben bei der Übernahme eher ab. Studie 3 ergab Hinweise, dass neben den Aufgabenmodalitäten auch kognitive Beanspruchung die Übernahmeleistung beeinträchtigen kann. Studie 4 beschäftigte sich mit der Mensch-Maschine-Schnittstelle (HMI) für HAF-Systeme. Die Ergebnisse ergaben, dass eine explizite Vorankündigung von Übernahmesituationen die Selbstregulation des Fahrers unterstützen kann.

Die Arbeit zeigt die Eignung der multiplen Ressourcentheorie als Rahmenmodell für Forschung im Bereich HAF. Praktische Implikationen ergeben sich für mögliche gesetzliche Regelungen über erlaubte Tätigkeiten beim HAF, genauso wie konkrete HMI-Gestaltungsempfehlungen.

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1 Introduction

"The irony [is] that the more advanced a control system is, so the more crucial may be the contribution of the human operator." (Bainbridge, 1983, p. 775)

The rise of automated driving is considered to be one of the greatest revolutions for mobility behavior, with the potential to significantly reduce the number of crashes, traffic jams, and vehicle ownerships (e.g. Fitch, 2015). However, from the perspective of the automotive industry and given the stepwise adjustments of legal foundations, the development seems more like an evolutionary process (see also chapter 2.1.2 for an overview on automation levels). Beginning with driver assistance systems like Adaptive Cruise Control (performing longitudinal control) and Lane Keeping Assistants (performing lateral control), nowadays systems are available that relieve the driver from any continuous vehicle guidance, at least in specific application areas (e.g. highway driving). Examples for such system are Tesla's "Autopilot", introduced 2015, or General Motors' "Super Cruise", which entered the market 2017. Due to limited system capabilities, the driver is still in charge of monitoring the traffic environment and the automated driving system. This changes fundamentally with the next automation level: highly automated driving (Gasser et al., 2012), also referred to as conditional automated driving (SAE International, 2014). At this level the driver is relieved from continuous monitoring, however he must maintain readiness to take back vehicle control when prompted by the system ("take-over request" or "request to intervene", SAE International, 2014). During highly automated driving, the driver is allowed to temporarily engage in non-driving related tasks (NDR-tasks), e.g. reading, writing text messages, or watching videos.

Unfortunately, increased automation can be accompanied by human performance problems well known from aviation and other fields of engineering psychology (e.g. vigilance decrements, over-reliance, loss of situation awareness, and manual skill decay; see chapter 2.1.3). These aspects are crucial for lower automation levels, where the driver has to be prepared to intervene at any point in time, and remain relevant for highly automated driving.

A well-known safety issue for manual driving is driver distraction (c.f. Dingus et al., 2016). This topic deserves particular attention in highly automated driving, as people are likely to increase the frequency of NDR-task interactions (Carsten, Lai, Barnard, Jamson, & Merat, 2012; Llaneras, Salinger, & Green, 2013) when they are legal. Several studies have addressed take-over performance of distracted drivers (e.g. Damböck, Farid, Tönert, & Bengler, 2012; Gold, Damböck, Lorenz, & Bengler, 2013). However, little is known about the impact of specific types of NDR-tasks and how drivers self-regulate their task engagement to situational circumstances. These topics have been intensively studied for distracted manual driving (c.f. Regan, Lee, & Young, 2008). It remains unclear so far, which methodological approaches and theoretical frameworks of driver distraction research are also applicable to highly automated driving and where new models have to be considered.

It is the aim of this thesis to systematically investigate the impact of different NDR-tasks on take-over performance under consideration of drivers' self-regulatory behavior. Wickens' (2008) well-established *multiple resource theory* is used as a general framework under consideration of specific aspects of highly automated driving (see chapter 3). The architecture of multiple resource theory consists of *multiplicity* (task interference due to resource overlap), *mental workload* (considering task demand or difficulty), and aspects of *executive control* (or self-regulation). Three consecutive driving simulator studies are carried out to assess these different building blocks. Study 1 focuses on self-regulation: When do drivers decide to interact with NDR-tasks considering the current driving mode (i.e. manual vs. highly automated) or the predicted distance to take-over situations? The main emphasis of Study 2 is to assess the impact of NDR-task's stimulus and response modalities on take-over performance. A model task is developed that enables for systematic variation of modalities whilst keeping the task itself as constant as possible. Another focus of this study is drivers' self-regulation in terms of NDR-task disengagement in take-over situations. Study 3 aims to replicate the main findings of Study 2 and, in addition, takes the role of mental workload into account. This time, an NDR-task is used that allow for modifications of task difficulty whilst keeping the stimulus and response modalities constant.

Based on findings of Study 1 to 3 and additional pre-studies (focus groups and interviews), three different HMI variants are developed and integrated into the driving simulator. The concepts differ in the information content presented to the driver and the number of warning stages in take-over situations. In addition, the usage of driver state monitoring is considered to allow for adaptive warnings. Study 4 evaluates how the different HMI concepts support drivers in their self-regulation (e.g. timely disengagement from NDR-tasks before take-over situations) and which impact this has on take-over performance and user experience.

2 Theoretical Background

This chapter provides insights into theoretical concepts and empirical research related to the thesis' topics. Section 2.1 introduces the psychological fundamentals of the (manual) driving task as well as benefits and challenges of automation in a general manner. Section 2.2 deals with the specific human factors aspects of highly automated driving and gives an overview on driver distraction research. On this basis, the research questions of the thesis are derived (chapter 3).

2.1 Psychological Aspects of Driving and Automation

2.1.1 The Driving Task

From a psychological perspective driving can be considered as a goal-directed (i.e. reaching a planned destination) and highly complex task with dynamically changing demands. The driving task has been usually defined within a hierarchical structure in order to classify the different psychological processes involved (for a comprehensive review see Ranney, 1994).

Rasmussen (1983) provides a general three-level-framework to describe human performance in interaction with technical systems. *Skill-based behavior* is located at the lowest level and represents sensory-motor performance, based on well-learned automated behaviors without conscious control. At this level, a virtually direct stimulus-response association is assumed. Behavior on the *rule-based level* involves the recognition of a familiar problem and the selection of an appropriate behavioral scheme. The top level of Rasmussen's framework is formed by *knowledge-based behavior*. It applies to novel situations where no cognitive schemata are available and, therefore, conscious problem solving is necessary.

The building blocks of Rasmussen's framework have been proposed to also apply to the driving task (Michon, 1985; see also Donges, 1982). In the context of driving, a distinction is made between a *strategic*, *maneuvering*, and *control level*. The control level includes the actual vehicle control inputs (steering wheel and pedals), which can be considered as well-learned action patterns and are thought to be controlled in the time frame of milliseconds (e.g. small steering corrections in lane keeping). The maneuvering level involves the handling of the current driving situation and the execution of defined maneuvers such as entering the traffic stream or driving through intersections. This level is assumed to have typical time frames in the order of seconds. Finally, the strategic level describes general trip planning and, for instance, the choice of routes. This top level is assumed to have the largest time scale, in terms of minutes or hours. In the context of vehicle automation, it is important to note that some or all levels of the driving task might be performed by a system instead of a human driver (see chapter 2.2 of this thesis).

The two hierarchical frameworks have been related to each other and combined into integrated models (e.g. Hale, Stoop, & Hommels, 1990; Donges, 1999; Weller, 2010). Figure 2-1 shows Rasmussen's Skills-Rules-Knowledge model on the left side and Michon's levels of the driving task to the right. The figure illustrates the separate processes for each level and also the dynamic relationship between the levels. This dynamic interactions and parallel control loops are the basis for a flexible and robust accomplishment of the driving task.

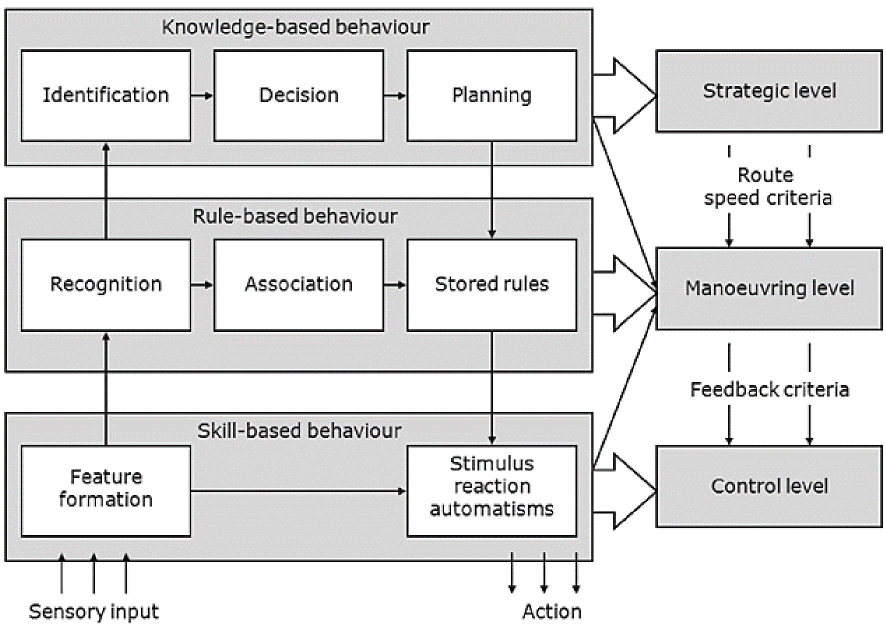

Fig. 2-1: **Combination of Rasmussen's (1983) performance levels and the model according to Michon (1985). Figure taken from Weller (2010; modified from Donges, 1999).**

Another approach to describe the driving task can be derived from linear models of human information processing (Fig. 2-2). Although some aspects of human information processing can be executed in parallel (e.g. Salvucci & Taatgen, 2008; Matthews, Davies, Westerman, & Stammers, 2000), the serial representation of different stages has a long tradition in cognitive psychology (e.g. Donders, 1868; Sternberg, 1969) and still provides a useful framework for task analyses and the identification of human factors issues in engineering psychology (Wickens, Hollands, Banbury, & Parasuraman, 2013).

During driving, a high number of stimuli (e.g. elements of the road scenery and in-vehicle displays) is processed by the human senses, in particular by the visual system ("Sensory Processing" in Fig. 2-2). The extraction of meaningful objects or events ("Perception") from the sensory input requires selective attention and a link to semantic information stored in long term memory (e.g. the meaning of traffic signs). According to early filter models (Broadbent, 1958; Cherry, 1953) or Treisman's (1964) attenuation model, only attended information is further processed, while the remaining sensory information is blocked or not further processed.

After perception, a distinction can be made between rapidly triggered well-learned reactions (lower path in Fig. 2-2) and deeper cognitive processing (including the acquisition and maintaining of situation awareness, see chapter 2.1.3), preceding response selection and execution (upper path in Fig. 2-2). An example for the lower path might be moment-to-moment lane keeping and for the upper path it might be the decision between overtaking and staying behind a lead car on a rural road. Thus, the parallel paths can be linked to Rasmussen's (1983) distinction between skill-based behavior and the higher levels of rule-/knowledge-based behavior. This also applies for Michon's (1985) levels of the driving task, which require different amounts of cognitive processing, increasing stepwise from the control level to the strategic level (Fig. 2-1).

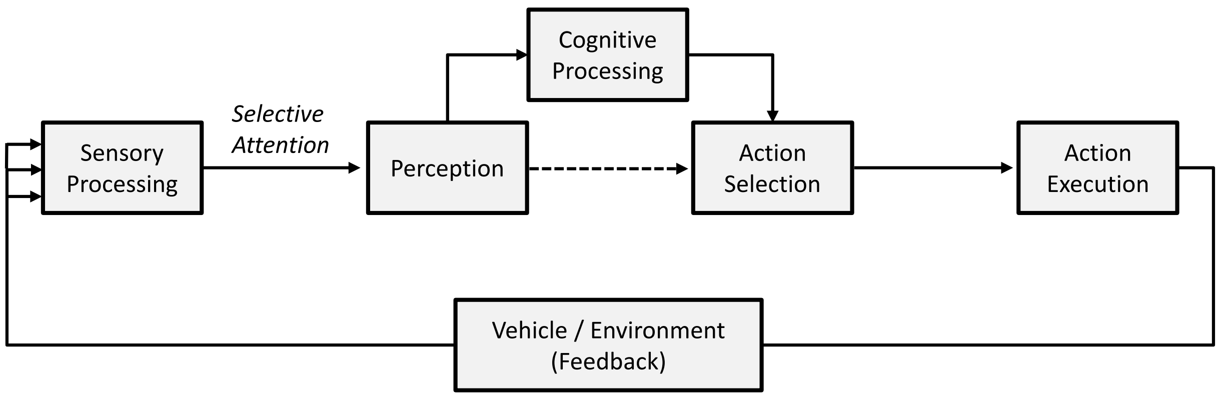

Fig. 2-2: Information processing loop for the driving task. The figure integrates certain aspects of models proposed by Ma & Kaber, 2005; Wickens et al., 2013; Sheridan, 2004.

Every resulting action by the driver (i.e. steering or braking/accelerating) leads to moment-to-moment changes in the vehicle-/environment system, which in return create new patterns of information to be sensed. This aspect is represented by a feedback path at the bottom of Figure 2-2 which closes the loop to the beginning ("Sensory Processing"). Hence, for manual vehicle guidance the driver can generally be considered to be "*in the loop*". The problem of driver distraction is excluded here, but is discussed in chapter 2.2.3.

In the context of vehicle automation, the driving task is partially or completely performed by a system. In the following chapters, the changing role of the driver in the context of increasing automation will be outlined. This includes a consideration of the human factors challenges associated with the driver being "*out of the loop*" (Kaber & Endsley, 1997, see chapter 2.1.3).

2.1.2 Levels of Automation: General and Automotive Specific Approaches

Automation has been defined as the "execution by a machine agent (usually a computer) of a function that was previously carried out by a human" (Parasuraman & Riley, 1997, p. 231). Beginning with first steps in the middle of the 20th century nowadays automated systems can be found on all parts of our life. This includes e.g. the areas of manufacturing, health care, homes, and transportation.

Several taxonomies have been proposed within engineering psychology in order to categorize the different manifestations of automation. An early approach by Sheridan and Verplank (1978) suggested 10 levels of automation. On the lowest level, the whole task is carried out by the human user. With increasing automation level the computer offers possible action alternatives and, by reaching level 5, it executes a suggested action if the human approves. On level 7, the system automatically executes the selected action and only informs the human. Finally, a level 10 system acts fully autonomously and ignores possible human interventions.

Considering the stages of human information processing (see Fig. 2-2), the taxonomy by Sheridan and Verplank focusses mainly on the automation of action selection and execution. In order to overcome this limitation, Parasuraman, Sheridan, and Wickens (2000) propose an approach where automation can take place on all stages of a simplified information-processing model (Fig. 2-3). Within this framework, a system can involve different degrees of automation (from low to high) on four stages of information processing (see example systems A and B in Fig. 2-3). Automation within the *information acquisition stage* applies to systems, which support human sensory or selective attention processes. A low level of automation might refer e.g. to an unspecific warning, while a higher level might involve a directed warning with a certain amount of contextual information. Automation on the *information analysis stage* refers e.g. to preprocessing of incoming data (low automation) or the combination of several measures into one integrated value to support the human operator (high automation). Automation on the stage of *decision selection* refers to systems that provide e.g. a list of action alternatives (low automation) or a single best choice (high automation). Finally, the physical execution of the selected action might be carried out manually or by a machine (*Action implementation stage*).

As one might expect, the number of automation levels in the model by Parasuraman et al. (2000) might differ between the four stages and distinctive gradations have not been defined. This can be considered as a limitation when analysing and comparing concrete automation systems (Save & Feuerberg, 2012). Therefore, domain-specific taxonomies (e.g. for the manufacturing or transport sector) are inevitable.

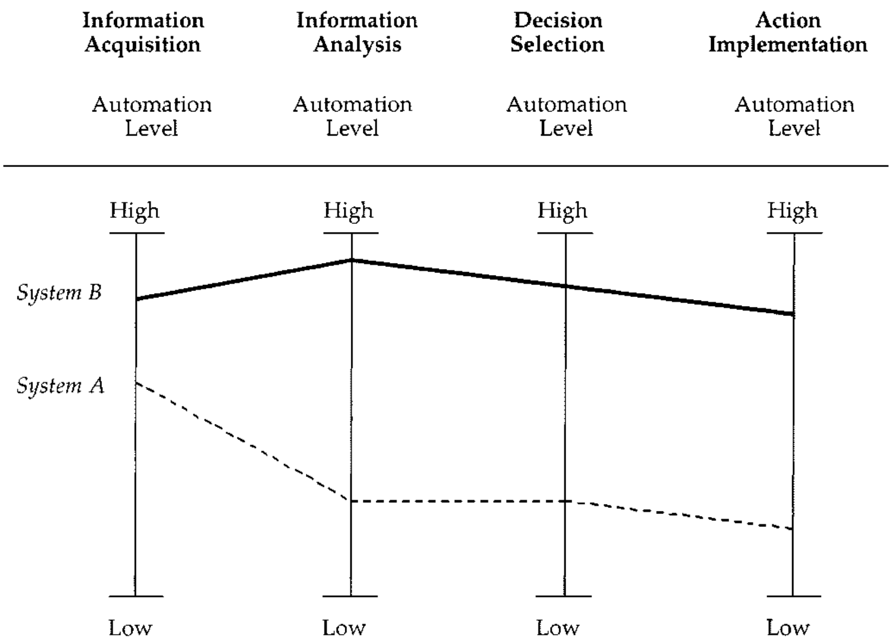

Fig. 2-3: Levels of automation for different stages in information processing (from Parasuraman et al., 2000). Two example systems (System A and System B) are included for illustration.

Due to the increasing proliferation of Advanced Driver Assistance Systems (ADAS) in recent years, severall attempts have been made to provide an exhaustive and unified taxonomy for vehicle automation. A widespread categorisation was developed by an expert working group under the lead of the German Federal Highway Research Institute (BASt). Five levels of vehicle automation are distinguished in this approach (Gasser et al., 2012), and for each level it is defined which aspects of the driving task (i.e. longitudinal and lateral control) are performed by the human driver or a system. A similar classification was published in 2013 by the U.S. National Highway Traffic Safety Administration (NHTSA), which also includes five automation levels (NHTSA, 2013). Based on these approaches, the Society of Automotive Engineers (SAE International, 2014) developed a slightly different taxonomy with six automation levels, which nowadays is the most common categorisation used in the automotive industry, administration, and scientific community (Fig. 2-4).

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
Human driver **monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system **("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Fig. 2-4: Levels of vehicle automation (from SAE International, 2014).

SAE level 0 (see Fig. 2-4) refers to manual driving, where the human driver performs the complete driving task (but might be supported by warning systems, e.g. forward collision alert or park distance control). In recent years an increasing number driver assistance systems (ADAS) has entered the market. These systems are capable to carry out longitudinal (e.g. "Adaptive

Cruise Control”) *or* lateral (“Lane Keeping Assistant”) vehicle control (SAE level 1). By combining these systems or using a dedicated system, the level of partially automated driving (SAE level 2) is reached. At this level of automation, longitudinal and lateral control is delegated to the vehicle while the driver is still responsible to monitor the traffic environment and the automated driving system.

The role of the driver changes significantly with the next level (SAE level 3). Here, the driver is allowed to temporarily withdraw himself or herself from monitoring the driving task “with the expectation that the human driver will respond appropriately to a request to intervene“ (SAE International, 2014; Fig. 2-4) when reaching a system limit (e.g. construction sites, highway exits). The present thesis focusses on human factors aspects of such SAE level 3 systems, designed for highway driving up to 130 km/h. Although named “Conditional Automation” in the SAE classification (Fig. 2-4), in this thesis the more common term “Highly Automated Driving” is used, following the original BASt taxonomy (Gasser et al., 2012). For the same reason, the term “take-over request” is used instead of the SAE term “request to intervene”.

The SAE classification includes two more levels. In level 4 automation, the human driver is not required as a fallback anymore. In cases where the human driver might not respond to a request the system must be able to handle the situation by its own. Level 5 automation refers to systems that perform every aspect of the driving task “under all roadway and environmental conditions that could be managed by a human driver” (SAE International, 2014; Fig. 2-4).

2.1.3 Humans and Automation

This section is intended to provide an overview on benefits and human factors challenges of increasing automation in a general manner. Chapter 2.2 specifically addresses the potential issues associated with highly automated driving systems.

There are several reasons for the introduction of automated systems, strongly depending on the area of application. Wickens et al. (2013) suggest several categories. From an economic point of view, automation is often introduced with the purpose of cost reduction (e.g. assembly robots in the manufacturing sector). In addition, there are tasks which cannot be performed by humans (e.g. highly complex mathematical calculations or working in hazardous environments) or where humans would perform poorly due to high system complexity and information load. Due to the limited mental resources of humans (e.g. Kahneman, 1973) automation is usually designed with the purpose to reduce the human user's physical and mental workload.

Although automation can generally offer significant benefits, human factors aspects have to be considered. Unfortunately, automation can be accompanied by so called Out-of-the-loop (OOTL) performance problems (Kaber & Endsley, 1997). These problems occur in particular in the interaction with imperfect automation that requires "supervisory control" (Sheridan, 1997) and, therefore, passive information processing.

In this context, Kaber and Endsley (1997) point out four possible human factors problems associated with the usage of automation:

- Vigilance decrements
- Over-trust in computer controller (complacency)
- Loss of system or situation awareness
- Manual control skill decay

Vigilance (or sustained attention) describes the ability of maintaining alertness and focused attention to relevant stimuli over prolonged periods of time (Warm, 1993). Unfortunately, staying vigilant is error-prone and stressful for humans (Warm, Parasuraman, & Matthews, 2008; Grier et al., 2003). This can potentially lead to misses of relevant changes in system parameters. A second problem field arises from inappropriate trust in automation. This applies to situations where subjective trust is not aligned to the actual automation reliability. While under-trust might be associated with a "disuse of automation", over-trust can lead to a "misuse of automation" (Parasuraman & Riley, 1997). More precisely, the human factors issues associated with over-trust have been described as the related concepts of *automation bias* and *complacency* (Parasuraman & Manzey, 2010). Automation bias refers to systems that provide decision support in complex environment. The human operator might come to decisions that are strongly biased by the automatically generated advice and that are not based on a comprehensive situation assessment. Complacency primarily refers to automated systems that include supervisory control and has been defined as an "unjustified assumption of satisfactory system state" (Billings, Lauber, Funkhouser, Lyman, & Huff, 1976, p. 23). This can lead to an insufficient monitoring frequency and potential performance problems in case of system limits. On the one hand, reduced monitoring frequency will decrease the chance to detect automation malfunctions. On the other hand, even when detected, the operator might have problems to deal with the situation appropriately (Wickens et al., 2013). The latter is strongly related to the third OOTL performance problem mentioned above: loss of situation awareness.

Situation awareness has been defined as “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.” (Endsley, 1988, p. 792). Thus, situation awareness allows for a mental representation of the current situation and also the anticipation of upcoming changes. These are necessary prerequisites for many every day or work-related tasks including driving a vehicle. The mental representation of system states is considered to be one component of situation awareness (see Endsley, 1995), but also the specific term *system awareness* has been used (Kaber & Endsley, 1997).

Within the context of automation, it can be assumed that situation awareness might be negatively affected. One the one hand, manually controlled actions usually lead to deeper cognitive processing compared to passive observation (*generation effect*: Farrell & Lewandowsky, 2000; see also Endsley & Kiris, 1995). On the other hand, the issues of vigilance decrements and automation over-trust are associated with a reduced amount of monitoring, which is expected to further impair situation awareness.

The last component of OOTL performance problems suggested by Kaber and Endsley (1997) considers the gradually loss of the operator’s skill to perform the automated task manually. Manual skill decay has been reported e.g. for aircraft pilots and, as a countermeasure, pilots are encouraged to fly manually from time to time (Wiener, 1988; Ebbatson, Harris, Huddlestone, & Sears, 2010). However, it seems that infrequently practiced pilots show performance decrements mainly in the cognitive tasks needed for manual flight (e.g. tracking the aircrafts position or the execution of navigational subtasks) and not in the manual control skill itself (Casner, Geven, Recker, & Schooler, 2014).

2.2 Human Factors Challenges in Highly Automated Driving

From a human factors perspective, highly automated driving (HAD, level 3 automation according to SAE International, 2014) offers several advantages compared to lower automation levels (level 1 and 2). Level 3 systems relieve the human driver from the error-prone and stressful task of sustained supervisory control (see section 2.1.3). Nevertheless, the human driver still serves as a fallback in case of system limits and is expected to appropriately respond to a take-over request. Thus, human performance in take-over situations has to be critically investigated under consideration of system properties, environmental factors, and the driver state. The latter is highly influenced by the engagement in NDR-tasks, which is the main emphasis of this thesis.

2.2.1 Mode Transitions and Performance Metrics

A specific characteristic of highly automated driving (Level 3, SAE International, 2014) is the occurrence of *mode transitions*, also referred to as *control authority transitions* (Lu & de Winter, 2015). That is due to the fact that such systems are designed for limited domains (e.g. highway driving) and that even within such a domain situations may arise which the system cannot handle (e.g. construction sites or missing lane markings), resulting in a take-over request. Although some authors assessed the use of partially automated driving as fallback level of highly automated driving (e.g. Gold, Lorenz, Damböck, & Bengler, 2013), in the context of this thesis only transitions between highly automated and manual driving are considered (see Fig. 2-5 for an overview of possible transitions between these two driving modes).

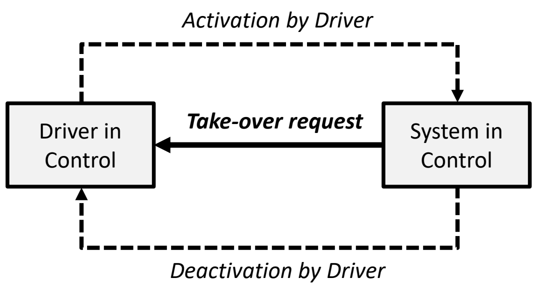

Fig. 2-5: Possible mode transitions between manual driving (Driver in Control) and HAD (System in Control).

When driving manually and reaching conditions within the operating range of the HAD system, the system can be engaged (upper path in Fig. 2-5) by a so called driver-initiated transition (Lu & de Winter, 2015; Eriksson & Stanton, 2017). Another driver-initiated transition is taking back manual vehicle control after a period of HAD without the occurrence of a take-over situation (lower path in Fig. 2-5). However, the most safety-relevant transition is a system-initiated take-over request (central path in Fig. 2-5), which has received considerable attention by researchers (for a review: Eriksson & Stanton, 2017) and is also the main focus of this thesis.

The system-initiated transition to manual control can be described within process models. Marberger et al. (2017) propose a comprehensive model (Fig. 2-6) that was developed within the German funded project Ko-HAF (Cooperative highly automated driving) and refines earlier approaches (e.g. Damböck et al., 2012; Gold & Bengler, 2014). The model considers basic system states (bottom stream in Fig. 2-6) and the required processes performed by the human driver during the transition to manual driving (top stream in Fig. 2-6). A number of time windows and intermediate steps are defined and will be used further within this thesis.

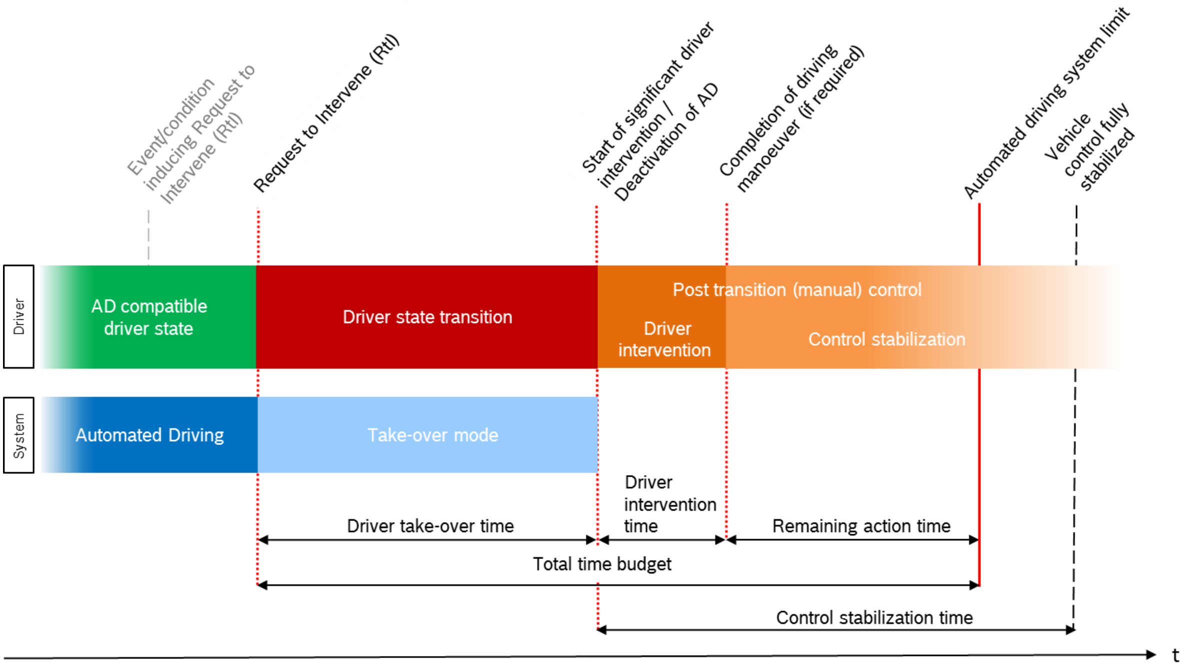

Fig. 2-6: Model of system-initiated transitions from HAD to manual control (from Marberger et al., 2017).

The most important aspects and time spans of the model (Fig. 2-6) are now further outlined. An upcoming automated driving system limit" (e.g. construction site or accident ahead) is causing the "request to Intervene" (or take-over request). The time span between system limit and take-over request constitutes the "total time budget". As soon as the take-over request is issued, the system has to bypass the time until the driver has resumed control. During this "take-over mode" the level 3 system is usually considered to maintain its basic functionality. The time it takes for the driver to resume manual control (e.g. deactivation with button press or significant intervention on the primary vehicle controls) is defined as the "driver take-over time". The required "driver state transition" is further discussed in chapter 2.2.2. Finally, the "control stabilization time" refers to the fact that it might take additional time for the driver to fully re-establish his/her optimal performance level, even after the system limit itself has been managed (see e.g. Merat, Jamson, Lai, Daly, & Carsten, 2014).

When assessing driver's *take-over performance*, usually timing and quality metrics are considered (Gold & Bengler, 2014; Zeeb, Buchner, & Schrauf, 2016, Marberger et al., 2017). The most relevant *timing aspect* is the already mentioned take-over time (Fig. 2-6). For the assessment of critical take-over situations in simulator studies, thresholds of two degrees change in steering wheel angle or brake pedal position of 10 % have been interpreted as the beginning of a conscious driver intervention (Gold et al., 2013; Zeeb, Buchner, & Schrauf, 2015; Gold, 2016). In addition to the take-over time itself, the time until the first gaze back on the road and the time until hands are back at the steering wheel (hands-on time) are often analyzed (all metrics measured from the beginning of the take-over request).

Quality aspects of driver's take-over performance have to be considered in strong relation to the characteristics and requirements of the particular take-over situation. For assessing critical take-over situations that require braking and/or an evasive steering maneuver Gold (2016) suggests the following well-established metrics: Maximum absolute accelerations (longitudinal and/or lateral), minimum time to collision (TTC, the hypothetical time until a collision with an obstacle, given constant relative speeds), and the occurrence of collisions as a clearly defined pass/fail criterion.

2.2.2 Determinants of Take-Over Performance

Based on the data of 25 reviewed papers, Eriksson and Stanton (2017) report a high variability of take-over times, with mean values varying from 1.14 to 30 seconds. A number of factors might influence the actual take-over performance of a driver. Based on a comprehensive literature review Vogelpohl, Vollrath, Kühn, Hummel, and Gehlert (2016) propose the following high level categories of potential influence factors:

- Driver variables (e.g. age, experience, trust in automation, distraction by NDR-task)
- Environmental variables (e.g. type of take-over situation, speed, traffic density)
- System variables (e.g. range of functions, execution of emergency maneuver)
- HMI variables (e.g. design of take-over request, interaction concept)

Fuller's (2005) task-capability interface model provides a general framework to cluster these influence factors. According to Fuller's model success or failure in a given driving situation is determined by the task demand (in the present case strongly determined by the environmental, system, and HMI variables) in relation to the current capability of the driver. The driver's capability is influenced by higher-level traits (e.g. age, experience) and the current driver state (e.g. distraction, drowsiness, motivational, and emotional state; Fuller, 2005). The most relevant building blocks of the current driver state have been subsumed under the constructs *energetic state* (alertness/arousal) and *attentional state* (Rauch et al., 2009; Knipling & Wierwille, 1994). The energetic state is assumed to be primarily impaired by vigilance decrements, fatigue, and drowsiness, while the attentional state in particular depends on the engagement in NDR-tasks (Rauch et al., 2009). As the latter is a key aspect of this thesis, it is further discussed in separate chapters (2.2.3 and 2.2.4).

According to the Yerkes-Dodson Law (1908), which is still prominent in the psychological literature (Teigen, 1994), a medium arousal level should be associated with the best performance. Performance problems in manual driving may be often caused by conditions of overload/high demand (leading to "active fatigue"; May & Baldwin, 2009). It can be assumed that there might be a shift to conditions of underload/low demand (leading to "passive fatigue"; May & Baldwin, 2009) when using automated driving systems (Radlmayr & Bengler, 2015). Empirical research provides some evidence for this assumption (Schömig, Hargutt, Neukum, Petermann-Stock, & Othersen, 2015; Vogelpohl, Vollrath, & Kühne, 2017; Neubauer, Matthews, & Saxby, 2012). However, there are ambiguous results on this topic (Feldhütter, Gold, Schneider, & Bengler, 2016; Neubauer, Matthews, & Saxby, 2014).

Concerning *environmental factors* characteristics of the take-over situation seem to have a considerable influence on driver's take-over performance. Take-over situations have been described within the following dimensions: urgency, predictability, criticality, and complexity (Gold, Naujoks, Radlmayr, Bellem, & Jarosch, 2017). In several studies the available time budget (reflecting urgency and predictability) showed significant effects on take-over behavior, indicating reduced performance for shorter time budgets (Damböck, et al., 2012; Gold, et al., 2013; van den Beukel & van der Voort, 2013). Interestingly, the take-over time itself might even become faster in highly urgent scenarios, but usually at the cost of impairments in quality aspects (Gold et al., 2013). Overall, for considered time budgets up to seven or eight seconds, quality metrics (e.g. maximum accelerations) were shown to be impaired in comparison to manual drivers (Damböck et al., 2012; Gold et al., 2013). Also the complexity of the situation (to some extent confounded with the criticality) seem to play a major role when modelling take-over performance (Gold, 2016). An increased complexity in terms of required driver response (e.g. vehicle stabilization vs. lane changing, Damböck et al., 2012) or surrounding traffic density (Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Körber, Gold, Lechner, & Bengler, 2016) was associated with increased take-over times and impairments in quality metrics.

The *system's functionality and HMI concept* might also play a major role in take-over performance and user experience (Fitch, 2015). Most importantly, the take-over request has to be presented highly salient and multimodal (e.g. visual-auditory) to enable quick driver reactions (Naujoks, Mai, & Neukum, 2014). In this context, speech output might be a beneficial extension to generic audio chimes (Naujoks, Forster, Wiedemann, & Neukum, 2016). Also the usage of augmented reality might support the driver in take-over situations, e.g. when displaying a safe corridor which the driver can follow to avoid a collision (Lorenz, Kerschbaum, & Schumann, 2014). Other concepts include a deactivation ("lockout") of NDR-tasks simultaneously with the take-over request (Melcher, Rauh, Diederichs, Widlroither, & Bauer, 2015) or an automated braking application (Gold, Lorenz, & Bengler, 2014). Some of these concepts were implemented in the HMI concepts used in the empirical studies of this thesis and are described in further detail in the respective sections (see Chapter 5 and 7).

2.2.3 Distraction and Self-Regulation in Manual Driving

Unfortunately, the engagement in NDR-tasks is not a specific phenomenon for automated driving. This issue is well known for manual driving since decades (Treat et al., 1979) and has been subject of intense research (for an overview: Regan et al., 2008). Driver distraction can be considered as a specific form of driver inattention and has been defined as "the diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving” (Regan, Hallett, & Gordon, 2011; p. 1776).

Besides classical epidemiological research (McEvoy & Stevenson, 2008), so called “Naturalistic Driving Studies” are a promising approach to provide valid estimations of prevalence and risk associated with driver distraction. In these studies, participants’ vehicles are equipped with sensors and cameras that continuously collect vehicle parameters as well as driver behavior during everyday vehicle usage. In the U.S. SHRP 2 naturalistic driving study data of more than 3,500 drivers was collected for the duration of three years (Dingus et al., 2016). Tab. 2-1 provides prevalence values and odds ratios (factor of crash risk increase/decrease compared to baseline driving) for NDR-tasks performed during driving. Remarkable is the high NDR-task prevalence of more than 50 % of the driving time. The tasks with the highest prevalence in the SHRP 2 dataset were passenger conversations, directly followed by the usage of cell phones or in-vehicle devices. Besides reaching for objects and extended glance durations to external objects, the usage of cell-phones, tablets, and in-vehicle devices was associated with the highest crash risks. The European UDRIVE naturalistic driving study reports an overall lower prevalence of NDR-task engagement but, consistently to the SHRP 2 data, handheld cell phone use was identified as a widely spread phenomenon (overall 4 % prevalence, UDRIVE, 2017).

Tab. 2-1: Prevalence (right column) and odds-ratios (center column, 95% confidence intervals in brackets) of NDR-tasks in the SHRP 2 naturalistic driving study (table from Dingus et al., 2016).

*Observable Distraction***		
Overall	2.0 (1.8 - 2.4)	51.93%
Major distraction sub-categories (observed in crash and baseline events)		
In-vehicle radio	1.9 (1.2 – 3.0)	2.21%
In-vehicle climate control	2.3 (1.1 – 5.0)	0.56%
In-vehicle device (other)	4.6 (2.9 – 7.4)	0.83%
Total in-vehicle device	2.5 (1.8 - 3.4)	3.53%
Cell browse	2.7 (1.5 – 5.1)	0.73%
Cell dial (handheld)	12.2 (5.6 - 26.4)	0.14%
Cell reach	4.8 (2.7 - 8.4)	0.58%
Cell text (handheld)	6.1 (4.5 - 8.2)	1.91%
Cell talk (handheld)	2.2 (1.6 - 3.1)	3.24%
Total cell (handheld)	3.6 (2.9 - 4.5)	6.40%
Child rear seat	0.5 (0.1 – 1.9)	0.80%
Interaction with adult/teen passenger	1.4 (1.1 – 1.8)	14.58%
Reading/writing (includes tablet)	9.9 (3.6 - 26.9)	0.09%
Eating	1.8 (1.1 - 2.9)	1.90%
Drinking (non-alcohol)	1.8 (1.0 - 3.3)	1.22%
Personal hygiene	1.4 (0.8 - 2.5)	1.69%
Reaching for object (non-cell phone)	9.1 (6.5 - 12.6)	1.08%
Dancing in seat to music	1.0 (0.4 - 2.3)	1.10%
Extended glance duration to external object	7.1 (4.8 - 10.4)	0.93%

The NDR-task categories used by Dingus et al. (2016) can be described as so called *phenomenological approaches* (Schömig, Schoch, Neukum, Schumacher, & Wandtner, 2015; Naujoks, Befelein, Wiedemann, & Neukum, 2017) as they distinguish between practically relevant and observationally distinctive classes of NDR-tasks. In contrast, *demand-based approaches* aim to account for underlying task characteristics and psychological aspects of different NDR-tasks. Klauer, Dingus, Neale, Sudweeks, and Ramsey (2006) distinguish three levels of NDR-task complexity in terms of the required number of off-road glances and button presses. Another widely used distinction has been provided by NHTSA (2013, p. 3):

- Visual distraction: Tasks that require the driver to look away from the roadway to visually obtain information;
- Manual distraction: Tasks that require the driver to take a hand or hands off the steering wheel and manipulate an object or device;
- Cognitive distraction: Tasks that are defined as the mental workload associated with a task that involves thinking about something other than the driving task.

The Governors Highway Safety Association (GHTSA, 2011) also takes auditory distraction as “hearing something not related to driving” (p. 3) into account. It is important to note that many naturalistic tasks (e.g. handheld cellphone conversations) involve demands on two or more dimensions (simultaneously or sequentially, see also Caird, 2015). In particular, nearly every NDR-task will require cognitive resources to a certain degree.

Experimental research found significant performance impairments for visual-manual as well as auditory-cognitive distraction. Visual-manual distraction (e.g. writing text messages or visual search tasks with manual responses) is usually associated with impaired lateral and longitudinal vehicle control (Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; Hosking, Young, & Regan, 2009; Ranney, Baldwin, Parmer, Martin, & Mazzae, 2012). In addition, delayed reaction times for sudden critical events have been reported (Drews et al., 2009; Regan & Hallett, 2011; Kircher, Patten, & Ahlström, 2011). Increased reaction times have also been found for auditory-cognitive distraction (e.g. hands free cellphone conversations or auditory presented memory tasks, Strayer et al., 2015; Jamson & Merat, 2005; Caird, Willness, Steel, & Scialfa, 2008). Qualitatively different to visual distraction, cognitive load seems to lead to an increased gaze concentration towards the road center (Engström, Johansson, & Östlund, 2005), unfortunately sometimes associated with the so called “looked-but-failed-to-see” phenomenon

(Kircher et al., 2011) and possibly leading to degraded peripheral hazard perception (Jamson & Merat, 2005). Lane keeping is usually not impaired by cognitive tasks or shows even less variability compared to manual driving (Engström et al., 2005; Cooper, Medeiros-Ward, & Strayer, 2013).

Taken together, NDR-tasks involving visual and manual distraction can be considered as particular detrimental for driving performance and crash risk (Dingus et al, 2016, c.f. Tab. 2-1; Dingus, Hanowski, & Klauer, 2011; Louw, Zschernack, & Gobel, 2013; Regan & Hallett, 2011). In order to describe the underlying psychological mechanisms of these findings, multiple resource theory (Wickens, 1984; Wickens, 2008) provides a useful framework. Other than Kahneman's (1973) model of a single limited "pool" of mental capacity, Wickens postulates several resource pools, with dual-task interference being greatest when the tasks demand the same type of processing resources. For instance, Wickens considers separate mental resources for perception/working memory on the one side, and response selection/execution on the other side. In particular, different resources for visual vs. auditory stimulus modalities and manual vs. vocal responses are hypothesized. As driving can be considered a visual-manual task, an additional NDR-task that also requires visual and manual resources (e.g. texting) will lead to greater performance decrements as an auditory-vocal task (e.g. passenger conversation). However, the theory also takes the role of cognitive workload into account. Therefore, when one or more of the concurrent tasks are highly demanding, performance decrements might occur even when there is no overlap in resource structure. As it is an attempt of this thesis to establish multiple resource theory as a framework for NDR-task engagement in highly automated driving, the theory is described in further detail in chapter 3.1.

In order to assess the psychological processes of distracted driving on a fine-grained level, Levy, Pashler, and Boer (2006) used the so called PRP paradigm, which is widely used in cognitive psychology (Tombu & Jolicoeur, 2002). PRP is the abbreviation for psychological refractory period and refers to a period of time during which the response to a second stimulus is slowed because a first stimulus is still being processed (Pashler, 1994). It is assumed that this effect occurs because central processing (response selection in Fig. 2-2) is a bottleneck, where processing is obligatory serial. This central bottleneck has been considered to cause dual-task interference (Pashler, 1994). It should be noted that the assumption of an all-or-none bottleneck is a competing theoretical approach to the more flexible idea of limited processing capacity in resource theories (see previous paragraph). The central bottleneck theory is still prominent in the current literature, although the strict assumption of exclusively serial response selection has been more and more attenuated (Koch, 2008; Logan & Gordon, 2001; Navon & Miller, 2002). In the driving simulator study by Levy et al. (2006) participants drove behind a lead car that occasionally braked, which required the participants to apply the brakes too. A simple choice task with different stimulus and response modalities was used as NDR-task. The time delay between the onset of the choice task and the braking task (= stimulus onset asynchrony) was systematically varied. Results indicate that with a shorter time delay between the two tasks, brake response times increased, showing the PRP effect. Consistent with multiple resource theory, brake response times were shorter when the choice task was presented auditory compared to visual, although effect sizes were rather small. Overall, this study features a successful application of cognitive psychology in the field of driver distraction research and facilitates the understanding of underlying mental processes that might account for dual-task interference.

Another psychological phenomenon that has received growing attention in driver distraction research is compensatory behavior or self-regulation. In the context of driver distraction self-regulation can be described as the way drivers "adjust their driving behavior in response to changing or competing task demands to maintain an adequate level of safe driving" (Young, Regan, & Lee, 2008, p. 336). Research has shown that drivers tend to reduce speed when distracted (Jamson & Merat, 2005; Haigney, Taylor, & Westerman, 2000; Rakauskas, Gugerty, & Ward, 2004). Increased following distance has been found as well (Strayer et al., 2015; Jamson, Westerman, Hockey, & Carsten, 2004). However, it cannot finally be judged to which extent these behaviors can be attributed to adaptive self-regulation or, instead, might represent degraded driving performance caused by too much attention allocation to the NDR-task (Young et al., 2008; Strayer et al., 2015).

In addition to changes in driving behavior, there is considerable evidence that individuals also adapt their NDR-task engagement to situational demands. Schömig and Metz (2013) found in a simulator study that drivers preferred to engage in an NDR-task mainly in low demanding situations, and during task engagement they continuously monitored the traffic situation with short control glances. Tivesten and Dozza (2015) showed in a naturalistic driving study that experienced drivers considered current and upcoming driving demands to decide when to engage in visual-manual cell phone tasks (e.g. dialing or writing text messages). In a study by Wandtner, Schumacher, and Schmidt (2016) drivers were free to engage in a self-paced texting task at any time during a simulated test drive. Results revealed that drivers interacted less frequently with the NDR-task during demanding or critical driving situations. In addition, self-regulated NDR-task interaction was associated with less impairments in driving performance in comparison to a control group with mandatory task engagement. However, it is still matter of debate under which circumstances drivers show situation-adaptive task interactions (see e.g. Horrey & Lesch, 2009; Liang, Horrey, & Hoffman, 2015).

Self-regulatory behavior in the interaction with NDR-tasks has been described within three-level models (Schömig & Metz, 2013; Young et al., 2008). These models are related to the hierarchical model of the driving task (see chapter 2.1.1), but focus on NDR-task interaction instead of driving behavior. According to the model proposed by Schömig and Metz (2013), it is determined on a planning level how a driver will generally deal with NDR-tasks during a drive. For instance, a driver might decide to turn his or her cell phone completely off during driving. On the decision level it is assessed whether the current driving situation allows for NDR-task engagement. To decide whether attending to an NDR-task is safe, an adequate mental model of the current and emerging driving situation is necessary (see also the concept of situation awareness, chapter 2.1.3). Lastly, when an NDR-task is started, the driving situation is constantly monitored and the task is interrupted if there are increases in situational demands (control level). Within this thesis the three level model is modified to the context of highly automated driving (chapter 3.1.3) and used as a framework to assess driver's self-regulation in the empirical studies (see chapter 4 in particular).

Finally, it has to be noted that self-regulation regarding the driving task and the NDR-task should be considered together. According to Platten, Schwalm, Hülsmann, and Krems (2014) these adaptations might reflect different ways to deal with conditions of high perceived workload. Depending on the circumstances (e.g. interruptibility of the NDR-task or requirements of the current traffic situation) compensatory behavior might take place in terms of driving behavior (e.g. reducing speed), NDR-task processing (e.g. reducing interaction frequency), or for a limited amount of time, by increasing the invested effort.

2.2.4 Non-Driving Related Tasks in Highly Automated Driving

Experimental research indicates that drivers are likely to increase their NDR-task engagement with higher automation levels (Carsten et al. 2012; Llaneras et al., 2013; Naujoks, Purucker, & Neukum, 2016). In a meta-analysis by de Winter et al. (2014) highly automated driving was associated with an increase of NDR-task engagement of 261 % compared to manual driving. As highly automated driving systems have not yet entered the market, surveys have been conducted to get an idea what type of NDR-tasks might be performed when using such systems in the future. Fraedrich, Cyganski, Wolf, and Lenz (2016) carried out a large internet-based survey (N = 1,000), where participants indicated that they would mainly utilize highly automated driving time with window gazing, passenger conversations, and relaxing. In another online survey (N = 5,000) by Kyriakidis, Happee, and de Winter (2015) participants rated their willingness to engage in pre-defined NDR-tasks when using manual and automated driving modes. For highly automated driving, participants indicated an increased motivation (compared to manual and partially automated driving) to engage in the following tasks: Resting, phoning, mailing, watching movies, reading, eating and drinking, passenger conversations, and observing the landscape.

Compared to extensive research on distraction in manual driving (see previous chapter 2.2.3), so far only few studies addressed the impact of NDR-task engagement on take-over performance in highly automated driving. These studies were almost exclusively conducted in driving simulators. Widely used NDR-tasks in these studies have been the visual-manual Surrogate Reference Task (SuRT; e.g. Gold et al., 2013; Lorenz, Kerschbaum, & Schumann, 2014; Beller, Heesen, & Vollrath, 2013) or the cognitive demanding "Twenty Questions Task" (e.g. Körber, Gold, Lechner, & Bengler, 2016). Other studies focused on more naturalistic tasks such as reading news articles (Naujoks, Mai, & Neukum, 2014) or internet search using the car's multimedia system (Zeeb et al., 2015).

Research on highly automated driving mainly addressed the question how much time (from displaying the take-over request until the system limit is reached) the driver needs to take over in a safely manner. For determining this minimal time budget, usually a highly distracting NDR-task was used to take the driver completely out of the loop before encountering a take-over situation. Differences between NDR-tasks were usually not in the scope of these studies. Significant performance impairments were found for the SuRT task compared to control groups of non-distracted manual drivers (Damböck et al., 2012; Gold et al., 2013). Similar effects of the SuRT were also reported in comparison to highly automated driving without NDR-task engagement (Feldhütter et al., 2016).

So far, only few studies implemented more than one NDR-task and addressed the question which impact different NDR-tasks have on drivers' take-over performance. Radlmayr et al. (2014) compared the SuRT task with the cognitive n-back task (repeating a series of numbers with an offset of n steps; in this study a two-back task was used). Results indicated similar take-over performance for the two tasks, apart from a higher collision rate for the SuRT in one of four take-over situations.

Gold, Berisha, and Bengler (2015) used the same two NDR-tasks and added a laptop-based texting task and a cognitive-motoric task ("shape-sorter ball"). For less complex take-over situations compared to Radlmayr et al. (2014), the visual-manual SuRT impaired take-over performance significantly more than the two-back task. Taking the results for the other tasks into account, motoric engagement seemed to be the crucial factor for drivers' take-over-performance in this study.

In an experiment by Petermann-Stock, Hackenberg, Muhr, and Mergl (2013) participants performed different NDR-tasks during highly automated driving in a traffic jam setting. Three versions of a quiz game were implemented with the purpose to induce increasing workload. In all task versions a question was presented auditorily, but the answer options were displayed differently (acoustic or visual). The response modalities were varied as well (speaking or typing). The largest impairments in take-over performance were found for a task version including a combination of acoustic, cognitive, visual, and motoric load.

Diederichs et al. (2015) compared two versions of a reading tasks (handheld smartphone vs. high-head integrated display) with a baseline of supervised automation. The slowest take-over reactions were found in the smartphone condition, while there was no significant difference between the high-head reading and baseline condition.

In a study by Vogelpohl et al. (2016) participants performed two different NDR-tasks on a handheld tablet computer: reading a news article as well as playing a Tetris game. Compared to a control group of supervised automation, take-over times were significantly longer for both NDR-tasks. Pairwise comparisons found no differences between the two NDR-tasks. The results were similar across four different take-over scenarios.

Zeeb et al. (2016) also investigated the impact of naturalistic NDR-tasks on take-over performance. All tasks were presented in the vehicle's infotainment system (center display) and required the driver to look away from the road. There were no significant effects on response times (hands on steering wheel or system deactivation). However, take-over quality in terms of lateral control was impaired for a news reading and video task compared to a control group without any task. Writing an email did not lead to any performance decrements in comparison to the control group, although participants rated this task as most distracting.

So far, the reviewed studies suggest that NDR-tasks have an impact on drivers' take-over performance. In particular, visual and motoric demanding tasks seem to impair the ability to take over quickly and accurately. However, in many cases effects were rather small or not consistent between timing and quality metrics (e.g. Zeeb et al., 2016; Körber et al., 2016). Based on regression models for different measures of take-over performance, Gold (2016) reports an overall small effect of NDR-task engagement, which was not significant in many of the tested models. Some authors did not find significant effects of NDR-task engagement at all (Neubauer et al., 2014) or even faster brake response times for phone-use due to enhanced alertness (Neubauer et al., 2012).

Overall, previous research provides valuable insights, which properties of NDR-tasks might be relevant for predicting take-over performance. However, the wide range of results does not yet provide a uniform picture. In this context, some methodological aspects have to be considered. Besides the limited comparability of investigated NDR-tasks across the reviewed studies also the take-over scenarios differed in various aspects (e.g. criticality and complexity, see chapter 2.2.2). It also became obvious that it is challenging to identify a set of NDR-tasks which only differs in one specific dimension. For example the SuRT and n-back task differ not only in their resource demands (visual-manual vs. cognitive) but also in terms of their task codes (spatial vs. verbal), duration, and response format. Thus, in many cases it is not determinable which specific task dimensions account for the effects on take-over performance. Hence, the generalization of the results is limited to a certain degree and there is a clear need for more research to complete the picture. In addition, the moderating role of drivers' self-regulation in dealing with NDR-tasks has to be considered (c.f. chapter 2.2.3).

3 Development of Research Questions

Recent evidence suggests that the introduction of highly automated driving will be accompanied by an increased prevalence of NDR-task engagement (see chapter 2.2.4). Compared to extensive research on distraction in manual driving (chapter 2.2.3) only few studies have addressed the influence of NDR-task engagement on take-over performance in the context of highly automated driving (chapter 2.2.4). The existing literature provides valuable first insights, but also offers a wide range of different results. Thus, there is a need for more research in this area. This also includes a strengthening of the theoretical basis to allow for specific predictions of take-over performance under the presence of different types of NDR-tasks.

3.1 Theoretical Framework

Aim of the present thesis is to extend previous research by investigating specific NDR-task characteristics based on a well-established psychological framework. As outlined in the theoretical background, in a critical take-over situation the driver has to deal with the demands of two tasks: the ongoing NDR-task and re-engaging in the driving task. A widely used theoretical concept for performance prediction in multiple-task situations is Wickens' multiple resource theory (Wickens, 1984, 2008). The theory has been successfully used to predict performance decrements of NDR-task engagement during manual (e.g. Horrey & Wickens, 2004) and partially automated driving (Spiessl & Hussmann, 2011). Although the theory originally focused on concurrent dual-tasking scenarios (as it is the case for manual driver distraction), it has also been applied for sequential multi-tasking, e.g. the interruptions paradigm (Ho, Nikolic, & Sarter, 2001; Ho, Nikolic, Waters, & Sarter, 2004; Latorella, 1998). This can be justified by the fundamental similarities of underlying cognitive mechanisms across different multitasking paradigms (c.f. Koch, Poljac, Müller, & Kiesel, 2018).

This thesis considers a transfer of multiple resource theory to the context of NDR-task interactions in highly automated driving. In the following, the general components and mechanisms of the theory are outlined. Specific aspects of highly automated driving are then taken into account to derive hypotheses for the empirical research of this thesis.

According to multiple resource theory, the overall performance decrement (= task interference) in a multitasking setting is determined by two factors. First, task interference is higher for tasks that require a large amount of mental workload (= *resource demand*). Second, the performance decrement will be greater if tasks require the same type of mental resources

(= *resource structure*). For example, two visual tasks cannot be time shared as well as a visual and an auditory task (see also chapter 2.2.3). Besides sensory modalities (auditory vs. visual), other relevant dimensions for the efficiency of multitasking are stages in information processing (perceptual/cognitive vs. response), processing codes (verbal vs. spatial), and the required type of response (vocal vs. manual). These different resources can be represented in a "cube" form (Fig. 3-1). A given task occupies one or several cells of the cube and the amount of multitasking interference is determined by the number of overlapping cells between two tasks. In further extensions of the model channels of visual information (focal vs. ambient) and the tactile modality (besides auditory and visual) were added (Wickens et al., 2013).

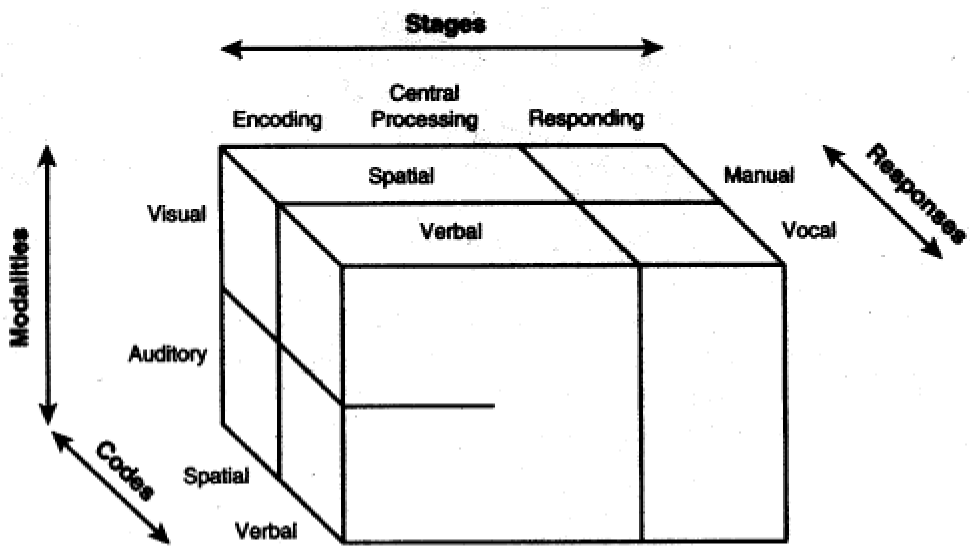

Fig. 3-1: Structure of processing resources (from Wickens, 1984).

The combination of resource demand and resource structure determines the overall performance decrement. However, another aspect within multiple resource theory is the *allocation of resources.* This refers to mechanisms of cognitive control (or self-regulation), e.g. the prioritization of tasks and the handling of interruptions. The three described components together constitute the so-called *architecture of multiple resource theory* (Wickens, 2008; Fig. 3-2).

Multiple resource theory captures determinants of multiple-task performance at a high level and, in contrast to process models (e.g. Pashler, 1994), it does not explicitly model the time course of interference. However, focussing on the macroscopic level provides the advantage that the theory can be used as a general heuristic for a variety of multiple-task situations.

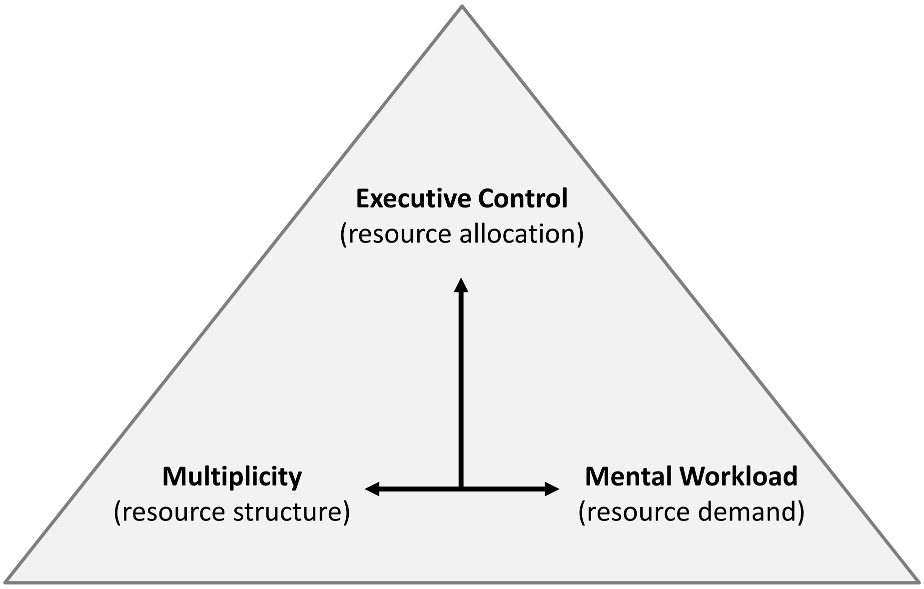

Fig. 3-2: Architecture of multiple resource theory (adapted from Wickens et al., 2013).

3.1.1 Resource Structure (Multiplicity)

In the following, a transfer of multiple resource theory to take-over situations in highly automated driving is outlined, beginning with the component of resource structure (Fig. 3-1).

Driving can be considered as a visual-manual task with mainly spatial coding and varying demands on all stages of information processing (perception, cognition, and responding). In the context of take-over situations in highly automated driving, the requirements for the driver include different steps (Petermeijer, de Winter, & Bengler, 2016; Zeeb et al., 2015; Naujoks et al., 2017): Noticing the take-over request, shifting visual attention to the road, perception and cognitive processing of the traffic situation (regaining situation awareness), action/maneuver selection, establishing motor readiness (i.e. hands on steering wheel and feet to the pedals), and finally the execution of the selected response (e.g. braking and/or steering). It is assumed that some of these processes can be executed in parallel (e.g. establishing motor readiness and cognitive processing of the traffic situation) and others sequentially (e.g. attentional switch to the road scenery and cognitive processing of the traffic situation; Zeeb et al., 2015).

Based on this background, assumptions about the impact of different NDR-tasks can be derived. Within the scope of this thesis, the role of task modalities (stimulus and response) is of particular interest. That is due to the fact that NDR-task modalities are relevant for performance prediction of distracted manual (e.g. Dingus et al., 2011; Louw et al., 2013) and partially automated driving (Spiessl & Hussmann, 2011). The existing research on highly automated driving also points in this direction (chapter 2.2.4). In addition, these task dimensions can be detected relatively easy by driver state monitoring systems (Marberger et al., 2017) and may provide a basis for adaptive HMI concepts. Within the framework of multiple resource theory, and under consideration of take-over process models (Petermeijer et al., 2016; Zeeb et al., 2015), predictions on the role of task modalities can be drawn.

As a baseline for the following considerations a vigilant, but not necessarily attentive driver is considered who is not performing any specific NDR-task. Conditions of hypovigilance due to passive or active drowsiness (May & Baldwin, 2009) are not in the scope of this thesis. Hence, the potential activating effects of NDR-tasks (e.g. Neubauer et al., 2012; Schömig et al., 2015) are not further considered. In addition, it is assumed that the take-over request is presented highly salient and multimodal. Potential problems in noticing the take-over request are not further considered.

Predictions for the impact of NDR-task modalities on take-over performance are the following:

- Auditory-vocal task demands: Depending on workload (see next section), *little or no deterioration* of take-over performance is expected as there is no overlap in stimulus or response modalities to the driving task. However, interference potential exists due to a general overlap in the stages of information processing (Fig. 3-1). As visual attention is not required for the NDR-task, it might already be focussed on the road scenery when the take-over request is issued. Hence, cognitive processing and response selection might be enhanced in comparison to visual tasks.
- Visual task demands: *Medium to high deterioration* of take-over performance is expected. Interference may occur at shifting attention back to the road. As a result of delayed perception, cognitive processing of the driving situation and response selection may be negatively affected as well.
- Manual task demands: *Medium to high deterioration* of take-over performance is expected. Interference may occur at establishing motor readiness (putting hands back at the steering wheel) and execution of the selected maneuver (e.g. steering or braking). In particular, high interference is assumed if the NDR-tasks requires the need to hold

an item (e.g. smartphone or tablet computer) in the hands, as this will extend the duration until the hands can be put back to the steering wheel. Furthermore, the additional task arises where to deposit the handheld item. The latter involves further cognitive and visual processes which might delay the attentional switch to the traffic situation as well as cognitive processing and maneuver selection.

As the overall interference is expected to be proportional to the number of shared resources (Wickens, 2002), a visual-manual NDR-task is assumed to be the worst case combination in terms of resource structure - in particular if it is performed handheld.

3.1.2 Resource Demand (Mental Workload)

At this point, it is important to take mental workload (resource demand) into account. For instance, an auditory-vocal task might still lead to performance decrements if it includes complex stimulus material or heavily relies on working memory (e.g. due to the mere fact that auditory material is highly fragile; Latorella, 1998).

Regardless of modalities, a high degree of workload might delay the attentional switch to the driving task (“cognitive tunnelling”; Dehais, Causse, & Tremblay, 2011) and this effect might be further augmented if the NDR-task is inherently interesting for the driver (Horrey & Wickens, 2006). As there is usually some sort of “task rehearsal” (Altmann & Trafton, 2002; see also Zeigarnik, 1938) during and after suspension of the ongoing task, further aspects of the transition process (e.g. regaining situation awareness or maneuver selection) might be affected, too. Taken together, it is hypothesized that mentally demanding NDR-tasks can have detrimental effects on drivers’ take-over performance.

3.1.3 Resource Allocation (Executive Control, Self-Regulation)

Finally, resource allocation or self-regulation is expected to strongly affect take-over performance. For instance, take-over performance will likely be facilitated if the driver immediately disengages from the NDR-task and focuses all his resources on taking over the driving task instead of trying to complete the ongoing (sub-) task. As outlined in chapter 2.2.3, there is considerable evidence from driver distraction research that individuals not only adjust their driving behavior according to demands of the traffic situation but also their NDR-task engagement (Schömig & Metz, 2013; Tivesten & Dozza, 2015; Wandtner et al., 2016). This self-regulatory behavior in interaction with secondary tasks has been described within a three-level model (Schömig & Metz, 2013). In the context of this thesis, the model was adapted for highly automated driving (Tab. 3-1). In particular, for every level of the model (planning, decision, and control), appropriate self-regulation was defined as reference point for empirical research. The model and its implications are further described in the introduction of Study 1.

Tab. 3-1: Three-level model of self-regulation in highly automated driving.

Level	Description	Appropriate Self-Regulation
Planning	Determination how a driver will generally deal with NDR-tasks during a drive.	Limiting task engagement to sections of highly automated driving (considering predicted system availability).
Decision	Decision whether the current situation allows for an engagement in an NDR-task.	Assessment of driving situation / system status. Task engagement only if applicable (considering estimated task duration and predicted system availability).
Control	Regulating NDR-task processing, interruption if necessary.	Maintenance of take-over readiness. Rapid task disengagement and take over when prompted.

3.2 Empirical Research

This thesis aims to evaluate the outlined theoretical considerations based on empirical research. For this purpose, the different building blocks of multiple resource theory (resource allocation, resource structure, and resource demand) were addressed in three consecutive driving simulator studies in the context of highly automated driving. In a fourth study, practical implications for HMI design are considered and evaluated.

Study 1 focused on the *resource allocation* component which is labelled self-regulation in the following, with respect to the term used in driver distraction research (e.g. Young et al. 2008, Wandtner et al., 2016). In the driving simulator study participants had the opportunity to decide whether to engage in a given NDR-task, under consideration of the driving mode (manual vs. highly automated) and upcoming take-over situations. On the basis of the three-level model of self-regulation (Tab. 3-1) NDR-task engagement and disengagement was analysed and linked to take-over performance.

In Study 2, the *resource structure* component of multiple resource theory was addressed in detail. The main objective of this simulator study was to investigate the impact of different NDR-task modalities on take-over performance. For this purpose, a model NDR-task was designed that enabled for different stimulus and response modalities whilst keeping the task itself as constant as possible. Additionally, in one experimental group the NDR-task was locked out simultaneously with the take-over request while task continuation was possible in a control group. This distinction was included to further investigate the role of drivers' self-regulation concerning NDR-task disengagement.

The goal of Study 3 was to take *resource demands* (mental workload) into account when assessing drivers' take-over performance. For this purpose, one of the NDR-tasks of Study 2 was re-used and compared with a newly designed task version, which differed in the required mental workload whilst keeping task modalities constant. Another aspect of the third simulator study was a variation of the available time budget in take-over situations.

On the basis of the simulator studies and additional requirement analyses in the form of focus groups and interviews, practical implications for the HMI design were derived. In Simulator Study 4, different HMI versions were evaluated in terms of their effects on NDR-task processing and take-over performance. The overall goal of the HMI concepts was to facilitate a safe and comfortable NDR-task disengagement in predictable, as well as suddenly emerging take-over situations. In addition, one of the HMI versions included an adaptive approach that considered drivers' current NDR-task engagement, based on driver state monitoring.

Each of the four simulator studies, as well as resulting implications, are described in detail in the following chapters. Finally, the results are taken together in an integrated discussion (chapter 8).

4 Study 1: NDR-task engagement and disengagement[1]

4.1 Introduction and Research Questions

In previous studies on highly automated driving, rigid experimental block designs have been widely used. Drivers are forced to engage in specific NDR-tasks prior to a critical take over situation (see also chapter 2.2.4). Different timing aspects of the driver reaction are then assessed, e.g. time to first gaze at the scenery, time until the hands touch the steering wheel, and time until the driving maneuver is initiated (e.g. Damböck et al., 2012; Gold et al., 2013, Gold & Bengler, 2014). Additionally, quality aspects of the take-over reaction are analyzed, e.g. crash avoidance, trajectories, and maximum accelerations. NDR-task engagement is usually not separately considered. As participants are forced to engage into a specific task, results should be interpreted as worst-case performance out of maximum distraction.

The purpose of the present study was to extend the understanding of driver behavior when dealing with NDR-tasks in a more naturalistic way. In terms of the thesis' theoretical framework, mainly the *resource allocation* (or self-regulation) component was addressed (see chapter 3.1). According to Young et al. (2008, p. 336) "self-regulation in the context of driver distraction can be understood as the way drivers adjust their driving behavior in response to changing or competing task demands to maintain an adequate level of safe driving". In addition, there is evidence that individuals not only self-regulate their driving behavior according to situational demands but also their NDR-task interaction. Relevant studies have been discussed in chapter 2.2.3 of this thesis.

Self-regulation of NDR-task interactions in manual driving has been described within a three-level model (Schömig & Metz, 2013). In the context of this thesis, the model was transferred to highly automated driving (chapter 3.1.3) and appropriate self-regulatory behavior was defined for the separate levels as reference point for empirical research (Tab. 3-1). On the *planning level* it is determined how a driver will generally deal with NDR-tasks during a trip. As the driver is allowed to engage in NDR-tasks in highly automated driving mode, appropriate self-regulation would be to limit NDR-task interaction to such periods and concentrate on the driving task in manual driving mode. The *decision level* refers to the current situation. Before the

[1] Parts of chapters 4 to 6 have been published in: Wandtner, Schömig, & Schmidt (2018a, 2018b) and Wandtner, Schmidt, Schömig, & Kunde (2018).

driver begins his interaction with an NDR-task, the driving situation as well as the system status have to be considered. This also includes the estimated task duration and the predicted availability of the highly automated driving system for this time period. Finally, the *control level* refers to self-regulatory processes during the execution of an NDR-task. The driver has still to be aware of the current system state during task interaction. In particular, when a take-over request is issued, a quick disengagement from the task is required to ensure an appropriate take-over reaction.

The goal of the present simulator study was to investigate to which extent drivers self-regulate their NDR-task engagement in terms of the three-level model. In particular, it was assessed if a preview of automated driving sections would prompt strategic scheduling of NDR-task processing (planning/decision level in Tab. 3-1) and facilitate safe take-over behavior (control level).

The preview display was implemented in accordance to previous research on human-automation interfaces. Following Billings' (1997) "principles of human-centered automation", main goals for the human machine interface (HMI) are to keep the operator well informed and making the automation predictable. Beggiato et al. (2015) found in an expert focus group and a subsequent simulator study that a preview of oncoming driving situations is an important user need for highly automated driving. Performance benefits for predictable take-overs were reported by Dogan, Deborne, Delhomme, Kemeny, and Jonville (2014) and Larsson (2017). In the present study, it should be evaluated how a detailed preview may facilitate safe driver behavior – in particular in scheduling NDR-tasks engagement under consideration of the availability of a highly automated driving system.

In the study, drivers completed a simulated test drive with alternating sections of manual and highly automated driving and had the opportunity to decide when to engage in a secondary texting task. It was assumed that self-regulatory behavior was facilitated and quality of transitions to manual driving improved with drivers who had a preview of upcoming sections of the track (predictive HMI) compared to drivers who had not (basic HMI).

4.2 Method

4.2.1 Participants

Twenty participants (10 men, 10 women) were recruited from a study panel and agreed to participate on a voluntary basis. Prerequisites for study participation were a valid driver's licence and experience with touchscreen devices, e.g. smartphones and tablet computers. Only right-handers were considered to prevent possible difficulties with the texting task, which was presented on a tablet computer mounted on the center console (Fig. 4-1). The participants were of young or mid age (mean age M = 27.6 years, standard deviation SD = 6.2, range 20-44) and had an average annual mileage of 17,925 km (SD = 16,421). The drivers received a monetary compensation for their participation. There were no dropouts for the data analysis as all participants successfully completed the test drive.

4.2.2 Driving Simulator and Highly Automated Driving System

The experiment took place in a driving simulator at the WIVW GmbH (Würzburg Institute for Traffic Sciences, Fig. 4-1). The motion-base driving simulator has six degrees of freedom, resulting from six electronic and three pneumatic actuators. The projection system displays a 180 degrees field of view to the front. The dynamics model simulates the behavior of a midsize car with automatic transmission.

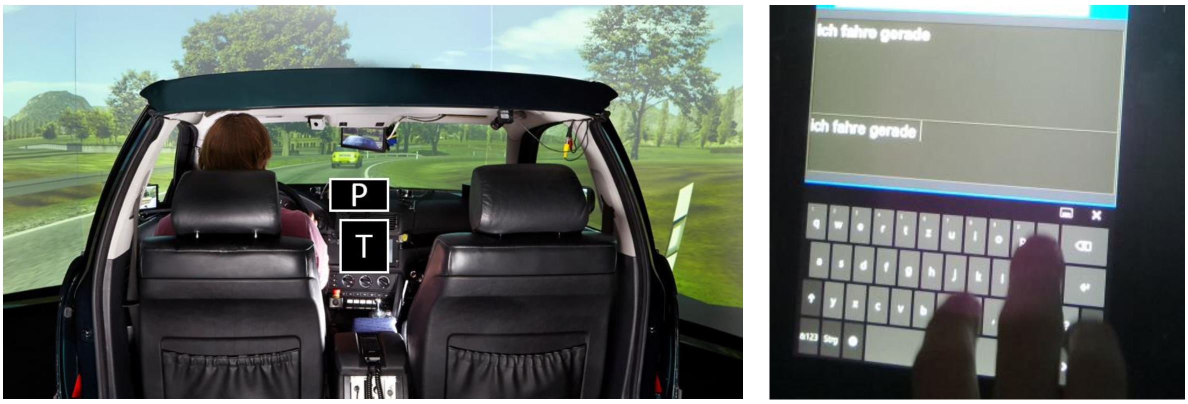

Fig. 4-1: Left: Driving simulator (P = Preview, T = Tablet). Right: Texting task on tablet. Photos: WIVW GmbH.

The highly automated driving system was able to control lateral as well as longitudinal vehicle guidance on highway roads. The availability of the system was indicated by an auditory chime and a white icon in the cluster display behind the steering wheel. The system could then be activated with a button on the steering wheel and the system status icon changed to green. When activated, the system adjusted the vehicle's speed to 120 km/h. Automated lane changes or overtaking were not implemented. A take-over request was indicated by an auditory warning and a red icon in the instrument cluster. The system could be deactivated by either the steering wheel button, braking or a steering input.

4.2.3 HMI Versions

Two HMI versions were implemented for the study. One group of drivers had a preview of the current and upcoming sections of the track (predictive HMI group) to enable for self-regulation of NDR-task engagement on the planning, decision, and control level (Tab. 3-1). The other drivers served as a control group (basic HMI group). In both experimental groups driving related information (speedometer, driving mode and take-over requests) was displayed in the cluster display behind the steering wheel. An additional display on top of the mounted tablet was used for the predictive HMI (Fig. 4-1 and Fig. 4-2).

The predictive HMI contained information about the current and upcoming sections of the track as well as the predicted system availability (e.g. based on map data and/or car-to-x communication). In contrast, for the basic HMI group the display was only used as a progress bar to show how much of the whole track was already completed.

Fig. 4-2: Predictive HMI displayed in the center console. A preview of the entire test track was depicted in the upper area (green sections = automated driving available; white sections = manual driving). A detail view of the current section was shown in the lower area. During the drive, the two bars were filled to highlight the current position. In this example, a third of the whole trip is completed (upper display), the current driving mode is manual (white section) and there are 5.5 km left until a section of highly automated driving (green section) will be reached.

4.2.4 Simulated Test Track

The track consisted of a two-lane highway with a total length of 72 km. There was medium traffic density around the participant's car. The track contained alternating sections of manual and highly automated driving with an average length of 6 km (range 5 to 7 km, see also Fig. 4-2). The participants were instructed to always stay in the right lane and keep a speed of 120 km/h. This was also the target speed of the highly automated driving system.

The six sections of highly automated driving each ended with the same take-over scenario. The system requested the driver to take over control of the vehicle when approaching a sharp bend to the left. The take-over request was prompted eight seconds before the vehicle would have exceeded the lane markings without steering input from the driver. No other vehicles were present when passing through the curve.

4.2.5 Non-driving related Tasks

A visual-manual texting task was implemented in order to simulate demands that are common to modern in-vehicle information systems and mobile devices. Sentences were presented on a tablet computer mounted at the center console (Fig. 4-1). The participants were instructed to transcribe the given text quickly and accurately. For this purpose a virtual keyboard was used. The text entered by the participants was shown below the given text. Words entered incorrectly could be deleted with a backspace key and then re-entered. To ensure that all participants were at the same position of the text at a given point in time, the task was paced by the system. This was important for the controlled analysis of take-over situations. The given text was not presented as a whole, but word by word in a specific time interval.

The participants were free to either accept or reject a given task within a decision time of five seconds to enable for self-regulation. The task was implemented with two lengths: short sentences (30 characters) and long sentences (90 characters). A reward system was used to ensure that the drivers were motivated to deal with the NDR-task. For a completed short sentence 10 points could be awarded, for a long sentence 30 points. If a task was started but not completed, the same number of points were subtracted. Typing errors were penalized with one point per word. The overall score was payed as Euro Cent in addition to the regular compensation. The maximum bonus score that could be achieved was 3.20 Euro.

The texting task was offered during both driving modes (manual and highly automated driving) and also prior to take-over situations. In total, 22 tasks were offered (11 during manual driving, 11 during highly automated driving). Prior to take-over situations there was either no task offered (two times), a short sentence (two times) or a long sentence (two times). When the take-over request was issued, there were about 10 characters remaining to complete the sentence, regardless of task length.

The task was implemented with two lengths to enable for an assessment of different aspects of self-regulation. An appropriate self-regulation on the planning/decision level (Tab. 3-1) would have been to reject NDR-tasks during manual driving, in particular the highly distracting long sentences. Another aspect refers to the control level of self-regulation. Here, the goal was to assess drivers' disengagement from NDR-tasks in take-over situations. It was expected that drivers would have greater difficulties to interrupt long sentences because of the larger invested effort and the greater potential loss in terms of the reward system (see also Lee, 2014; Fox & Hoffmann, 2002).

4.2.6 Procedure

All participants had successfully completed a simulator familiarization prior to the study. The current study began with a short introduction into highly automated driving and the participants completed a driving practice. In a first step this included a manual driving session. Afterwards, the handling of the highly automated driving system (e.g. activation and deactivation) was trained. Additionally, the drivers experienced a first uncritical take-over request. Next, the NDR-task was instructed and the participants had the opportunity to practice the task without driving. Then, the NDR-task was practiced during manual as well as highly automated driving until the participants felt familiar in dealing with the task. Finally, the additional HMI screen in the center console (predictive or basic HMI) was explained to ensure that all drivers had a correct and similar understanding of the depicted information.

The experimental drive began after an optional break and lasted about 40 minutes. Beforehand, the participants were instructed to drive safely at all times, but also to solve as many tasks as possible. In addition, the reward system was explained. Driving parameters, NDR-task engagement, and gaze data (eye tracker by Smart Eye AB) were recorded during the experiment. After the drive, the participants were asked to fill in a questionnaire about their experiences during the experiment. The questions addressed participants' strategies of NDR-task engagement and disengagement and a subjective evaluation of the HMI concepts.

4.2.7 Data Analysis

A mixed design was used for the present study. Independent variables were HMI version (basic vs. predictive) as between-subject factor, as well as driving mode (manual vs. highly automated) and NDR-task (no task, short sentence texting task, long sentence texting task) as within-subject factors.

Several dependent variables were selected to assess drivers' self-regulation of NDR-task interaction as well as driving performance in take-over situations. The number of accepted tasks in dependence of the current driving mode was used as a measure for drivers' self-regulation on the planning/decision level. In take-over situations, drivers' disengagement from NDR-tasks (task canceled vs. task continued) was considered as a measure for drivers' self-regulation on the control level. Finally, drivers' take-over performance was assessed by inspecting timing aspects (time until first gaze on road, time until hands were back at the steering wheel, time until system deactivation, and time until initiating steering) and quality aspects (variability of lateral position, lane exceedances, and maximum accelerations).

Mixed-design ANOVAs were calculated for statistical testing of differences. The level of significance was set at $\alpha = 0.05$. All analyses were performed with IBM SPSS Statistics 22.

4.3 Results

4.3.1 Analysis of NDR-task Engagement

From a total of 22 tasks, 13 tasks were accepted on average (predictive HMI: M = 12.90, SD = 5.04; basic HMI: M = 12.70, SD = 5.62) and 11 of them completed (predictive: M = 11.20, SD = 4.98; basic: M = 10.40, SD = 5.76). There was a clear preference for task engagement during highly automated compared to manual driving (F (1,18) = 49.85, $p < .001$, $\eta^2_p = .735$; Fig. 4-3). During manual driving 3.10 tasks (SD = 4.27) were accepted on average. In contrast, during highly automated driving participants engaged averagely in 9.70 (SD = 1.90) tasks. No differences were found regarding HMI versions (F (1,18) = 0.01, $p = .94$, $\eta^2_p < .001$) and there was no interaction between driving mode and HMI version (F (1,18) = 0.11, $p = .92$, $\eta^2_p < .001$).

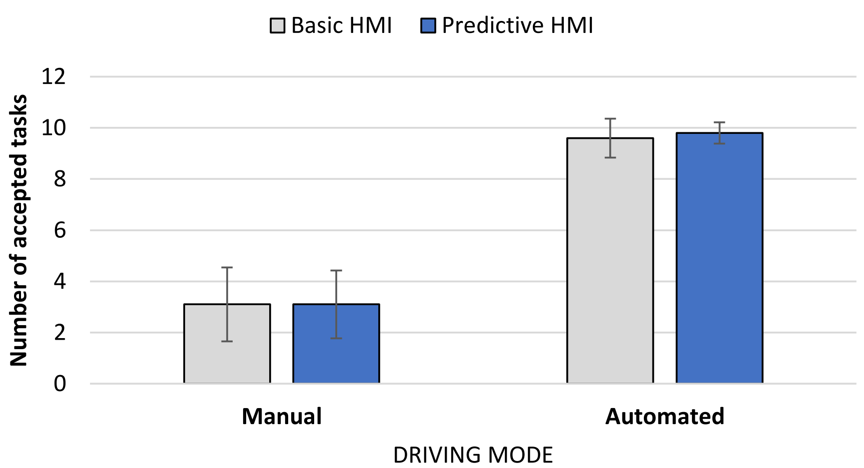

Fig. 4-3: Task engagement during manual and highly automated driving. The mean numbers of accepted tasks are depicted for both HMI groups. Error bars represent the standard errors of the means.

The role of task length was considered in a subsequent analysis. On average, 87 % (SD = 21 %) of the short and 90 % (SD = 17) of the long sentences were accepted in highly automated driving. In contrast, only 35 % (SD = 44 %) of the short and 20 % (SD = 37) of the long sentences were accepted in manual driving. Thus, the preference for task engagement in highly automated vs. manual driving was more pronounced for long compared to short sentences. This was confirmed by a repeated measurements ANOVA (F (1,19) = 6.77, p = .02, η^2_p = .26).

Focusing on self-regulatory behavior in the context of highly automated driving, task engagement was analyzed during normal operation of the highly automated driving system and in take-over situations. Of particular interest was task engagement in the predictive HMI group, where drivers had the opportunity to anticipate upcoming take-over situations. The number of accepted tasks was analyzed for uncritical (i.e. task could be completed during highly automated driving) and critical task offers (i.e. task duration interfered with an upcoming take-over situation). Every driver experienced seven uncritical and four critical task offers during highly automated driving. The percentage of accepted uncritical and critical tasks was calculated for each driver and then aggregated. While there was neither a significant main effect for task offer (uncritical vs. critical: F (1,18) = 3.17, p = .09, η^2_p = .15) nor for HMI (predictive vs. basic: (F (1,18) = 0.03, p = .86, η^2_p =.002), the interaction between the factors was significant (F (1,18) = 6.45, p = .02, η^2_p = .26). Drivers with predictive HMI accepted fewer tasks prior to take-over situations compared to uncritical tasks, whereas this tendency was not found for the basic HMI (Fig. 4-4). Here, a similar number of critical and uncritical tasks was accepted.

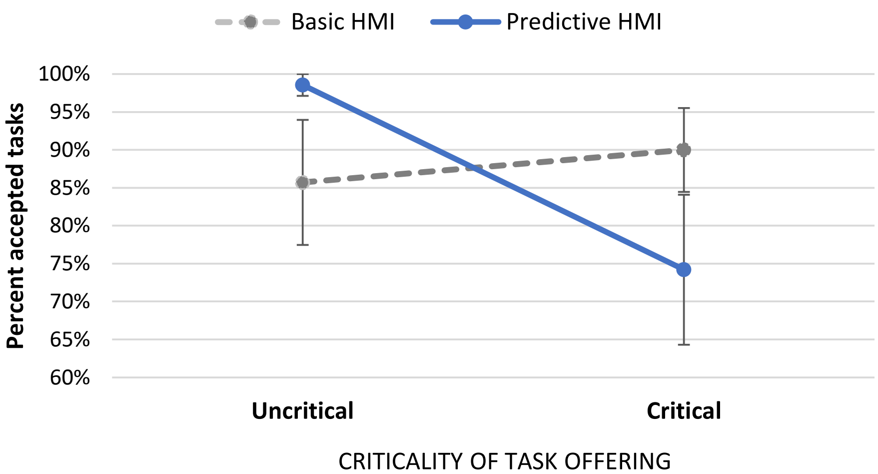

Fig. 4-4: Mean percentage of accepted task for uncritical and critical task offers during highly automated driving. Uncritical = task could be completed during highly automated driving, critical = task duration interfered with an upcoming take-over situation. Error bars represent the standard errors of the means.

For more insights into self-regulatory behavior, task engagement was descriptively analyzed over time, focusing on the four critical tasks offered during highly automated driving (Fig. 4-5). In the predictive HMI group, there was a clear decrease in the number of accepted tasks over the first three task offers, whereas it remained at a nearly maximum level in the basic HMI group. This trend broke down at the fourth task. This task was accepted by 7 of 10 drivers in both groups. When taking the task lengths into account, it seems that anticipative behavior only occurred for the short sentences (task 2 and task 3).

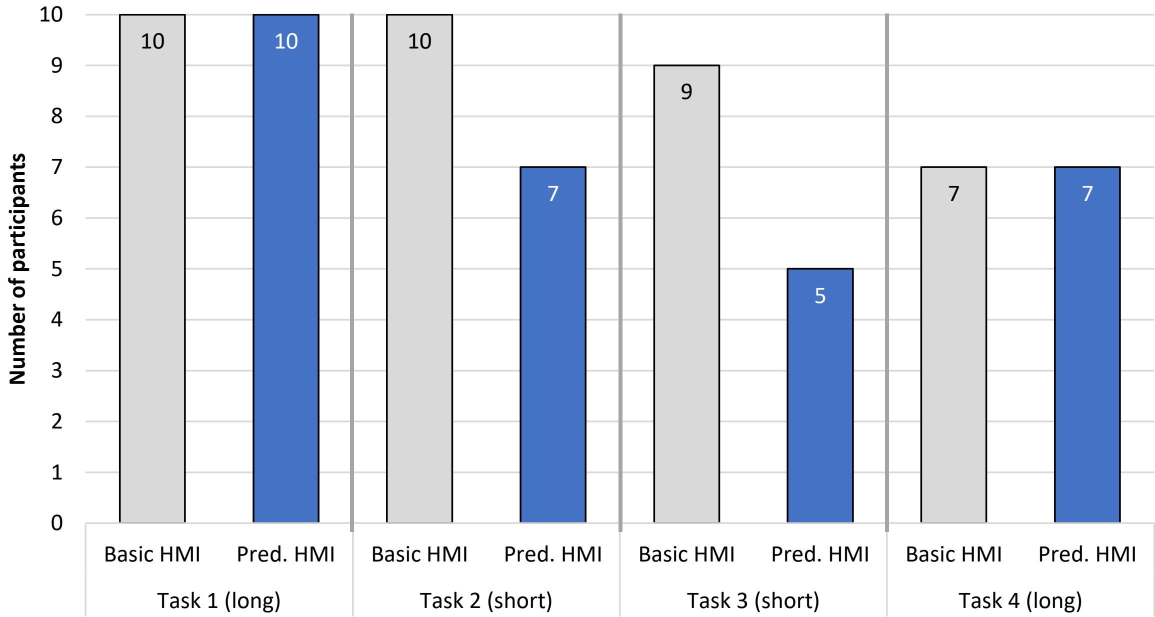

Fig. 4-5: Total number of accepted critical tasks during highly automated driving over time. Task engagement is shown for the two HMI groups (predictive vs. basic). Additionally, the task type (long or short) is indicated.

Another relevant aspect of self-regulation as well as driving safety was task disengagement in take-over situations (control level in Tab. 3-1). As outlined above, appropriate self-regulation in a take-over situation would have been an immediate NDR-task disengagement and switch to the driving task. It was assessed for both HMI groups to which extent drivers disengaged from a started NDR-task or continued texting in take-over situations (Fig. 4-6). Continuing a task was defined as entering two or more characters after the take-over request was issued.

Results showed that in most cases drivers continued texting after being prompted to take over. In the predictive HMI group, a started NDR-task was continued averagely in 65 % of the cases (SD = 46 %), in the basic HMI group even in 76 % (SD = 22). Differences between the groups were not significant (F (1,18) = 0.45, p = .51, η^2_p = .02). Long sentences were continued in 63 % of the cases (SD = 43 %) on average, short sentences in 85 % (SD = 29). This difference did not reach statistical significance (F (1,16) = 3.43, p = .08, η^2_p = .18).

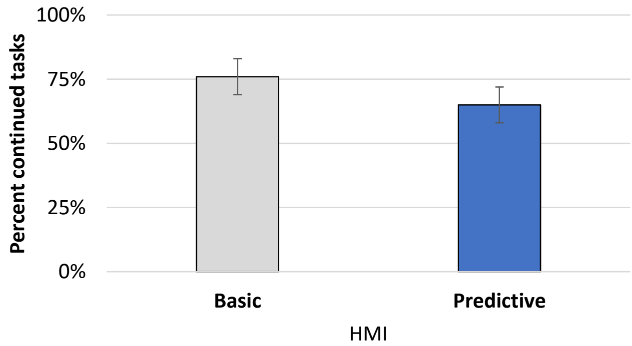

Fig. 4-6: Mean percentage of continued tasks in take-over situations for both HMI groups (predictive vs. basic HMI). Error bars represent the standard errors of the means.

In a second step, the percentage of completed tasks was analyzed. Completing a task required the input of approximately 10 characters after the take-over request was issued. In the predictive HMI group, 50 % (SD = 39 %) of the started tasks were completed during the take-over situation (passing through the curve), in the basic HMI group 45 % (SD = 38 %). Again, group differences were not significant (F (1,18) = 0.85, p = .77, η^2_p = .005). Long sentences were completed in 43 % of the cases (SD = 44 %) on average, short sentences in 56 % (SD = 46). This difference was not statistically significant (F (1,16) = 0.79, p = .39, η^2_p = .05).

4.3.2 Analysis of Take-Over Performance

Timing aspects of take-over reaction: In a first step, the timing of drivers' take-over reaction was evaluated. A distinction was made between take-overs where the driver was engaged in the NDR-task when the take-over request was issued, and takeovers without NDR-task engagement (Fig. 4-7). As there were no significant differences between the HMI groups (all p-values > .05) data was combined for this figure. Every driver faced six take-over situations during the test drive. Mean values were calculated for every driver and the data was aggregated. For determining the first gaze on road, only the cases where the driver was fixating the NDR-task at the start of the take-over request were included. For this reason, data of four drivers had to be excluded. "Hands on" was defined as the time from issuing the take-over request until drivers touched the steering wheel (measured with capacitive sensor). Thus, cases where drivers had their hands already at the steering wheel when the take-over request was issued could not be used. For this reason, data of two drivers had to be excluded. "System deactivated" reflects the time until the system was deactivated, either by the steering wheel button, steering input or braking. When there was no reaction by the driver, the system was automatically deactivated four seconds after the take-over request had been issued. Lastly, "Begin steering" represents the time from issuing the take-over request until turning into the curve (four degrees change in steering wheel angle).

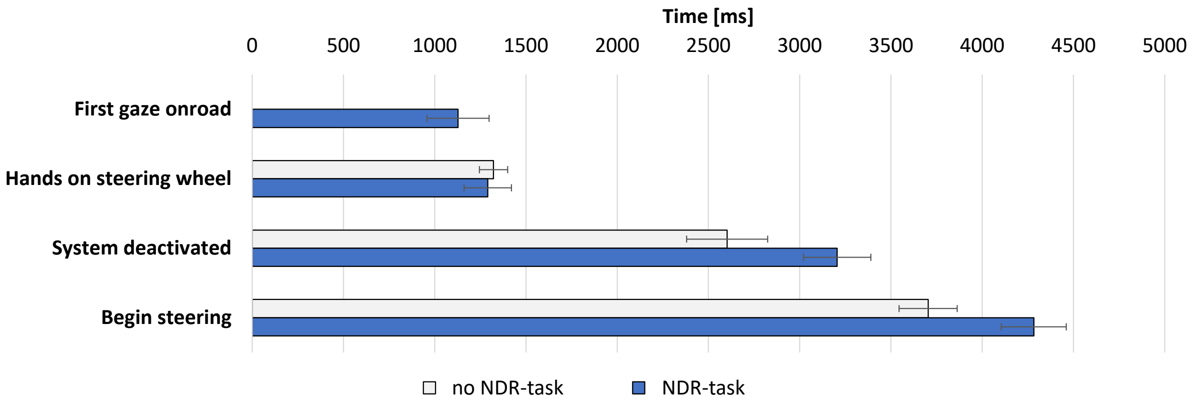

Fig. 4-7: Mean take-over times (in milliseconds) with and without NDR-task engagement (combined data from both HMI groups). Error bars represent the standard errors of the means.

There was no significant difference regarding the first motoric reaction (hands on) in dependence of NDR-task engagement (F (1,16) = 0.002, p = .96, η^2_p < .001). However, the time until system deactivation (the steering wheel button was used in 92 % of the cases) was significantly delayed when drivers were engaged in the NDR-task compared to baseline (F (1,18) = 8.52, p = .01, η^2_p = .32). In addition, the time until drivers began steering was also delayed when engaged in the NDR-task (F (1,18) = 8.00, p = .01, η^2_p = .31).

Quality aspects of take-over reaction: In a second step, quality aspects of drivers' take-over performance were evaluated, comparing take-over situations with and without NDR-task engagement. All analyses refer to the time span from issuing the take-over request until the end of the sharp bend (367 m). As there were no significant group differences (all p-values > .05) data of both HMI groups was combined for the following figures. Standard deviation of lateral position (SDLP) and percentage of lane exceedances (more precisely: percentage of time slices where at least one wheel was out of lane) were used to assess lateral control quality (Fig. 4-8).

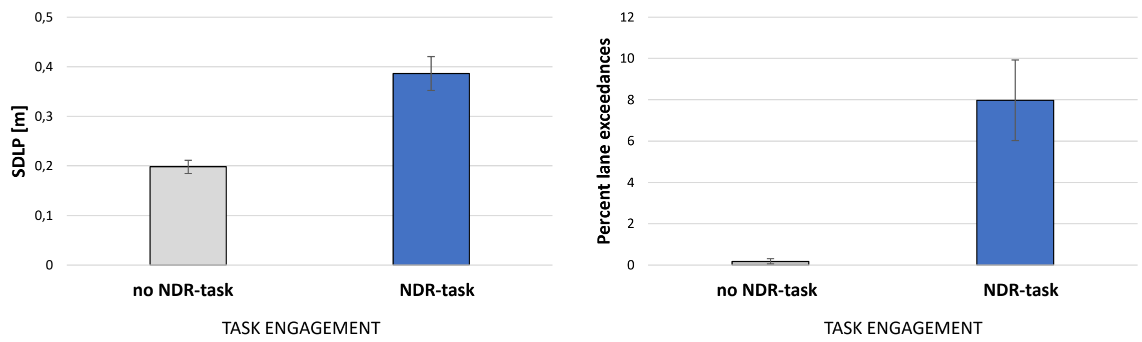

Fig. 4-8: Standard deviation of lateral position (= SDLP, left figure) and percentage of lane exceedances (right figure) with and without NDR-task engagement during the take-over situation. Error bars represent the standard errors of the means.

SDLP was significantly increased when drivers were engaged in the NDR-task compared to baseline without NDR-task (F (1,18) = 33.82, p < .001, η^2_p = .65). A similar performance decrement was found for the percentage of lane exceedances (F (1,18) = 15.44, p = .001, η^2_p = .46). There were almost no lane exceedances in absence of the NDR-task (M = 0.18 %, SD = 0.56). In contrast, task engagement was associated with a significant increase in the percentage of lane exceedances (M = 7.98 %, SD = 8.74). In absolute numbers, distracted drivers showed lane exceedances of approximately 0.90 seconds (SD = 0.99) or 29.29 meters (SD = 32.08) when passing through the sharp bend.

Another aspect of take-over performance can be derived from the vehicle dynamics (i.e. accelerations) that occurred during the maneuver (Gold et al., 2013). By knowing the lateral and longitudinal accelerations when passing through the sharp bend, the maximum acceleration potential (= resulting acceleration) can be calculated (Fig. 4-9). Results showed that drivers generated significantly higher maximum accelerations when engaged in the NDR-task compared to baseline without NDR-task engagement (F (1,18) = 30.20, p < .001, η^2_p = .63).

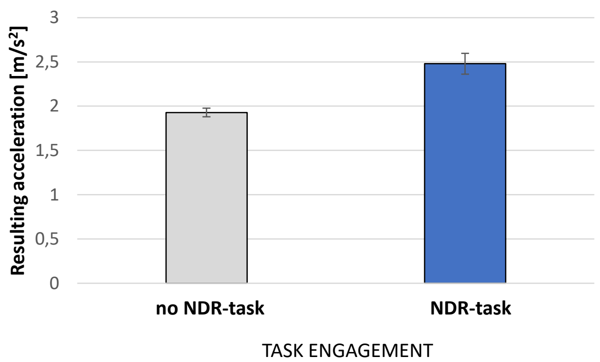

Fig. 4-9: Means of maximum resulting accelerations with and without NDR-task engagement during the take-over situation. Error bars represent the standard errors of the means.

As outlined above, drivers tended to continue their NDR-tasks engagement even in take-over situations. Exemplary for SDLP, data was descriptively analyzed post hoc for the cases where drivers immediately disengaged from the task and cases where drivers continued texting when passing through the sharp bend (Fig. 4-10). Again, continuing a task was defined as entering two or more characters after the take-over request was issued. When the task was interrupted, SDLP was on a similar level as without any task engagement (No NDR-task: M = 0.20 m, SD = 0.06; Task interrupted: M = 0.23 m, SD = 0.09). However, SDLP was increased when texting was continued during the take-over situation (M = 0.44, SD = 0.14).

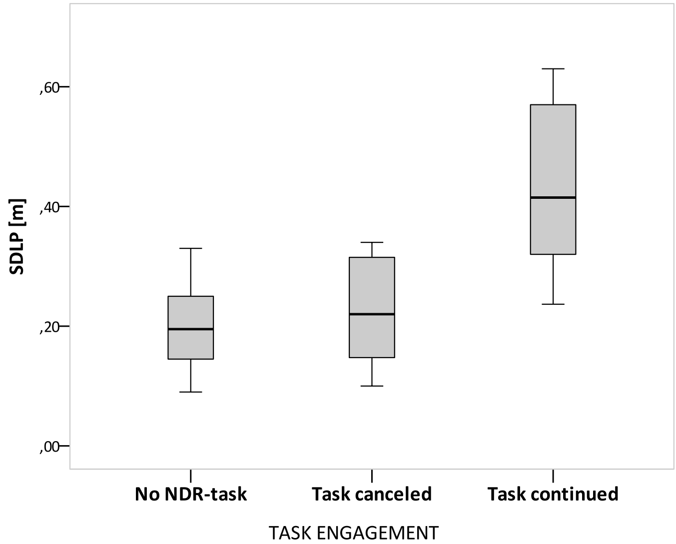

Fig. 4-10: SDLP during the take-over situation for cases without NDR-task, cases where the task was interrupted following the take-over request, and cases where the task was continued.

4.3.3 Subjective Data

Drivers evaluated the HMI concept in a questionnaire after the test drive was finished. All drivers (from both HMI groups) agreed to the statements that the HMI was easy to understand and straightforward (approval rate = 100 % for both statements). Drivers were also asked if the preview screen was helpful to decide when to engage in the NDR-task. On a scale from 0 (= not helpful at all) to 15 (very helpful) the average score was 10.0 (SD = 4.30) for the predictive HMI group, and 2.58 (SD = 3.12) for the basic HMI group.

In addition, driver's strategies in dealing with the NDR-task were addressed in questions with free answer format. 16 drivers (8 of each HMI group) stated that the current driving mode was crucial for their decision to accept or reject an offered task, with the preference for task engagement in highly automated driving. Six drivers of the predictive HMI group explicitly mentioned that they also considered the task length in relation to the remaining distance in automated driving mode, provided by the preview screen. In addition, five drivers of the predictive HMI group and three drivers of the basic HMI group reported that they performed regular control glances during task processing.

4.4 Discussion

The main focus of this first study was to examine NDR-task interactions in the context of highly automated driving while taking aspects of self-regulation into account. For this purpose, a texting task was offered during manual and highly automated driving and also prior to take-over situations. To enable self-regulation, drivers were free to accept or reject an offered task, taking the situational circumstances into account. With reference to the three-level model of self-regulation (Tab. 3-1), results regarding the planning and decision levels are discussed first. In a second step, aspects of task disengagement (control level) and take-over performance are considered.

Results showed that drivers accepted significantly more tasks during highly automated driving compared to manual driving. This clear preference can be considered as appropriate self-regulation (on the planning/decision level) as the driver is allowed to temporarily withdraw himself or herself from monitoring the driving task during highly automated driving (SAE level 3, SAE International 2014). Another aspect of self-regulation on the planning or decision level was the number of accepted tasks during normal operation of the highly automated driving system compared to take-over situations. Of particular interest was task engagement in the predictive HMI group, where drivers had the opportunity to anticipate upcoming take-over situations using the preview screen. Results indicate that drivers had a benefit from the predictive information and rejected significantly more tasks prior to take-over situations compared to regular sections of highly automated driving (Fig. 4-4). This behavior can be considered as appropriate self-regulation as task-engagement during take-over situations was associated with significant performance decrements and, therefore, should be avoided. However, it has to be considered that even with predictive HMI a remarkable high number of critical tasks was accepted. First, this may be due to the fact that participants were encouraged to engage in the NDR-task by the reward system. On a scale from 0 to 15, participants rated their motivation averagely with 10.45 (SD = 3.28). Second, the study was conducted in a driving simulator without risk of real accidents.

For more insights into drivers' NDR-task management the absolute numbers of accepted tasks were analyzed over time, focusing on the four critical tasks offered during highly automated driving (Fig. 4-5). Results showed that the predictive HMI was most effective at task 2 and 3. Two aspects may have led to this finding. First, when deciding whether an offered task might interfere with an upcoming take-over situation, participants had to evaluate the approximately task duration and compare it with the distance left until the system limit was reached. It can be assumed that this was difficult for the first task and became easier as participants gained experience with the NDR-task during the test drive. Another aspect that needs to be considered is task length. As task 2 and 3 were short sentences, they were offered notably closer to the take-over situation than the long sentences (task 1 and 4). Thus, the interference of the NDR-task and take-over situation might have been more obvious for the participants.

It can be summarized that the predictive HMI is a promising approach, which facilitates appropriate NDR-task management on the planning and decision level. This was also supported by subjective data. However, some adaptations might be needed to increase the effectiveness of the preview. For example, it might be useful to display the estimated time left in addition to the distance left.

An additional aspect of self-regulation was task disengagement in take-over situations: the control-level in the three-level model of self-regulation. An appropriate self-regulatory behavior in take-over situations would have been an immediate NDR-task disengagement and switch to the driving task. Unfortunately, results showed that, once engaged in an NDR-task, drivers tended to continue texting even in take-over situations. This tendency occurred regardless of the task length and its associated points in the reward system. It can be assumed that even the short sentences provided enough (external and/or internal) incentive to persist in the task. On a descriptive level there was a slight advantage for the predictive HMI, but the effect missed the criterion of statistical significance. Drivers' behavior must be considered as maladaptive, in particular as take-over performance was clearly impaired when texting was continued throughout the take-over situation (Fig. 4-10). The tendency to complete a task and neglect actually more important goals (safe driving) is well known from driver distraction research (Lee, 2014). This so called task perseverance has been subject to research since decades (e.g. Zeigarnik, 1938; Fox & Hoffmann, 2002) and occurs in particular when the task is goal-oriented, effort has already been expended to reach this goal and one nears the end of the task. According to the goal-activation model by Altmann and Trafton (2002), the activation for the goal of completing a task increases over time, leading to a neglect of competing tasks. These motivational aspects seem to be highly relevant for NDR-task processing in take-over situations and might explain drivers' difficulties in task disengagement - in particular for system-paced tasks that are difficult to interrupt. In the present study, this came together with a relatively low critical take-over situation which may have further facilitated task perseverance.

In addition to self-regulatory aspects, take-over performance was another focus point of the present study. NDR-task engagement was accompanied by significant decrements in take-over quality (referring to the time span from the take-over request until the end of the sharp bend). Performance impairments were found for parameters of lateral control and vehicle dynamics. Concerning system deactivation and the beginning of the steering maneuver, take-over times were significantly larger when engaged in the NDR-task. No difference was found for the time until the hands were back at the steering wheel. This is in line with recent research (Zeeb et al., 2015) indicating that visual distraction does not affect the time at which drivers establish motor readiness, as this is a mostly reflexive behavior following the take-over request. Take-over times in the current study were moderately larger than in previous studies (Gold et al., 2013; Radlmayr et al., 2014). This may be associated with learning effects due to the within-subject design and the relatively low critical take-over situation, where no immediate maneuver was crucial to handle the situation. Following Gold et al. (2013) take-over times are getting faster with increasing criticality of the take-over situation.

Finally, some methodological limitations of the present study should be considered. First, the sample of participants was relatively small in size and limited to young and mid age drivers. Second, the drivers were novices in dealing with the highly automated driving system, even there was a detailed instruction and a practice drive. The transferability of the study's results to other age groups and different levels of expertise has to be proven by further research. Finally, the HMI versions used in the present study were rather rudimentary. The HMI concept and particularly the timing and design of the take-over request are relevant influence factors and are therefore addressed in further studies of this thesis.

4.5 Conclusion

Study 1 offers insights into drivers' self-regulation when dealing with NDR-tasks in the context of highly automated driving. Based on the three-level model (Tab. 3-1) different aspects of self-regulation were investigated. To enable self-regulatory behavior, drivers were free to accept or reject a given task, taking the situational circumstances into account. Drivers showed a clear preference for task engagement during highly automated compared to manual driving. In addition, results showed that drivers rejected more tasks prior to take-over situations when they had the opportunity to anticipate these situations (predictive HMI). This can be considered as appropriate self-regulation on the planning and decision level. However, even with predictive HMI a notable number of critical tasks was accepted. Further research is needed to clarify to which extent this finding is due to the methodological framework of the study (e.g. the reward system) or if it reflects inappropriate task management strategies.

An additional aspect of self-regulation was task disengagement in take-over situations: the control-level in the three-level model of self-regulation. The results indicate a considerable amount of task perseverance: In most cases drivers continued texting even when the take-over request was issued. On the basis of these findings further research is needed to gain a better understanding of the factors that influence task perseverance and take-over performance in highly automated driving. This includes characteristics of the NDR-task (c.f. chapter 5) and take-over situation (c.f. chapter 6), as well as interactions amongst them. Also, the influence of different HMI concepts and particularly the timing and design of the take-over requests should be taken into account to complete the picture (c.f. chapter 7).

5 Study 2: NDR-task modalities and take-over performance

5.1 Introduction and Research Questions

Previous research provides valuable first insights on the impact of naturalistic and standardized NDR-tasks on take-over performance (chapter 2.2.4). However, results are heterogeneous and there is still a lack of knowledge about underlying task dimensions that account for performance decrements. The main goal of the current study was to investigate the impact of NDR-task modalities (stimulus and response) on take-over performance. As theoretical framework, the *resource structure* component within the architecture of multiple resource theory was selected (chapter 3.1.1).

The current study focuses on NDR-task modalities as they play an important role in distracted manual (e.g. Dingus et al., 2011; Louw et al., 2013) and partially automated driving (Spiessl & Hussmann, 2011). In addition, previous research on highly automated driving (chapter 2.2.4) as well as Study 1 of this thesis provide first evidence that these dimensions might still be relevant for level 3 automation.

In order to determine the role of NDR-task modalities in a controlled setting, a self-designed verbal NDR-task (reproducing given sentences) was implemented. Stimulus (visual vs. auditory) and response (manual vs. vocal) modalities of the NDR-task were systematically manipulated, while ensuring that other task characteristics remained as similar as possible. The different task variants were derived from naturalistic tasks to ensure ecological validity. Namely, the auditory-vocal task shared similarities with a hands-free cellphone conversation and the visual-manual task version was realized as a texting task.

A system-initiated task lockout (deactivation simultaneously with the take-over request) was implemented as a second experimental factor and contrasted with another group, where task engagement was possible even in take-over situations. This aspect was included as Study 1 of this thesis showed evidence for the psychological phenomenon of task perseverance. This phenomenon describes the tendency to complete a task once it has been initiated and potentially neglect more important goals such as safe driving (Lee, 2014). As mentioned above, task perseverance seems to occur particularly when the task is goal-oriented, effort has already been invested to reach this goal and the task is close to completion (Ovsiankina, 1928; Fox & Hoffmann, 2002). Thus, in the present study it was of interest whether an immediate task lockout would support the driver in take-over situations. For manual driving, lockout approaches showed benefits in mitigating effects of driver distraction (e.g. Donmez, Boyle, & Lee, 2006). However, in a simulator study by Jung, Kaß, Schramm, and Zapf (2017) a lockout strategy was associated with decreasing experience of autonomy and the development of psychological reactance (Miron & Brehm, 2006), which might counteract potential benefits of distraction mitigation.

Overall, Study 2 had two main objectives. First, the impact of different NDR-tasks on take-over performance was assessed. Following multiple resource theory, the greatest performance decrements were expected for the visual-manual tasks. The second aim of the study was to investigate effects of an NDR-task lockout in take-over situations. The hypothesis was that a lockout approach supports take-over performance, but might possibly be accompanied by acceptance problems.

5.2 Method

5.2.1 Participants

Thirty participants (15 men, 15 women) were recruited from a driver panel. A written informed consent was obtained from each driver. All participants were of young or mid age (M = 29.17 years, SD = 6.38) and had experience with touchscreen devices, e.g. smartphones or tablet computers. The participants had an average annual mileage of 17,033 km (SD = 13,213; range 3,000 to 60,000). The drivers were randomly assigned to either the task lockout group (N = 15) or the no lockout group (N = 15).

5.2.2 Driving Simulator and Highly Automated Driving System

The study took place in the motion-base driving simulator of WIVW GmbH (Würzburg Institute for Traffic Sciences) that was also used in Study 1 of this thesis. The simulator has six degrees of freedom (hexapod) and the projection system provides a 180 degrees field of view to the front. Rear view and side mirrors are realized by separate LCD screens. A 4.1 surround audio system provides a detailed sound background, including engine and driving sounds of the own and surrounding vehicles.

The highly automated driving system was able to control longitudinal and lateral vehicle guidance on highway roads and was similar designed to Study 1 of this thesis. The availability of the system was indicated by an audio chime and a white icon (generic steering wheel and lane markings) in the instrument cluster. The system could be activated with a steering wheel button and the system status icon changed to green. When activated, the system adjusted the vehicle's speed to 120 km/h. A take-over request was indicated by an auditory warning and a red status icon. In the task lockout condition, the take-over request was also presented on the tablet computer used for the visual NDR-tasks. The system could be deactivated by either the steering wheel button, braking (> 10 percent pedal position) or a steering input (> 4 degrees change in steering wheel angle).

5.2.3 Simulated Test Track and Take-Over Situation

The simulated test track consisted of a two-lane motorway with a total length of 90 km. Participants were instructed to always stay in the right lane and keep a speed of 120 km/h. This was also the target speed of the highly automated driving system.

Five similarly designed take-over situations occurred during the drive. The average distance between two take-over situations was 18 km (ranging from 14 to 22 km). While approaching a curve, the ego-lane was blocked by broken down vehicles (Fig. 5-1) and the lead car changed lanes close to the obstacle. As soon as the lead car changed lanes it was possible to detect the obstacle and the take-over request was issued. At this moment the time to collision was six seconds. The broken down cars were placed behind a hilltop to ensure that it was not possible for the driver to detect the obstacle before the take-over request was issued. Similar road sections and hilltops occurred several times throughout the test track without experiencing a take-over situation to avoid environmental cues. Because the left lane was blocked by a convoy of overtaking vehicles, a braking maneuver was the only way to solve the situation appropriately and to avoid a collision. Given the initial speed of 120 km/h and the vehicle model used in the simulation, an emergency braking had to be applied by the drivers within four seconds after the take-over request to prevent a collision. In addition to applying the brakes, a steering input by the driver was necessary to stabilize the vehicle as the situation took place in a curve. Participants could continue their drive after the convoy of overtaking vehicles had passed the ego-car and the left lane was free again. After 1.5 km of manual driving the system could be reactivated.

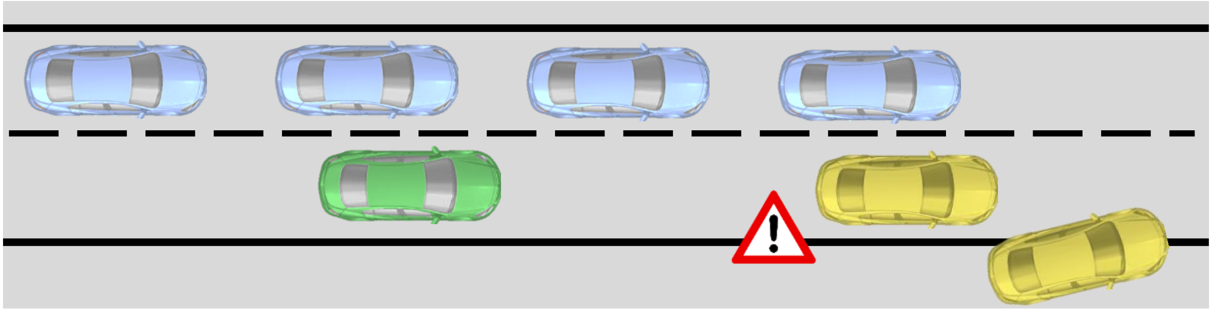

Fig. 5-1: Schematic representation of the take-over situation. The participant's car is depicted in green (right lane), the broken down cars in yellow (right lane and emergency lane) and the overtaking vehicles in blue (left lane). In the experiment, the situation took place in a curve instead of a straight.

5.2.4 Non-driving related Tasks and Task Lockout

In order to evaluate the assumptions of multiple resource theory, a model task was designed that enabled the manipulation of stimulus and response modalities while keeping other task characteristics as constant as possible. Short sentences (5-6 words, about 35 characters overall) were presented and the task was to repeat these sentences quickly and accurately. In the condition "auditory-vocal" the sentences were read out by a text-to-speech software and participants were required to repeat these sentences verbally. In the task "visual-vocal" sentences were displayed on a tablet computer mounted on the center console and participants read the sentences out aloud. In the "visual-manual" task version the sentences were again presented on the tablet computer and participants were asked to transcribe them using the integrated virtual keyboard of the tablet computer. There were two variants of the "visual-manual" task. In the condition "mounted" the tablet computer was attached at the center console and in the condition "handheld" participants worked on the task while holding the device in their hands. The visual-manual task was analogous to writing text messages to ensure practical relevance. The prevalence of texting during manual driving has increased in recent years (Dingus et al., 2016) and is often times associated with high mental workload, decreasing lateral control, and delayed responses to sudden traffic events (Owens, McLaughlin, & Sudweeks, 2011; Drews et al., 2009). Therefore, the transferability of previous research to highly automated driving is of high importance.

All tasks used in the present study were self-paced, i.e. there was no time limit to account for inter-individual differences in processing and typing speed. As soon as the drivers finished the ongoing task and requested a new one, the next task started immediately to keep the participants continuously engaged in the task. The task blocks were triggered on predefined sections of the test track and had a length of about 90 seconds. Blocks of each task version occurred once during normal operation of the highly automated driving system and once prior to a take-over situation. As drivers faced the highly critical take-over situation five times (four different NDR-tasks and a baseline condition without NDR-task), the order of NDR-tasks was completely counterbalanced to control for learning effects.

In the task lockout group the NDR-tasks were deactivated simultaneously with the take-over request and for the visual tasks (visual-vocal, visual-manual mounted and handheld) the take-over request was also presented on the tablet computer. In the no lockout group the tasks remained active and participants were free to interrupt or continue the tasks. In this group, the task was finally switched off automatically after 1.5 km of manual driving.

The participants were instructed to ensure safe driving at all times, but also to complete as many tasks as possible. To ensure that the drivers were motivated to deal with the NDR-tasks, an incentive was used. Drivers were told that they would receive a monetary bonus in addition to their regular compensation when they complete a sufficient, not further specified, number of tasks.

5.2.5 Procedure

After an introduction to the operation of the highly automated driving system, the participants completed a practicing run in the driving simulator. First, this included a short section of manual driving. Then the highly automated driving system became available and the handling of the system (e.g. activation and deactivation) was trained. Additionally, the drivers experienced a first take-over request. The take-over request was issued without a specific system limit just to demonstrate the design of the warning (audio chime and red icon in the instrument cluster) and the different possibilities to take back vehicle control. Next, the different NDR-tasks were explained and the participants had the opportunity to practice the tasks without driving.

The test drive began after an optional break and took about 45 minutes. Participants were asked to take their hands off the steering wheel and remove their feet from the pedals whenever the highly automated driving system was engaged. Driving parameters and NDR-task engagement were recorded during the experiment. After completing the test drive, the participants were asked to fill in a questionnaire about their experiences during the experiment. All collected data was analyzed in anonymous form.

5.2.6 Experimental Design and Statistical Analyses

In this study a 2 x 5 mixed design was used. The within participants factor was the type of NDR-task ("baseline without task", "auditory-vocal", "visual-vocal", "visual-manual mounted" and "visual-manual handheld") and the between participants factor was the design of the take-over request ("task lockout" vs. "no task lockout"). Dependent variables were timing and quality aspects of drivers' take-over reaction. For statistical testing of differences analyses of variance (ANOVA) were calculated. A significance level of 5 % was used.

5.3 Results

5.3.1 NDR-Task Processing in Take-Over Situations

For a comprehensive understanding of drivers' take-over performance, it has to be considered how participants dealt with the NDR-tasks in take-over situations. This is particularly relevant for the no task lockout group, where participants were free to continue task interaction even in take-over situations. As the scenario was designed as an emergency situation, an appropriate self-regulatory behavior would have been an immediate disengagement from the NDR-task and switching to the driving task. In fact, three different behaviors were observed for the no lockout group and descriptively analyzed (Fig. 5-2): immediate task interruption and no task resumption (“canceled” in Fig. 5-2), task interruption but resumption of the task after take-over reaction (“interrupted”), and strict continuation of task interaction during take-over and manual driving (“continued”).

Cochran's Q test determined that there was a significant difference in the proportion of canceled tasks (χ^2 (3) = 8.67, p = .03). It should be noted that the hypothetically most interfering tasks (from perspective of multiple resource theory) were also the tasks that were canceled most consistently. While the auditory-vocal task was continued in two thirds of the cases, the proportion of canceled tasks increased throughout the visual tasks and was highest for the visual-manual handheld task. This finding was in accordance with the subjective perception of safety while being engaged in the different types of NDR-tasks (Fig. 5-3). Additionally, in a forced choice question 26 of 30 participants rated one of the visual-manual tasks as most impairing in take-over situations (visual-manual mounted = 8 x, visual-manual handheld = 18 x).

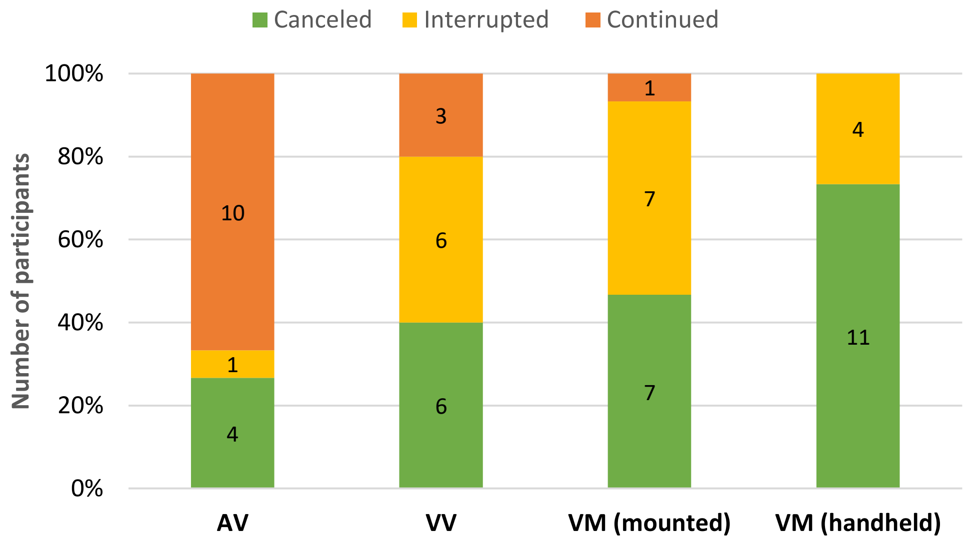

Fig. 5-2: Task disengagement in take-over situations for the no lockout group (N = 15). The proportion of canceled, interrupted, and continued tasks is shown for the different NDR-tasks (AV = auditory-vocal, VV = visual-vocal, VM = visual-manual).

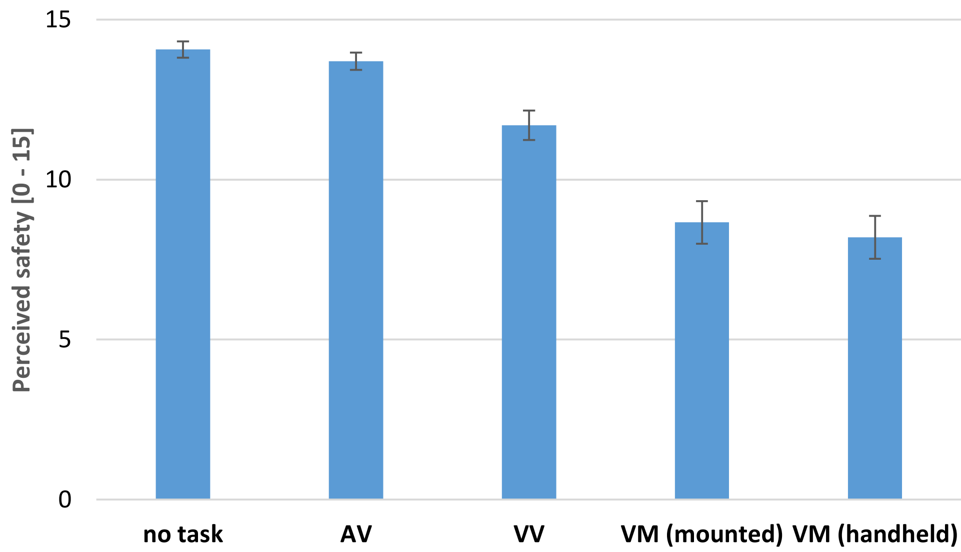

Fig. 5-3: Subjective perception of safety for the different NDR-tasks (one item question after driving, rating scale from 0 to 15). Higher values indicate a higher perceived safety. See Fig. 5-2 for an explanation of the abbreviations. Error bars represent the standard errors of the means.

After finishing the drive, the NDR-tasks were also rated in terms of subjective workload, using the items from the NASA TLX (Hart & Staveland, 1988). The overall workload ("Raw TLX"; Hart, 2006) on a scale from 1 (very low) to 15 (very high) was 7.27 (SD = 1.95) for the visual-manual mounted task and 7.06 (SD = 1.62) for the handheld version. In contrast, the overall workload for the auditory-vocals task was 3.32 (SD = 1.25) and for the visual-vocal task 4.00 (SD = 1.38).

The difference between tasks was statistically significant (F (3,87) = 101.28, p < .001, η^2_p = .78). Post-hoc tests (Bonferroni corrected) showed that the visual-manual tasks had higher subjective workload than the auditory-vocal and visual-vocal task (p < .01). In addition, the visual-vocal task had higher workload ratings than the auditory-vocal task (p < .01).

5.3.2 Analysis of Take-Over Times

In a first step, take-over performance was evaluated for the combined data of both experimental groups ("task lockout" and "no task lockout"). Fig. 5-4 shows the time from issuing the take-over request until first hand-contact with the steering wheel (= hands-on time, measured with capacitive steering wheel sensor, latency < 50 ms) for the different NDR-tasks. One driver had to be excluded from this analysis because he already had his hands on the steering wheel in two of five take-over situations. Results from a repeated measurement ANOVA revealed a significant main effect of NDR-task modalities (F (4,112) = 15.92, p < .001, η^2_p = .36). Post-hoc tests with Bonferroni adjustment showed differences between the baseline condition and two visual tasks (Baseline vs. visual-vocal: p < .01; Baseline vs. visual-manual handheld: p < .01). Hands-on times for the visual-manual handheld task were significantly higher compared to all other NDR-tasks (post-hoc: all p-values < .01). Remaining pairwise comparisons revealed no significant effects (all p-values > .05). In this context, it should be considered how drivers dealt with the tablet computer in the handheld condition. Five of the 30 drivers placed the tablet on the passenger seat before taking over, 12 drivers dropped the tablet onto their thighs, and 13 drivers kept the device in one hand and took over with the other hand.

Another, even more safety relevant parameter is the take-over time itself. The take-over time corresponds to the brake response time in the present study, as braking was the required take-over reaction to prevent a collision (Fig. 5-4). It was defined as the time from displaying the take-over request until the brake pedal travel was larger than 10 % (following Gold et al., 2013; Zeeb et al., 2015). ANOVA results revealed a significant main effect of NDR-task modalities (F (4,116) = 2.98, p = .02, η^2_p = .09). On a descriptive level, mean brake response times tended to be larger for the visual, particularly the visual-manual tasks. However, compared to hands-on times the variance in the data was larger and post-hoc tests (Bonferroni adjusted) failed the criterion for statistical significance (all p-values > .05). There was only a tendency that the visual-manual handheld task differed from baseline without any task (p = .10).

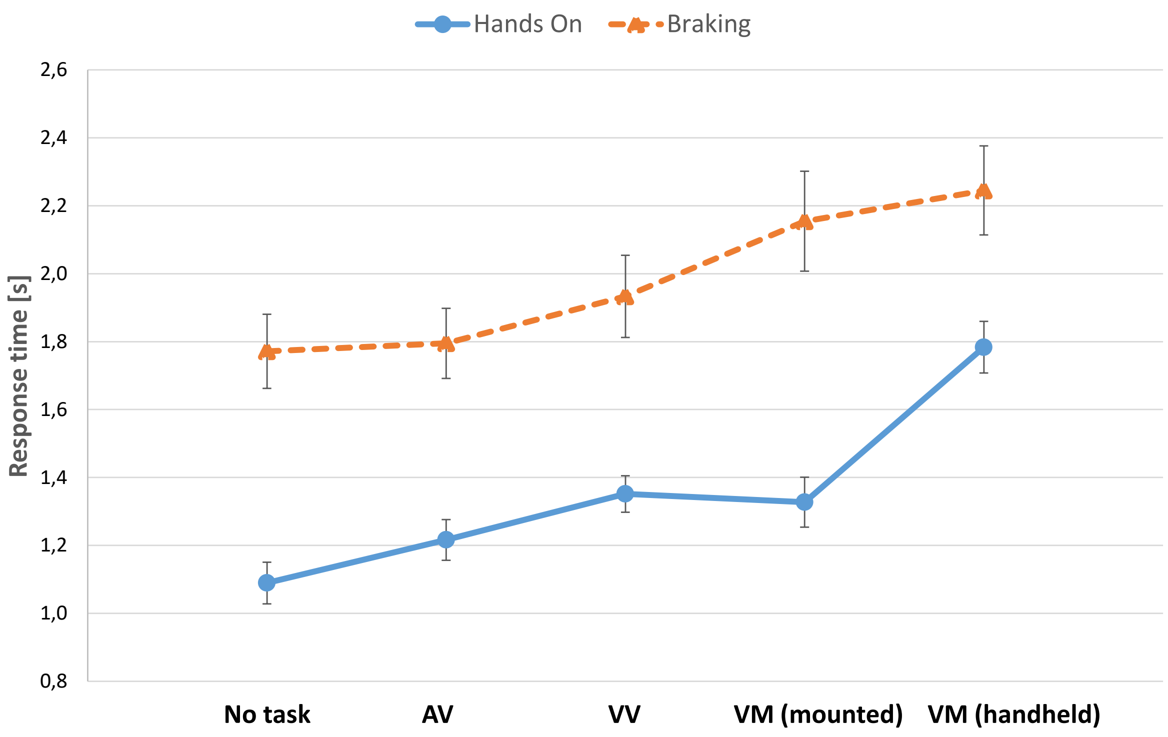

Fig. 5-4: Mean hands-on times (solid line) and brake response times (dotted line) for the different NDR-tasks. Error bars represent within-group standard errors of the means (O'Brien & Cousineau, 2014).

A relevant aspect for interpreting the response times is the chronological sequence of reactions. This was descriptively assessed in a separate analysis. When engaged in the visual-manual handheld task 9 of 30 drivers applied the brakes before taking their hands back to the steering wheel. This behavior occurred rarely in the other experimental conditions (baseline = 3 x, auditory-vocal = 2 x, visual-vocal = 5 x, visual-manual mounted = 5 x).

5.3.3 Analysis of Take-Over Quality

In a second step, quality aspects of drivers' take-over performance were evaluated comparing the different NDR-tasks. Again, data of the lockout and no lockout group was combined for the analyses (N = 30). Twenty collisions were counted from a total of 150 take-over situations (5 situations per driver). More than half of the collisions occurred at first contact with the take-over situation (11 of 20) and 11 of 30 drivers caused at least one collision. Included were collisions with the broken down car on the ego-lane (6 of 20 collisions) and with traffic on the left lane (14 of 20 collisions) due to inappropriate lane changes. There was only a tendency that the number of collisions differed for NDR-task type (Cochran's Q test: χ^2 (4) = 7.83, p = .10). Seven collisions occurred with the visual-manual handheld task, followed by the visual-manual mounted and visual-vocal task (each four collisions). Four collisions also occurred in the baseline condition. Only one collision was counted for the auditory-vocal task.

Another relevant parameter for assessing take-over quality is the minimum time to collision (TTC) during the take-over maneuver (Fig. 5-5). Four drivers had to be excluded from this analysis because they performed an evasive steering maneuver instead of braking in more than one take-over situation. A repeated measurement ANOVA revealed significant differences between the NDR-tasks (F (4,100) = 3.12, p = .02, η^2_p = .11). The visual tasks were associated with smaller TTCs compared to the other tasks. Post-hoc tests showed a significant difference between the visual-manual handheld task and the auditory-vocal task, where the highest TTC was measured (Bonferroni adjusted: p < .01). Other pairwise comparisons revealed no significant effects (all p-values > .05).

Another quality metric can be derived from vehicle dynamics during the take-over maneuver (Gold et al., 2013). No differences between NDR-tasks were found regarding maximum decelerations achieved in the braking maneuver (F (4,100) = 0.14, p = .97, η^2_p = .01). This indicates that differences in the minimum TTC were mainly caused by the timing of maneuver initiation and not by braking intensity.

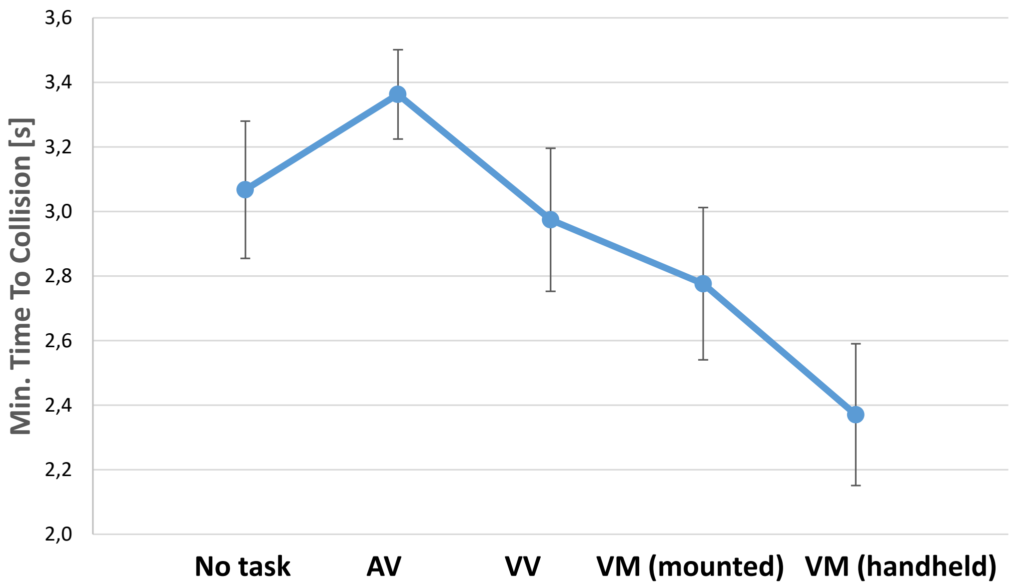

Fig. 5-5: Minimum time to collision for the different NDR-tasks. Collisions with the broken down car were included with a time to collision of zero seconds. Error bars depict within-group standard errors of the means.

5.3.4 Effects of Task Lockout

In order to assess the effects of task lockout, take-over performance for the visual NDR-tasks (visual-vocal, visual-manual mounted and handheld) was compared between the two experimental groups (lockout and no lockout).

For the assessment of hands-on time, data of 29 drivers could be used (Fig. 5-6). One driver was excluded for this analysis as he already had his hands on the steering wheel in two of five take-over situations. A two-factorial mixed ANOVA revealed a significant main effect for task lockout (F (1,27) = 5.74, p = .02, η^2_p = .18), indicating faster response times with task lockout. There was no evidence that the task lockout had different effects for the NDR-tasks as the interaction between the two factors was not significant (F (2,54) = 1.01, p = .37, η^2_p = .04).

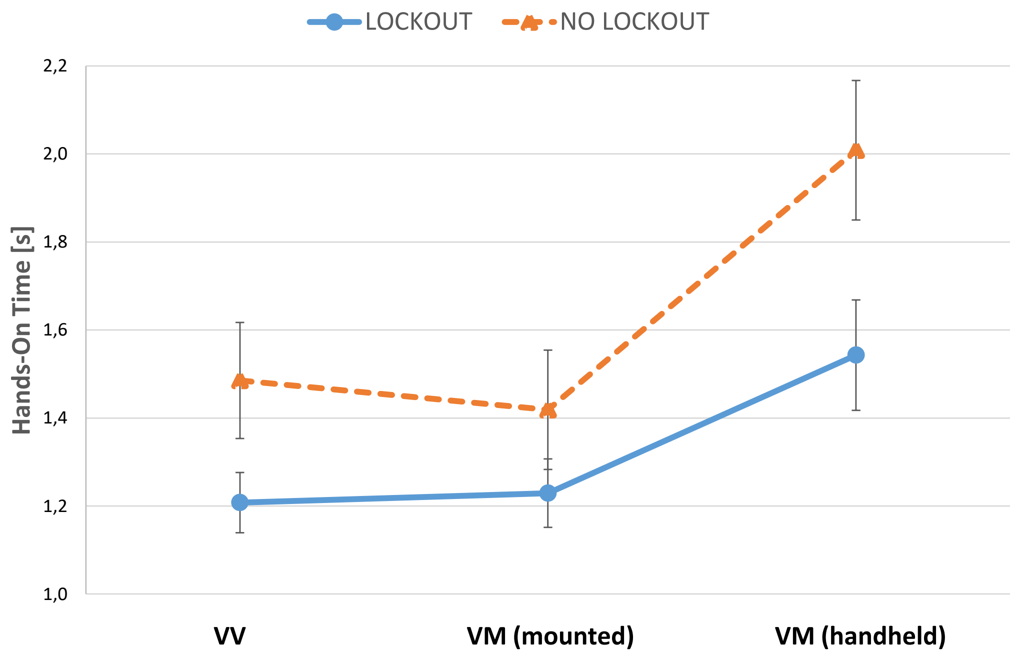

Fig. 5-6: Hands-on times for the visual NDR-tasks, comparing the lockout group (solid line) and no lockout group (dotted line). Error bars represent the standard errors of the means.

In contrast, no significant group differences were found regarding brake response times. There was neither a significant main effect for task lockout (F (1,28) = 0.36, p = .55, η^2_p = .01) nor an interaction between task lockout and NDR-task type (F (2,56) = 0.03, p = .97, η^2_p < .01). In addition, no effects were found for the number of drivers with at least one collision (χ^2 (2) =.14, p = .71): Six of these drivers were in the lockout group and five in the no lockout group.

Concerning subjective data, participants showed a high acceptance for a task lockout in take-over situations. On a rating scale from 0 (no acceptance) to 15 (very high acceptance) the average score was 13.87 (SD = 1.60).

5.4 Discussion

The main intent of Study 2 was to examine the effects of NDR-task interaction on take-over performance in highly automated driving. In a first step, the effects of stimulus and response modalities are discussed (referring to the *resource structure* component in the architecture of multiple resource theory, chapter 3.1.1). This also includes a consideration of the way drivers dealt with the NDR-tasks in take-over situations (referring to the *resource allocation* component, chapter 3.1.3). In this context, it is evaluated to which extent drivers were supported by a take-over request that included a task lockout.

Concerning the timing aspects of drivers' take-over reaction, the time until hands were back at the steering wheel was analyzed, as well as the time until the braking maneuver was initiated. Significant effects of NDR-task type were found for both variables. As expected, the fastest responses were measured for the baseline condition without any NDR-task and for the auditory-vocal task. The visual-vocal task was associated with longer response times, at least for hands-on. The slowest response times were found for the visual-manual tasks, particularly in the handheld version of the task. Results for the number of crashes and minimum time to collision were mainly in accordance with timing aspects. Overall, the results match with the predictions of Wickens' (2002) multiple resource theory, which suggests greater interference for visual-manual tasks since the driving task demands the same resources. However, specific aspects of highly automated driving have to be taken into account when interpreting the results (see also chapter 3.1.1).

Insights can be gained when comparing the graphs for hands-on and brake response time (Fig. 5-4). The motoric task load seemed to be the crucial factor for prolonged hands-on time, i.e. holding the tablet computer in the visual-manual handheld task. Hands-on times for the handheld task were significantly delayed compared to the mounted version of the same task. The manual task response itself (typing text) seemed to be less relevant, as the hands-on times for the visual-manual mounted task were not significantly different from the visual-vocal task. Here, a difference to distraction in manual driving becomes obvious. Performing a manual task simultaneously to the dynamic driving task leads to a direct interference (e.g. Dingus et al., 2011; Horrey & Wickens, 2004). However, in hands-off automated driving another crucial aspect is how fast the hands can be put back to the steering wheel. Disposing the tablet computer in take-over situations seemed to be challenging for the participants as nearly half of them kept the device in one hand during take-over.

The take-over time itself (time until initiating the braking maneuver) can be interpreted as the result of perceptual and cognitive processes including the decision for the appropriate take-over reaction. These processes can be mainly executed in parallel to the establishment of motor readiness, i.e. putting hands back at the steering wheel and moving feet towards the pedal system (Zeeb et al., 2015). The assumption was that visually demanding NDR-tasks would delay the perceptual processes needed for the achievement of situation awareness (Endsley, 1995) and, therefore, would be associated with prolonged take-over times. In fact, the slowest take-over times were found for the visual tasks (visual-vocal, visual-manual mounted and handheld). However, effects were small and post-hoc tests failed to be significant. In this context, it should be noted that due to the within-subject design each driver faced the same take-over situation several times. Hence, situation assessment and the decision for the appropriate take-over maneuver became easier over time which might have led to overall smaller effects.

Further insights can be gained when the first contact with the take-over situation is considered separately. As task sequences were counterbalanced, drivers' first take-over situation can be compared between subjects, at least on a descriptive level (N = 6 for each NDR-task). At first contact, take-over times were generally larger and tasks with a visual component were associated with the slowest responses (Appendix, Fig. A1, chapter 11.1). This supports the assumption that visual task demand might be a crucial factor for take-over time. Further studies with larger sample sizes and a lower number of take-over scenarios are necessary to confirm and extend these results. In addition, the role of cognitive demanding NDR-tasks should be further addressed. As the take-over time reflects the result of perceptional and cognitive processing (e.g. decision making), even NDR-tasks without visual or manual demands might lead to performance decrements when they heavily draw on cognitive resources (*resource demand* component within the architecture of multiple resource theory, c.f. chapter 3.1.2). The aspect of mental workload is further considered in Study 3 of this thesis (chapter 6).

When interpreting take-over performance it is important to take into account how the drivers in the no lockout group dealt with the NDR-tasks. When the take-over request was issued, drivers particularly canceled the tasks that were associated with large impairments in take-over performance. Whereas two thirds of the drivers continued the auditory-vocal task during take-over, the proportion of canceled tasks increased throughout the visual tasks and was highest for the visual-manual handheld task. This finding was in accordance with the subjective perception of safety and workload ratings for the different types of NDR-tasks, indicating that drivers were aware of the task specific performance impairments. Overall, the results can be interpreted as mostly appropriate self-regulation concerning task disengagement. However, a problematic aspect was the high number of drivers that interrupted the task in reaction to the take-over request, but continued task processing in manual mode after the braking maneuver was performed. When interpreting these results it should be noted that the NDR-tasks were self-paced and could be interrupted with relatively little effort. Study 1 of this thesis showed that for a system-paced texting task the proportion of continued tasks tended to be higher than found in the present study.

Another focus of the present study was the question to which extent participants were supported by a take-over request that included a task lockout. Results indicated a significant advantage for task lockouts only concerning hands-on times. Other time based measures and the number of collisions were not affected. This may be due to the fact that also the drivers in the no lockout group released themselves quickly from the most impairing tasks. Concerning subjective data, the acceptance for a task lockout in critical take-over situations was very high. Similar results were found in a study by Melcher et al. (2015) where a less critical take-over situation was used: No objective benefits for task lockout were measured, but the subjectively perceived safety increased for more than two thirds of the drivers compared to a basic take-over request. At the current state of research, the effects of a task lockout in take-over situations cannot be finally evaluated. On the one hand, even slight benefits might be a sufficient incentive to use this concept for in-vehicle devices. On the other hand, the acceptance of lockout approaches has to be further investigated. It can be assumed that there might be a decrease in acceptance when drivers are locked out from personally relevant and highly motivating tasks, as they occur in real world driving.

Finally, some methodological limitations of the present study should be considered. First, the study was conducted in a driving simulator which might have influenced the perceived criticality of the take-over situations and also the trust in the automated driving system. Another limitation arises from the design of the NDR-tasks. The goal was to use a prototypical task that allows for a manipulation of modalities while keeping other task characteristics as constant as possible. However, tasks still differed in some other dimensions (e.g. pacing or workload). Lastly, the study's sample was limited to young and mid age drivers and some participants had relatively low annual mileage. Thus, the transferability of the study's results to other age groups and different levels of driving experience has to be addressed in further research.

5.5 Conclusion

The present study offers insights into drivers' take-over performance depending on the NDR-task type. For a critical take-over situation task modalities seem to be relevant influencing factors. In particular, visual-manual tasks with high motoric load (including the need to get rid of a handheld object when being requested to take over) impaired take-over performance.

Further research is necessary to determine other safety-relevant characteristics of NDR-tasks, e.g. mental workload (see chapter 6) or motivational aspects (Lee, 2014). In addition, the impact of the take-over scenario (e.g. urgency and criticality) has to be further examined to evaluate possible interactions between NDR-tasks and situational aspects (c.f. chapter 6 and 7).

Increasing knowledge of the factors that determine take-over performances will help in the development of elaborated countermeasures. This might include legal frameworks and also the design of advanced HMI solutions to support the driver in take-over situations. Based on the results of the current study, a system-initiated lockout of highly impairing tasks might be a promising approach. However, further research is needed to determine the overall benefits under consideration of potential acceptance issues. Another approach might be the usage of driver monitoring systems for an online assessment of "driver availability" (Marberger et al., 2017), enabling adaptive transition concepts in take-over situations (see also chapter 7).

6 Study 3: NDR-task workload and effects of available time budget

6.1 Introduction and Research Questions

The goal of Study 3 was to replicate the main results of Study 2 and to additionally take the role of mental workload into account. Thus, the current study considered the final component in the architecture of multiple resource theory: *resource demand* (chapter 3.1.2).

Previous research in the field of manual driving found significant performance impairments for cognitive distraction, although usually not in the same magnitude as for mainly visual-manual tasks (chapter 2.2.3). In addition, there is first evidence that take-over performance in highly automated driving might deteriorate when being engaged in cognitive demanding tasks, although results are heterogeneous across studies (chapter 2.2.4).

In order to determine the impact of specific task dimensions in a controlled setting, an NDR-task was designed that enabled the usage of different stimulus and response modalities as well as cognitive demands. A second experimental factor in this study was the criticality of the take-over situation. The related research question was whether the impact of NDR-task modalities and mental workload would remain stable across two different time budgets or if interaction effects need to be considered.

6.2 Method

6.2.1 Participants

Fourteen participants (9 male, 5 female) were recruited from a driver panel. Participants in Study 2 of this thesis were not considered. All drivers had completed a simulator training beforehand. The participant sample was of young to mid age (mean age: M = 32.0 years, SD = 10.60) and all participants had experience with smartphone or tablet devices. Drivers' mileage in the last year was 17,700 km on average (SD = 13,520).

6.2.2 Driving Simulator and Highly Automated Driving System

The study was conducted in the motion-base driving simulator at WIVW GmbH (Würzburg Institute for Traffic Sciences), which was also used in the previous studies of this thesis. The simulator provides a hexapod (six degrees of freedom) for motion simulation and the projection system displays a 180 degrees front view of the driving scene. Rear view and side mirrors are realized by the usage of separate in-vehicle screens.

For the current study, a highly automated driving system was implemented into the simulator. Similar to Study 1 and 2, the system was available on motorways and could be activated by a steering wheel button. When activated, the system controlled longitudinal as well as lateral vehicle guidance. The target speed of the system was set to 120 km/h. When reaching a system limit, a take-over request was issued to the driver. The take-over request consisted of a warning chime as well as a visual warning in the instrument cluster. The driver could take back vehicle control by pushing the steering wheel button, braking (at least 10 % pedal position) or a steering input (at least 4 degrees change in steering wheel angle).

6.2.3 Simulated Test Track and Take-Over Scenarios

The simulated test track was designed as a two-lane motorway with a length of 120 km. Similar to Study 2, participants were asked to stay in the right lane and drive with a speed of 120 km/h. The system was available throughout the whole test track (apart from take-over situations) and drivers were instructed to use the system whenever it was available. There was always a lead vehicle present on the ego-lane and high traffic density on the left lane.

While engaged in different NDR-tasks (see next section), drivers faced a critical take-over situation. When approaching a curve, the ego-lane was blocked by broken down vehicles. The vehicles were placed behind a hilltop to ensure that the situation could not be detected earlier by the drivers. The left lane was occupied by a convoy of vehicles. Thus, a braking maneuver was the only way to solve the situation and prevent a collision (Fig. 5-1). The situation was similar to Study 2, but in the present study two different time budgets were implemented: The time to collision (TTC) was 6 vs. 8 seconds at the moment the take-over request was issued.

6.2.4 Non-driving related Tasks

The NDR-task was designed to enable for different stimulus and response modalities, as well as cognitive demands. In the condition “auditory-vocal” short sentences were read out by a text-to-speech software and participants were asked to repeat the sentences verbally. In the "visual-manual" version of the task, sentences were presented on a handheld tablet computer and participants should transcribe them using the virtual keyboard of the device. In the condition "visual-manual: high workload" the visual-manual task was used with the adaptation that each word had to be alphabetized by the participants (e.g. original text = drive, alphabetized response = deirv), inducing increased cognitive workload (Burge & Chaparro, 2012).

At particular sections of the track (during normal operation of the automated driving system as well as prior to take-over situations) NDR-task blocks were triggered. During a task block, a new sentence was presented immediately after the last one was finished and a new one requested. The goal was to keep the participants continuously engaged in the NDR-task right before take-over situations. The order of task blocks was counterbalanced between participants to control for learning effects.

The participants were instructed to ensure safe driving at all time, but also to complete as many NDR-tasks as possible. To ensure that participants were motivated to deal with the tasks a monetary incentive was used.

6.2.5 Procedure

After providing relevant background information on automated driving, participants completed a practicing drive in the simulator. This included the interaction with the automated driving system (e.g. activation and deactivation) and the experience of a first uncritical take-over request. In a next step, the different NDR-task types were explained and participants had the opportunity to complete example tasks to become familiar with the tasks.

After an optional break the test drive was started. Driving parameters as well as NDR-task interactions were recorded during the drive. After each take-over situation, participants were asked to rate the subjective perceived criticality of the situation on a scale from 0 to 10 (Neukum, Krüger, Mayser, & Steinle, 2008).

After finishing the test drive, participants completed a questionnaire about their experiences during the drive. The driving duration was one hour.

6.2.6 Experimental Design

In the current study a 3 x 2 within subjects design was used. The first experimental factor was the NDR-task type (auditory-vocal vs. visual-manual vs. visual-manual high workload) and the second factor was the time budget of the take-over situation (6 vs. 8 s). Dependent variables were metrics of drivers' take-over performance (timing and quality aspects) as well as subjective ratings. Repeated measurement analyses of variance (ANOVA) were calculated to test for differences (significance level = 5 %).

6.3 Results

6.3.1 Subjective Criticality

Drivers' ratings of subjective criticality were analysed in a first step (Fig. 6-1). One participant had to be excluded from this analysis due to inappropriate use of the rating scale. For another driver, one of overall six ratings had to be replaced with the group mean. His reaction in the first take-over situation was not comparable to the rest of the sample due to misunderstandings of the NDR-task instruction.

The resulting subjective ratings were mainly in the medium range of the scale ("uncomfortable"). There was a significant effect of time budget (F (1,12) = 10.82, p < .01, η^2_p = .47), revealing a higher subjective criticality for the six second condition. There was a tendency of the effect of NDR-task type (F (2,24) = 2.66, p = .09, η^2_p = .18), indicating that task modalities as well as cognitive workload influenced the subjectively perceived criticality. There was no interaction between time budget and NDR-task (F (2,24) = 0.20, p = .82, η^2_p = .02).

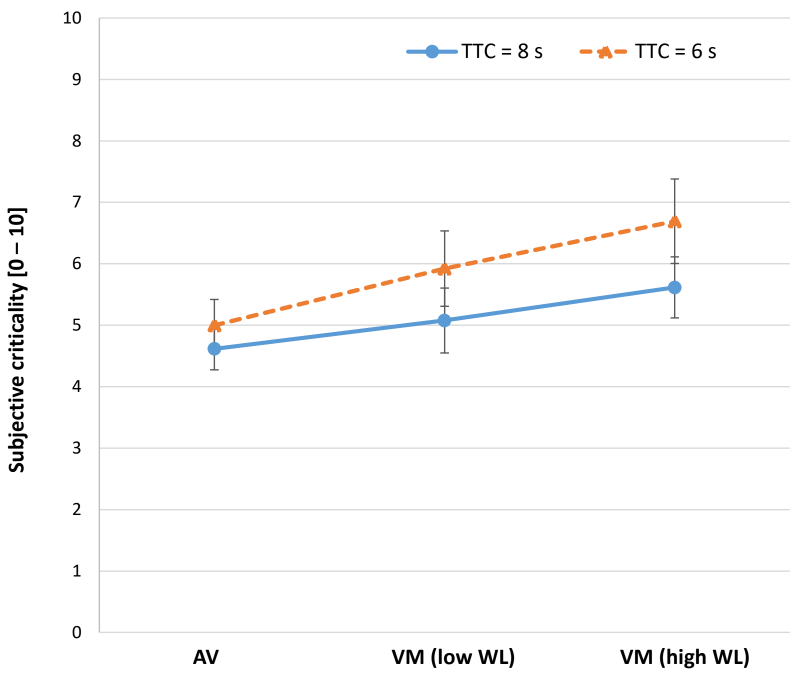

Fig. 6-1: Subjective criticality ratings (AV = auditory-vocal task, VM = visual-manual, WL = cognitive workload). Error bars represent within-group standard errors of the means (O'Brian & Cousineau, 2014).

6.3.2 Take-Over Performance and NDR-Task Disengagement

Timing and quality aspects were assessed in order to evaluate drivers' take-over performance. For statistical analyses, the full sample (N = 14) could be used. However, as described above, the first take-over situation of one driver was not equally comparable. In this single case, the group mean was used as replacement.

Concerning *timing aspects* of the take-over reaction two variables were analysed. First, the time from issuing the take-over request until hands were back at the steering wheel (= hands-on time) was assessed (Fig. 6-2). Results showed a significant main effect of NDR-task type (F (2,26) = 11.84, p < .01, η^2_p = .48). Post-hoc tests (Bonferroni adjusted) revealed that hands-on times for the auditory-vocal task were significantly shorter compared to the two visual-manual task (p < .01).

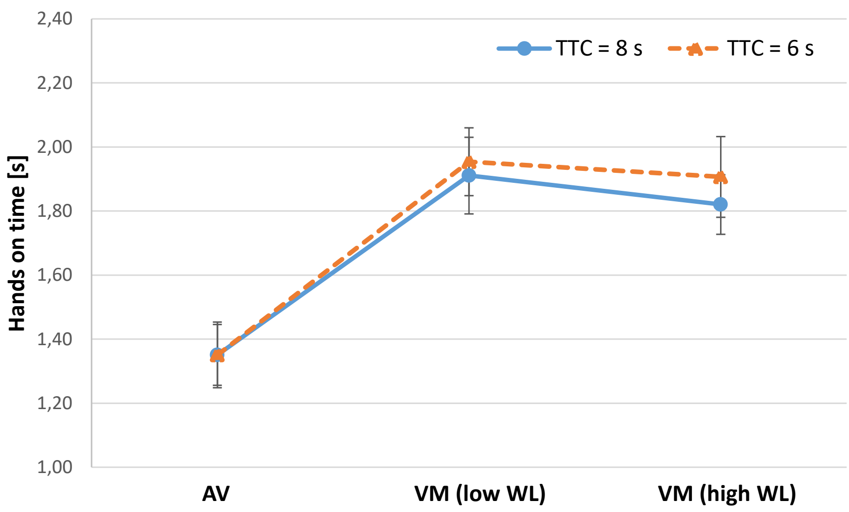

Fig. 6-2: Mean hands-on steering wheel time (AV = auditory-vocal task, VM = visual-manual, WL = workload). Error bars represent within-group standard errors of the means.

However, the visual-manual task with high cognitive load did not differ from the other, less demanding visual-manual task (p = .99). Additionally, there was neither a significant effect for time budget (F (1,13) = 0.31, p = .59, η^2_p = .02) nor an interaction between NDR-task and time budget (F (2,26) = 0.13, p = .88, η^2_p = .01).

As a second time-based metric, the take-over time was analyzed (Fig. 6-3). For the scenario used in the present study, the take-over time corresponds to the brake-response time as braking was the required action to prevent a collision. Thus, the take-over time was defined as the time from issuing the take-over request until the brake pedal travel was larger than 10 % (c.f.

Gold et al., 2013; Zeeb et al., 2015). Results revealed a marginally significant effect of NDR-task type (F (2,26) = 2.85, p = .08, η^2_p = .18). Descriptively inspected, the slowest responses were found for the high workload task, followed by the visual-manual task with low mental workload. The auditory-vocal task was associated with the fastest take-over times. Again, there was neither a significant effect for time budget (F (1,13) = 0.10, p = .75, η^2_p = .01) nor an interaction between NDR-task and time budget (F (2,26) = 0.11, p = .90, η^2_p = .01).

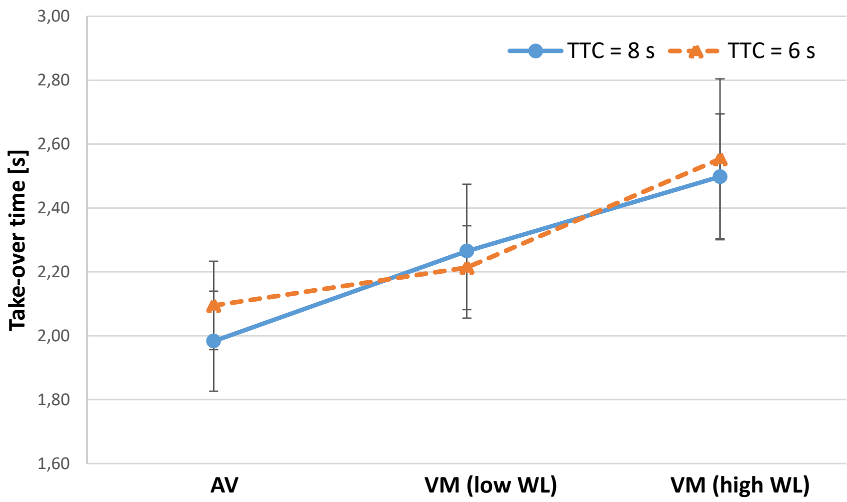

Fig. 6-3: Mean take-over time (AV = auditory-vocal task, VM = visual-manual, WL = workload). Error bars represent within-group standard errors of the means.

Concerning *quality aspects* of take-over performance, the number of collisions was analyzed as well as driving dynamics during the take-over maneuver. Overall, six collisions were counted. Each two collisions occurred in the conditions “visual-manual (8 seconds)”, “visual-manual (6 seconds)”, and “visual-manual high workload (6 seconds)”. No collisions were counted for the auditory-vocal task.

In order to assess the dynamics of the braking maneuver, maximum longitudinal decelerations were analyzed. There was neither a significant effect of NDR-task type (F (2,26) = 1.64, p = .21, η^2_p = .11) nor an interaction between task type and time budget (F (2,26) = 1.04, p = .37, η^2_p = .07). However, there was a significant main effect of time budget (F (1,13) = 98.70, p < .01, η^2_p = .88). The average maximum deceleration was 5.58 m/s^2 (SD = 0.32) for the 8 seconds conditions and 7.55 (SD = 0.01) for the 6 second condition.

When interpreting the results, it should also be considered in which way drivers dealt with the NDR-task in take-over situations (Fig. 6-4). It was distinguished between immediate task interruption and no task resumption (“canceled”), task interruption but resumption of the task after the take-over maneuver (“interrupted”), and continuation of task processing during take-over and manual driving (“continued”). Results indicate that drivers adapted their task engagement to the modalities of the NDR-task. While nearly the half of the drivers continued or only temporarily interrupted the auditory-vocal task, the visual-manual tasks were strictly canceled. The latter applied for both versions of the visual-manual task (low and high mental workload). No adaptations occurred regarding the available time budget (6 vs. 8 s).

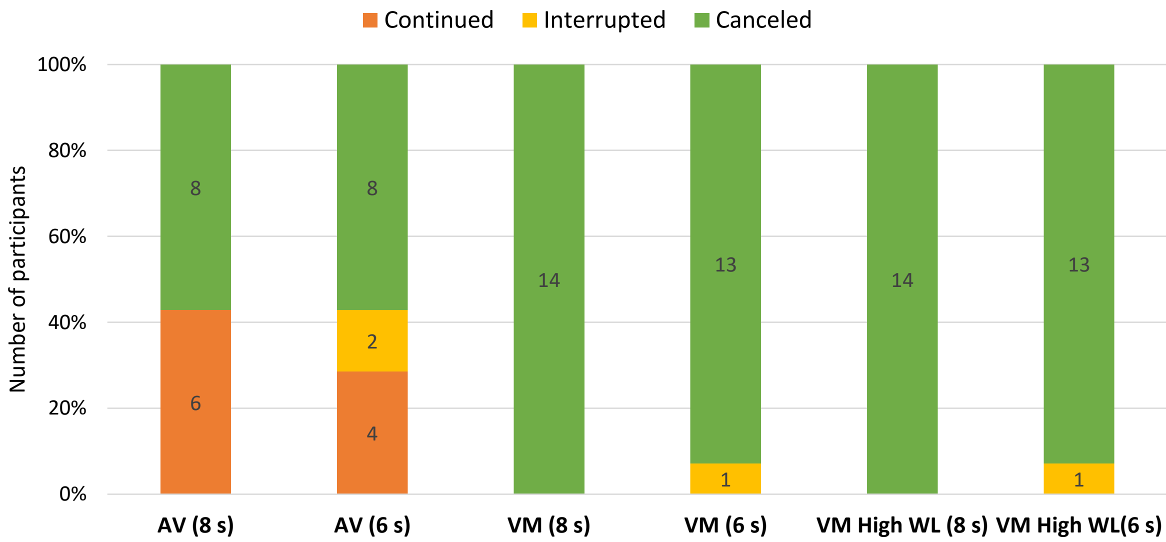

Fig. 6-4: NDR-task disengagement for the different NDR-tasks. Shown is the proportion of canceled, interrupted, and continued tasks (AV = auditory-vocal, VM = visual-manual, WL = mental workload).

The NDR-tasks were also rated regarding their subjective workload, using the items from the NASA TLX (Hart & Staveland, 1988). The overall workload (“Raw TLX”, Hart 2006) on a scale from 1 (very low) to 15 (very high) was 5.12 (SD = 2.03) for the regular texting task and 7.88 (SD = 1.77) for the alphabetizing task. The perceived workload for the auditory-vocal task was 2.62 (SD = 1.02). A repeated measurements ANOVA revealed a significant main effect (F (2,26) = 60.35, p < .001, η^2_p = .82) and Bonferroni adjusted pairwise comparisons were significant too (all p-values < .001). The mental demand subscale was separately assessed to ensure that the alphabetizing task induced the largest amount of cognitive workload. The average mental demand for the alphabetizing task was 11.07 (SD = 2.30), 6.21 (SD = 2.67) for the regular texting task, and 3.36 (SD = 1.74) for the auditory vocal task. Again, there were a significant main effect (F (2,26) = 71.51, $p < .001$, $\eta^2_p = .85$) and significant post-hoc tests (all p-values < .01).

6.4 Discussion

The main goal of Study 3 was to evaluate the impact of different NDR-tasks on take-over performance in highly automated driving. In addition, the criticality of the take-over situation was taken into account. In accordance with multiple resource theory, NDR-task modalities as well as cognitive workload seemed to have an impact on take-over performance. The time until hands were back at the steering wheel (= hands-on time) was significantly longer for the visual-manual tasks compared to the auditory-vocal task. For cognitive workload, no effect on hands-on time was found: The two visual-manual tasks were associated with similar reaction times. However, for the take-over time itself (= time until brake response) there was a tendency that both, task modalities and mental workload, were relevant influence factors. The slowest responses were found for the high workload task, followed by the visual-manual task with low mental workload. The auditory-vocal task was associated with the fastest take-over times. However, in absolute numbers the differences between the tasks were relatively small.

Concerning subjective ratings, the take-over situation with a time budget of six seconds was perceived as more critical than the eight seconds condition. Hands-on and take-over times were on a similar level, but in the six seconds condition drivers applied the brakes stronger and therefore reached higher decelerations.

Overall, results indicate that NDR-task modalities as well as cognitive workload were relevant determinants for take-over performance. Concerning the first driver reaction (i.e. putting hands back at the steering wheel) the motoric task load was the crucial aspect. High mental workload did not interfere with this mostly reflexive first reaction. In contrast, the actual take-over time (time until initiating the braking maneuver) has been interpreted as the result of perceptual and cognitive processes, including the decision for the appropriate reaction (Zeeb et al., 2015). The results of the current study provide support for this distinction. The visual task component may have mainly delayed the perceptual processing of the take-over situation. The cognitive demanding NDR-task may have additionally impaired the regaining of situation awareness as well as action selection and initiating of the take-over maneuver. Probably because of these interferences, the slowest brake response times were found for the visual-manual task with high cognitive workload.

Finally, some limitations of the study design have to be considered. First, the sample size of the study was relatively small and therefore a within-subject design was used, where drivers faced the take-over situation several times. Although order effects were controlled by using a counterbalanced design, findings should be validated in a larger between-subjects study. Second, the study took place in a driving simulator which may have influenced criticality perception and also the trust in automation. However, relative comparisons between experimental conditions are usually unaffected in driving simulator settings (“relative validity”; Blaauw, 1982).

Overall, Study 3 provides insights about relevant NDR-task characteristics influencing drivers’ ability to take over vehicle control in critical situations. Further research is necessary to extend the findings to other NDR-tasks. In addition, characteristics of the take-over situation need to be further considered (see also Study 4, chapter 7). Increasing knowledge about the impact of different NDR-tasks and situational demands may provide possible approaches for designing adaptive transition concepts or might help policy makers deciding on allowed NDR-tasks in automated driving.

6.5 Conclusion

The current study aimed to extend the findings of Study 2 regarding relevant NDR-task characteristics that affect drivers’ take-over performance. On the one hand, the crucial role of NDR-task modalities was supported by the current study. One the other hand, the results indicate that also the amount of cognitive workload should be taken into account. This is well aligned with the architecture of multiple resource theory (chapter 3.1) that considers both, resource overlap and resource demand, as important influence factors.

Another focus of the study was the role of the available time budget in take-over situations. Although the six second scenario was perceived as more critical than the eight second condition, the results of NDR-tasks remained similar. Hence, task modalities and workload seem to be relevant for driver performance even in less critical take-over situations than in Study 2.

7 Study 4: HMI development and evaluation

The previous studies of this thesis offer several insights into driver performance and self-regulatory behavior in take-over situations. In addition, Study 1 and 2 considered first HMI related topics (e.g. the use of a preview screen and task lockout approaches). Study 4 expands upon these findings and aims to evaluate more advanced HMI concepts designed for the context of HAD systems. The chapter begins with an overview of the HMI development process. Then the research questions, methodology, and results of Simulator Study 4 are outlined.

7.1 HMI Development Process and Pre-Studies

As framework for the HMI development process, a “Human-centered design” approach was chosen. The first steps within this approach are to specify the context of use and the HMI requirements. Based on the requirements analysis, HMI concepts and first prototypes are developed. Finally, the prototypes are iteratively evaluated in user tests.

Within the scope of this thesis, the context of use was specified to HAD systems (level 3; SAE International, 2014) on highways up to 130 km/h. Three different data sources were chosen for the user requirements analysis: literature, focus groups, and own simulator studies.

In the *literature analysis* general design recommendations were considered as well as previous empirical research on human factors in HAD. For instance, Billings (1997) provides “principles of human-centered automation” that were originally established for the aviation context. However, some of these recommendations can be considered as highly relevant for HAD, e.g. keeping the operator involved and informed or making the automation predictable (Billings, 1997). Also considered were heuristics for the avoidance of mode confusion (Chong, 2000). Beggiato et al. (2015) provide information needs specific for HAD, based on results of a focus group and a simulator study (e.g. system status, planned maneuvers, and a preview about oncoming special or critical driving situations). Results from Naujoks et al. (2016) indicate that the communication of upcoming automated maneuvers by speech might be a useful supplement to generic audio chimes. Hergeth (2016) found enhanced automation trust and user experience for an HMI concept that included a graphical representation of the driving environment (e.g. surrounding traffic and lane markings detected by the HAD system). Design heuristics as well as specific information needs derived from the literature were considered throughout the further HMI development process.

To complement the findings from the literature analysis, overall four *focus groups* with employees of Opel Automobile GmbH were carried out. Two focus groups were conducted with HMI experts from the active safety and infotainment domain (in total: N = 11; 8 men, 3 women; mean age = 32.82 years, SD = 5.06). Two additional focus groups were carried out with non-expert participants, e.g. from manufacturing engineering or administration (in total: N = 5; 3 men, 2 women; mean age = 39.80 years, SD = 7.60). Each focus group had a duration of two hours and the procedure was the following:

- Phase 1: Information needs during HAD
  - Presentation of different scenarios (e.g. HAD available, active, take-over req.)
  - individual work and group discussion of information needs for each scenario
- Phase 2: Creativity workshop
  - Poster of vehicle cockpit was provided to the group
  - Designing of possible HMI concepts that match requirements (group work)

The work sheets of the individual work as well as detailed transcripts were used for the subsequent data analysis. The information needs were categorized and analyzed (see also Appendix, chapter 11.2, for more details). In summary, the main requirements mentioned by the participants were: Clear and distinctive communication of system state and maneuvers performed, providing reasons for system state changes (transparency), preview of estimated system availability for the upcoming route, graphical representation of the current driving situation (including surrounding vehicles), extension of existing warning concepts for critical take-over requests (e.g. similar to multimodal front collision alert), and using speech output in addition to visual displays. It should be noted that the majority of information needs are in high accordance to the results of the focus group conducted by Beggiato et al. (2015).

Finally, the *previous simulator studies* of this thesis were considered in terms of HMI design implications. The predictive HMI (including a preview of estimated HAD availability) used in Study 1 showed benefits for drivers' self-regulation in the interaction with an NDR-task. Therefore, this concept was integrated in the further HMI development process. Study 2 and 3 revealed a significant impact of NDR-task modalities on take-over performance. As driver state monitoring systems allow for an online estimation of driver availability (Marberger et al., 2017; Goncalves & Bengler, 2015), adaptive HMI approaches seem to be a useful extension and were addressed in Study 4. Another finding of Study 2 was the potential benefit of an

NDR-task lockout in take-over situations. However, effects only occurred for hands-on time and not for take-over time, and it should be considered that drivers might engage in NDR-tasks that cannot be locked out (e.g. reading a book or using non-coupled electronic devices). Given these limitations and the goal to facilitate drivers' self-regulation in a less intrusive way, the lockout approach was not integrated in Study 4. Nevertheless, it might still be a relevant building block for future systems.

With support from the Opel design department, different graphical HMI prototypes were developed that took into account the findings of the requirements analysis. For the different systems states (e.g. manual driving, HAD available, HAD active, HAD ending) prototype screens of the instrument cluster were designed. Additional prototype screens were created for the preview of HAD availability in the center display. A pre-study with 13 non-expert Opel employees (7 men, 6 women, mean age = 35.08 years, SD = 9.21) was carried out to evaluate the comprehensibility and user experience of the screens. The static screens were presented to the participants and they were asked to describe the different elements and their assumed meaning in their own words. Participants' answers were transcribed and compared to the intended meanings of the different information units (e.g. system states, functionality of the HAD preview) by two raters. Based on the results of the study, small design modifications were applied and finally the HMI concepts were implemented into the driving simulator for further testing (see next section).

7.2 Research Questions and Study Overview

The main goal of Simulator Study 4 was to evaluate different HMI concepts regarding their potential to facilitate drivers' self-regulation in NDR-task interactions and take-over performance. In addition, user experience and acceptance of the HMI concepts were assessed. Similar to Study 2 and 3, drivers performed NDR-tasks with varying stimulus as well as response modalities and faced several take-over situations. In addition to non-predictable take-over situations (detected with onboard sensors), predictable transitions to manual driving were also considered (e.g. on the basis of car-to-x communication and dynamic map data). Three HMI versions were implemented, differing in the amount of presented information and adaptivity. The "*Basic HMI*" version shared information units with the predictive HMI used in Study 1. It contained information about the current system state (i.e. manual driving, HAD available, HAD active, take-over request) and a preview of upcoming, predictable take-over situations. The second HMI version ("*Adaptive HMI 1*") was the result of the comprehensive development process described in chapter 7.1 and included a situation-specific "take-over notification" one minute before predictable take-over situations. In addition, this HMI version provided a graphical representation of the surrounding traffic situation. Thus, this HMI can be considered as being situation-adaptive. The third HMI version ("*Adaptive HMI 2*") was similar to Adaptive HMI 1, but additionally took the current driver availability into account. Depending on the type of NDR-task (auditory-vocal vs. visual-manual handheld) different warning stages were included. In a worst case scenario the driver was supported by an automatic braking maneuver (minimum risk maneuver). The HMI versions will be described in further detail in chapter 7.3.5.

Besides the objective and subjective evaluation of HMI concepts, another research question of Study 4 referred to the take-over scenarios. Study 2 and 3 showed that NDR-task modalities were significant determinants of take-over performance. However, both studies focused on the same scenario (broken down vehicles on ego-lane). Study 4 aimed to extend the findings to another relevant scenario (narrow zone requiring a lane change and speed reduction).

7.3 Method

7.3.1 Participants

For this study, 36 participants (21 male, 15 female) were recruited from a test driver panel. The mean age of the sample was 34.11 years (SD = 11.50, range: 20 to 57) and the annual mileage was 13,811 km on average (SD = 14,910). All participants had experience with smartphone or tablet devices. It was ensured that none of the drivers had participated in Study 2 or 3 due to similar NDR-tasks and scenarios. The participants were randomly assigned to the three different HMI groups: Basic HMI, Adaptive HMI 1, and Adaptive HMI 2.

7.3.2 Driving Simulator and Highly Automated Driving System

The study took place in the dynamic driving simulator of WIVW GmbH that was also used in the previous studies. The motion-system provides six degrees of freedom to simulate vehicle dynamics. The projection system was extended in comparison to Study 1 to 3 and now displayed a 240° field of vision to the front and side. Rear and side mirrors were realized by additional LCD screens. The simulated vehicle model was a midsize car with automatic transmission.

The functionality of the HAD system was similar to the previous studies and enabled longitudinal and lateral vehicle guidance on highway roads. In accordance with the speed limit of the test track, the target speed was set to 120 km/h. For one HMI version (Adaptive HMI 2), an automatic braking application was added. It was triggered as a “minimum risk maneuver” in one specific, highly critical take-over situation (see chapter 7.3.5).

7.3.3 Simulated Test Track and Take-Over Scenarios

A two-lane highway track with a total length of 134 km was used for the current study. The participants were instructed to drive on the right lane with the indicated speed of 120 km/h (free driving) or 80 km/h (in working zones). The HAD system was available throughout the whole track (apart from take-over situations) and drivers were instructed to reactivate the system after each take-over situation. During most sections of the track a lead vehicle and passing vehicles on the left lane were present.

The simulated test track included overall eight take-over situations, presented in a counterbalanced order across participants. Two different types of scenarios were implemented. Similar to Study 2 and 3, broken down cars on the ego-lane were used, which required a braking maneuver by the driver because the left lane was occupied by overtaking vehicles (Fig. 5-1). As additional scenario, a narrow zone was implemented which required a speed reduction to 80 km/h (indicated by a traffic sign) and a lane change to the left because the ego-lane ended at barriers of a construction site (Fig. 7-1).

Both scenarios occurred with two different time budgets. A highly critical condition was implemented, with a time to collision (TTC) of six seconds regarding the broken down car on the ego-lane or the barrier of the construction site, respectively. These scenarios are named “*onboard-based*” in the following, as they were meant to be triggered by the vehicle’s onboard sensors (e.g. front radar or camera). The scenarios were placed behind hilltops and became visible not before the take-over request was issued to ensure that the situations could not be anticipated by the drivers. Both scenarios were also implemented in a so called “*server-based*” version. The assumption was that the information about these situations has been preemptively shared to the ego-vehicle, e.g. by car-to-x communication and dynamic map data. These take-over situations were announced in the preview screen 5 km (= 2.5 minutes with a speed of 120 km/h) in advance. Depending on the HMI version, an additional specific warning was presented 2 km (= 1 minute) and 1 km (= 30 seconds) in advance.

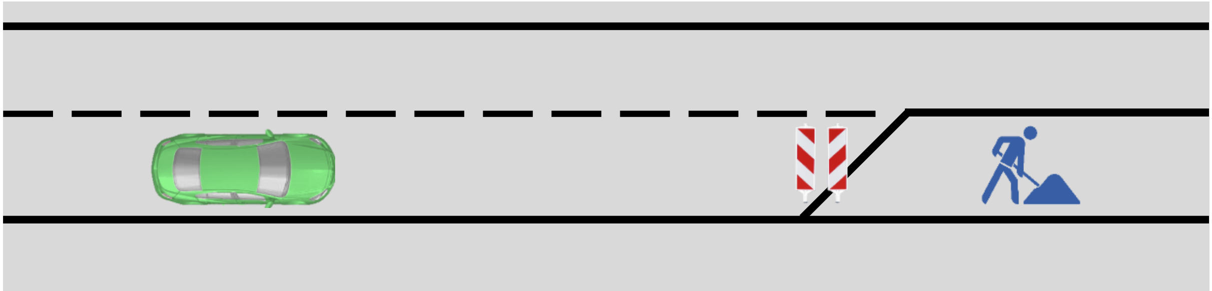

Fig. 7-1: Schematic representation of the narrow zone scenario. The participant's car is depicted in green (right lane). The situation required a speed reduction to 80 km/h (indicated by a traffic sign) and a lane change to the left because the ego-lane ended at barriers of a construction site.

7.3.4 Non-Driving related Tasks

The participants were instructed to perform NDR-tasks at pre-defined sections of the test track. The auditory-vocal as well as the visual-manual (handheld) task of Study 2 were reused. In the auditory-vocal task version, short sentences were read out by a text-to-speech software and the drivers were required to repeat the sentences verbally. In the visual-manual version of the task, short sentences were presented on a handheld tablet computer and participants were instructed to transcribe them using the tablet's virtual keyboard.

Compared to Study 2 and 3, small modifications were applied in terms of task material and task length. The goal was that the tasks should be as similar as possible, apart from the different stimulus and response modalities. Study 2 and 3 revealed that the tasks also differed in perceived workload: the auditory-vocal task was rated as less mentally demanding than the visual-manual task. Therefore, in the current study the complexity and length of the auditory presented sentences were slightly increased. For the visual-manual task, shorter sentences were used to account for the slower speed of typing compared to speaking. The average sentence length was 50 characters for the auditory-vocal and 35 characters for the visual-manual task, respectively. After the drive, participants completed the NASA TLX questionnaire to allow for an assessment of subjective mental workload.

NDR-task blocks were triggered on pre-defined sections of the test track (during normal operation of HAD as well as prior to take-over situations). As soon as the driver finished the ongoing task and requested a new one, the next task started immediately until the task block ended. Participants were instructed to ensure safe driving at all times, but also to complete as many NDR-tasks as safely possible. A monetary incentive was used in order to facilitate participants' motivation.

During the drive, the two NDR-task versions were combined with the different take-over scenarios and time budgets, resulting in overall eight combinations (see also chapter 7.3.7). The order of task blocks and take-over situations was counterbalanced between participants to control for learning effects.

7.3.5 HMI Versions

Three different HMI versions were implemented for this study, named Basic HMI, Adaptive HMI 1, and Adaptive HMI 2. All versions included the following system states: manual driving, HAD available (white state), HAD active (green state), and take-over request (red state, including a warning chime). When available, the system could be activated with a steering wheel button. The driver could take back vehicle control at any time by pushing the same steering wheel button, applying the brakes or with a steering input. The system state was presented in the instrument cluster display as well as in the center display. In addition, the center display provided a preview of the HAD availability and upcoming predictable take-over situations in the next five km.

The Basic HMI (top row in Fig. 7-2) included a standard analog speedometer and the preview screen showed upcoming predictable mode transitions. However, the type of take-over situation was not displayed and there was no specific announcement in advance to the take-over request that was triggered with a time budget of six seconds. Thus, drivers had to keep a watch on the preview screen from time to time to be prepared for server-based take-over situations. Overall, this HMI version shared a number of similarities to the predictive HMI of Study 1. It was included as a baseline condition to the more advanced HMI solutions based on the development process outlined in chapter 7.1.

Adaptive HMI 1 was designed in accordance to the requirement analysis described in chapter 7.1. It included all features of the Basic HMI with some modifications and extensions. First, the analog speedometer was only displayed in manual mode. As soon as the driver switched to HAD mode, the speedometer changed to a digital version and a graphical representation of the driving situation was shown. Thus, a clear graphical distinction between the driving modes was drawn and the driver had the opportunity to get an idea about the environmental model of the system (e.g. detected lanes and vehicles). Another important extension to the Basic HMI was a situation-specific “take-over notification” 60 seconds prior to predictable take-over situations. The notification consisted of a short flashing of the green status frame (see Fig. 7-2) and a speech-output (“Work zone / accident in two km. Please take back vehicle control.”, translated from German). Also, additional icons in the cluster and center display indicated the type of take-over situation. Thus, this HMI can be considered as being situation-adaptive.

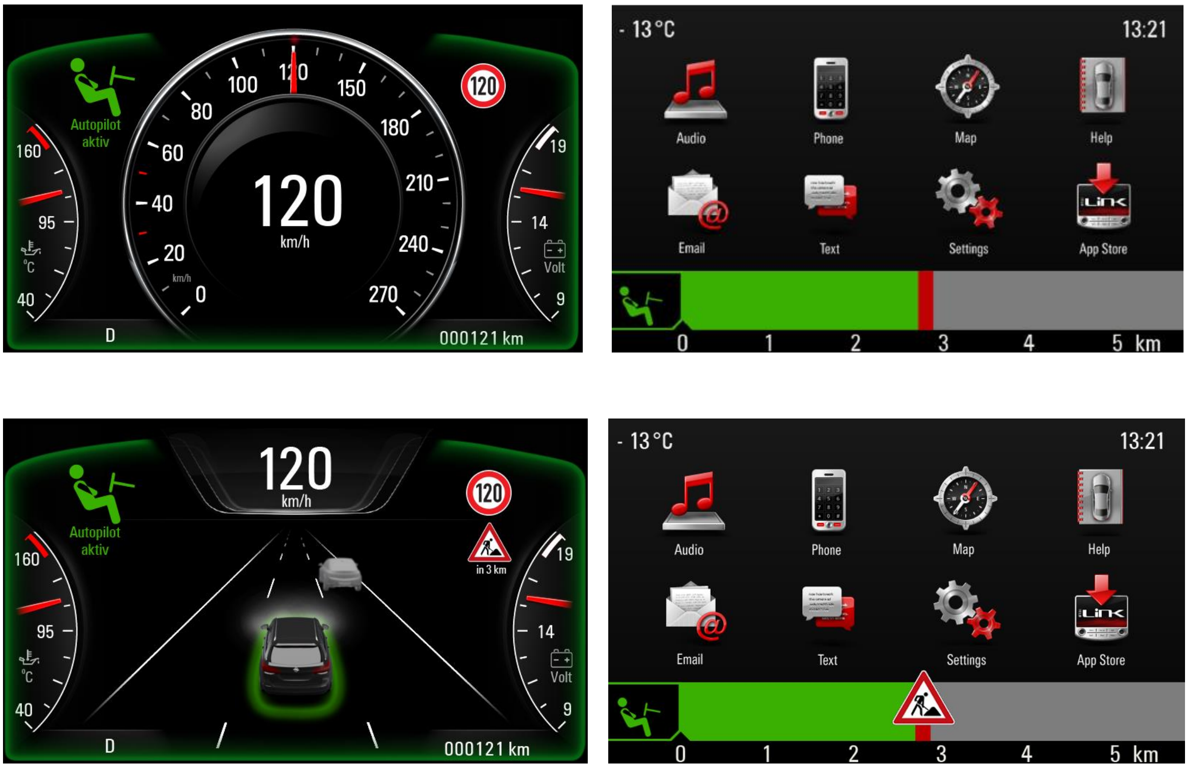

Fig. 7-2: The different HMI versions. Top row: Basic HMI, bottom row: Adaptive HMI 1 & 2. The left column represents the instrument cluster screen and the right column the center display. In this example situation, the vehicle is in highly automated driving mode and there are about 3 km left until a take-over situation (narrow zone in construction site) is reached.

The last HMI version (“Adaptive HMI 2”) included all elements of Adaptive HMI 1, but also took the current driver availability into account. Study 2 and 3 showed that the visual-manual handheld task can be considered as overall more safety-critical than the auditory-vocal task. To account for this finding, a task adaptive warning strategy was implemented. Two adaptations were used. The first adaptation referred to the announcement of server-based take-over situations. If the driver performed the visual-manual task and did not react to the take-over notification, the notification was triggered a second time with a remaining time budget of 30 seconds. In the current study, the notification was triggered by the experimenter in case the driver was still engaged in the NDR-task. Given the advancements in driver state monitoring systems, it is likely that there will be appropriate technical solutions in the future (c.f. Goncalves & Bengler, 2015). The second adaptation referred to the onboard-based broken down car scenario with the driver performing the visual-manual NDR-task. As this can be considered as a worst case scenario, the driver was supported with an automatic braking maneuver ("minimum risk maneuver") that avoided a crash even if the driver did not respond to the take-over request.

7.3.6 Procedure

After a brief introduction into general characteristics of HAD, the participants completed a practicing drive in the simulator. The experimenter explained all HMI elements including the preview in the center screen. The participants experienced the different system states in the practicing drive and got used to system activation and deactivation. In addition, drivers faced a first uncritical take-over request. Afterwards, the different NDR-tasks were explained and the participants performed several example tasks to become familiar with the tasks.

After an optional break the experimental drive was started, which lasted about 70 minutes. Driving parameters as well as video data were recorded during the test drive. Glance data was collected via video labeling of an interior camera. After each take-over situation participants rated their subjectively perceived criticality of the situation on a scale from 0 to 10 (Neukum et al., 2008). Subsequent to the test drive, participants filled in a questionnaire including ratings of subjective workload, acceptance, and user experience.

7.3.7 Experimental Design and Data Analysis

For the current study a 3 x 2 x 2 x 2 mixed design was used. The first experimental factor was the HMI version with three levels (Basic HMI, Adaptive HMI 1, and Adaptive HMI 2). The HMI version was implemented as between subjects factor (n = 12 for each group). The within subjects factors were NDR-task (auditory-vocal vs. visual-manual handheld), take-over scenario (broken down car vs. narrow zone), and predictability of the take-over situation (onboard vs. server-based). Dependent variables were take-over performance (timing and quality aspects), measures of NDR-task interaction (e.g. gaze data and task disengagement in take-over situations), and subjective data (e.g. workload ratings, acceptance, and user experience). Mixed analyses of variance (ANOVA) were calculated to test for differences (significance level = 5 %).

7.4 Results

7.4.1 Subjective Criticality and Workload Ratings

Subsequent to each take-over situation, drivers rated their subjectively perceived criticality using a scale from 0 to 10 (Neukum et al., 2008). The ratings were grouped in terms of scenario predictability, scenario type, performed NDR-task, and HMI group (Fig. 7-3). A repeated measurements ANOVA revealed a significant difference between server-based and onboard-based situations (F (1,35) = 90.49, p < .001, η^2_p = .72). In a subsequent mixed ANOVA, no main effect of HMI was found (F (2,33) = 0.37, p = .69, η^2_p = .02), but there was a significant interaction between situation predictability and HMI (F (2,33) = 8.98, p = .001, η^2_p = .35). For the Basic HMI, where no explicit take-over notification was implemented, ratings between server-based and onboard-based situations differed less than for Adaptive HMI 1 and 2. Considering scenario type, a repeated measurements ANOVA indicated the tendency that the broken down car scenario was overall perceived as more critical than the narrow zone (F (1,35) = 3.68, p = .063, η^2_p = .10). No significant differences were found for NDR-task type (F (1,35) = 1.51, p = .228, η^2_p = .04).

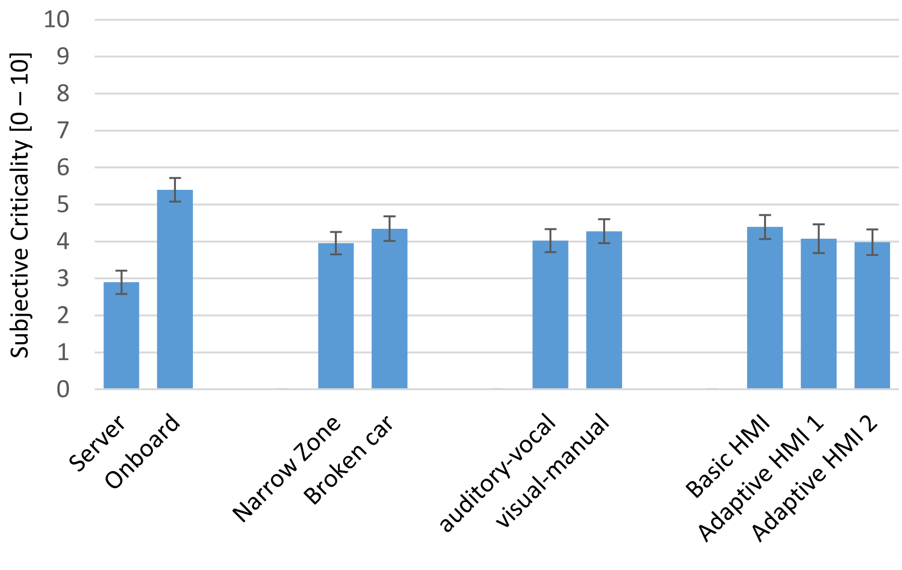

Fig. 7-3: Subjective criticality ratings. Mean values (with standard error bars) are grouped in terms of predictability, scenario type, NDR-task performed, and HMI group.

After completing the test drive, participants filled out a workload rating scale with the items of the NASA TLX (Hart & Staveland, 1988; Fig. 7-4). Results revealed that the overall workload score ("Raw TLX"; Hart, 2006) was significantly higher for the visual-manual compared to the auditory-vocal task (F (1,35) = 26.52, p < .001, η^2_p = .43). Significant differences were found for each subcategory of the NASA TLX (all p-values < .01), apart from mental demand (F (1,34) = 1.10, p = .30, η^2_p = .03; one missing value).

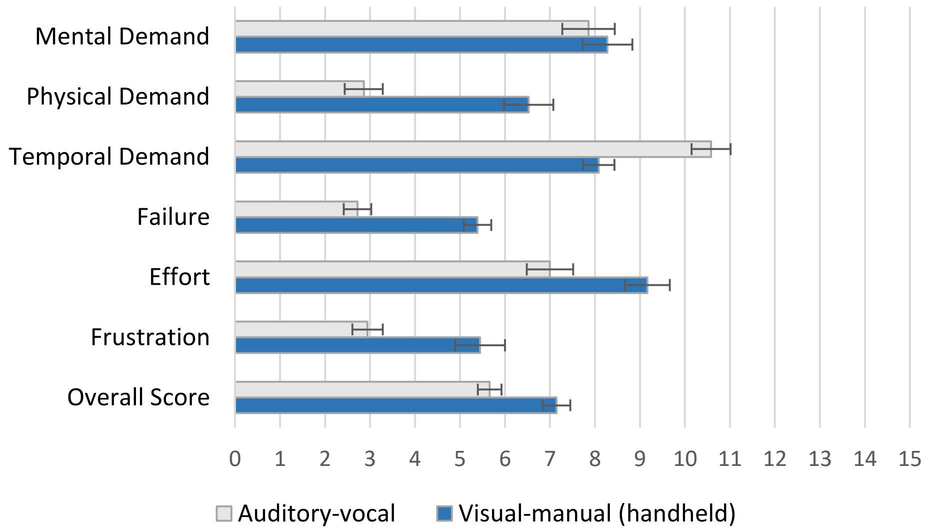

Fig. 7-4: Subjective workload ratings using the NASA TLX items. Mean values for the single items and the overall score are depicted separately for the two NDR-tasks. Error bars represent the standard errors of the means.

7.4.2 Driver Behavior in Server-based Take-Over Situations

In the server-based scenarios, the take-over situation could be anticipated with a comfortable lead time of 2.5 minutes (regarding the range of the preview screen implemented in all HMIs) or 1 minute (regarding the take-over notification implemented in the adaptive HMIs), respectively. In the following, it is analyzed to which extent drivers made use of the early information in terms of take-over time, NDR-task disengagement, and monitoring behavior.

Fig. 7-5 depicts, separately for all server-based situations, the number of participants that took over vehicle control before the take-over request would have been issued. Only very few participants in the basic HMI group deactivated the system within this time frame. Descriptively inspected, early system deactivations occurred more often for the adaptive HMIs that included a take-over notification. Adaptive HMI 2 was highly effective for the situations where drivers were engaged in the visual-manual task. In these situations, drivers received a second take-over notification if they had not interrupted the task after the first notification. This second notification was triggered in six cases (3 x narrow zone scenario, 3 x broken car scenario). In all cases the drivers immediately disengaged from the task and took over vehicle control.

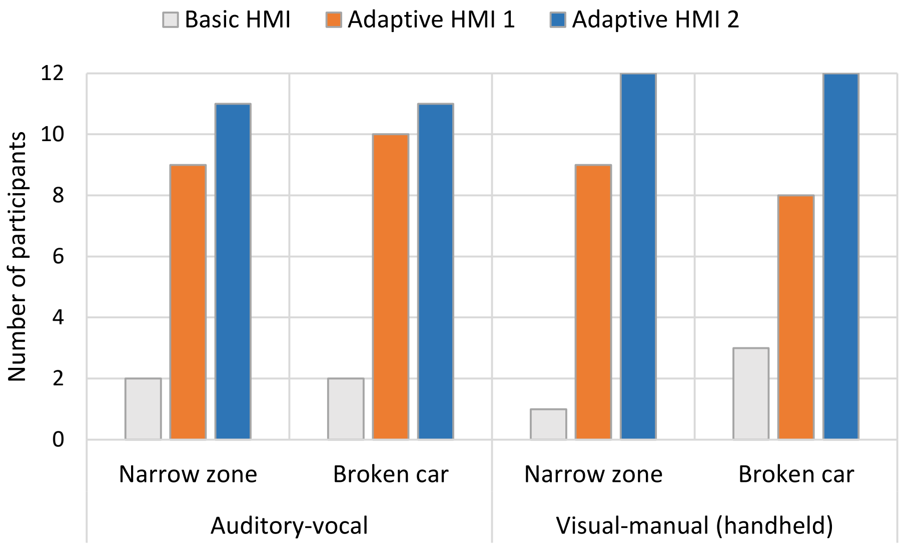

Fig. 7-5: Number of participants (N = 12 per HMI group) that deactivated the highly automated driving system before the take-over request would have been issued.

Overall, Fig. 7-5 suggests benefits for both adaptive HMI versions compared to the basic HMI concept. For a better understanding how drivers reacted to the take-over notification, the time from issuing the notification until system deactivation was analyzed (Fig. 7-6). Results indicated bimodal distributions of the take-over times (bimodality coefficients BC from left to right [Fig. 7-6]: .802; .634; .609; .616; all BC values > BC_{crit} of .555; see Pfister, Schwarz, Janczyk, Dale, & Freeman, 2013). Thus, the typical behaviors were an immediate take-over subsequent to the take-over notification or a system deactivation right before the end of the highly automated driving sections, respectively.

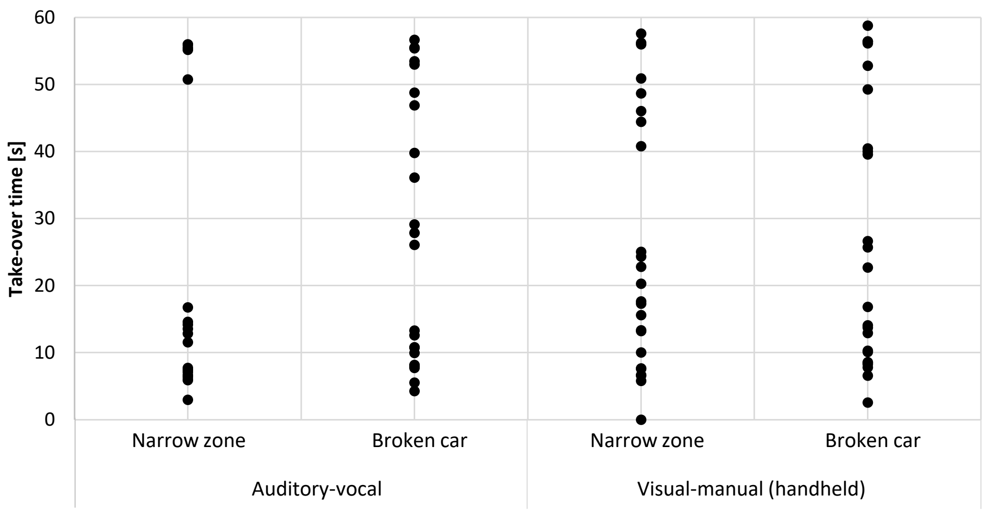

Fig. 7-6: Response time from displaying the take-over notification until system deactivation for the different take-over scenarios. Individual take-over times for the 24 participants of Adaptive HMI 1 and 2 are depicted.

It is important to stress that a late system deactivation does not necessarily indicate inappropriate self-regulation. There might still be adaptations in NDR-task engagement and monitoring frequency that reflect a preparation for the upcoming system limit. These aspects are analyzed with a focus on the probably most critical server-based situation (c.f. section 7.4.1): The broken down car scenario in combination with the visual-manual task.

Fig. 7-7 depicts the proportion of drivers that disengaged from the NDR-task during the last 60 seconds before reaching the system limit. All drivers were engaged in the task at the beginning of the depicted time interval. However, 50 % of the drivers that received the take-over notification (Adaptive HMI 1 and 2) stopped their task interaction within 15 seconds. In the Adaptive HMI 2 group (additional take-over notification after 30 seconds), all drivers had disengaged from the task about 20 seconds before the system limit. More time passed for Adaptive HMI 1, however at the moment the take-over request was issued, only one driver was still engaged in the task. The drivers in the basic HMI group showed a different behavior. Here, more time passed until the first drivers stopped their task interaction (about 40 seconds). In addition, about 40 % of the drivers were still engaged in the task when the take-over request was issued.

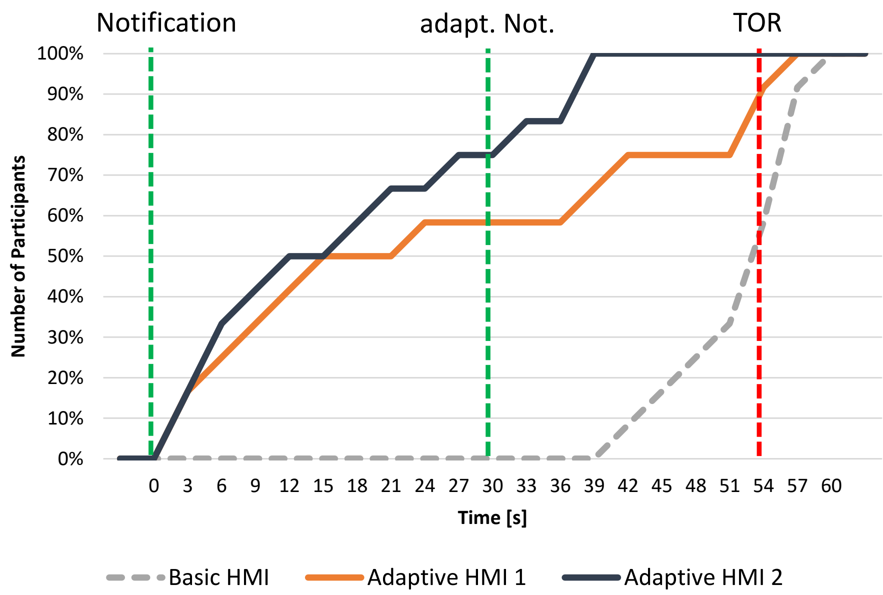

Fig. 7-7: Disengagement from the visual-manual task in the broken car scenario (TOR = take-over request).

The same type of analysis was also conducted for the broken down car scenario with auditory-vocal task (Fig. 7-8). Again, a number of drivers with the adaptive HMIs disengaged from the task in reaction to the take-over notification. However, in comparison to the visual-manual task, the proportion of drivers that continued their task interaction was notably higher. Seven drivers switched to manual mode after the take-over notification but did not quit the task. More than half of all drivers even continued task processing throughout the take-over situation; a behavior that also occurred in the onboard-based situations (see section 7.4.3).

Similar descriptive analyses of task disengagement were also conducted for the server-based narrow zone scenario with analogous results (Appendix, chapter 11.2, Fig. A2 and Fig. A3).

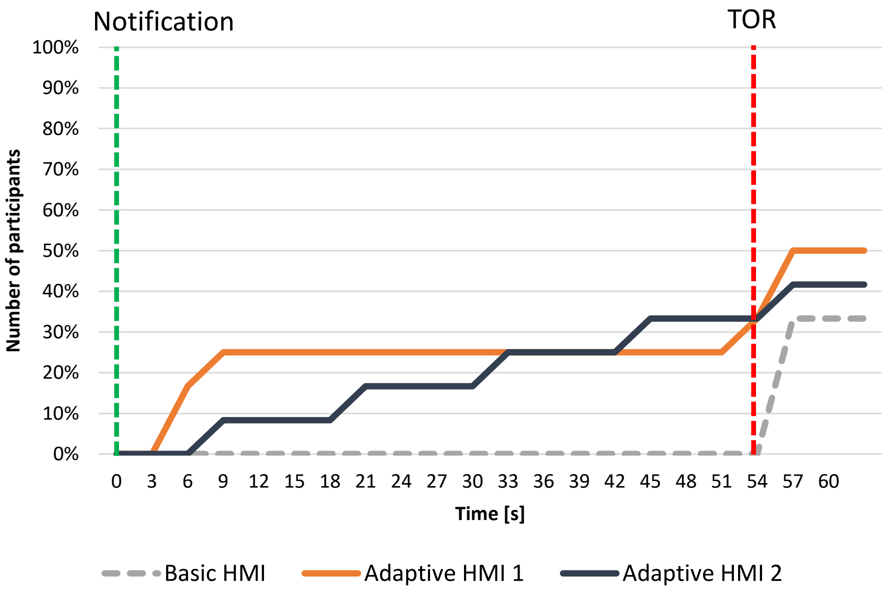

Fig. 7-8: Disengagement from the auditory-vocal task in the broken car scenario for the different HMI groups.

Further insights into drivers‘ self-regulation can be gained when analyzing the monitoring/glance behavior. The broken down car scenario in combination with the visual-manual task was chosen for the analysis. Fig. 7-9 shows the percentage of traffic related glances (based on the duration of windshield and side/rearview mirror glances) from the beginning of the NDR-task until reaching the system limit. Throughout the first two minutes of task processing only few monitoring glances were made. It seems that the take-over notification (Adaptive HMI 1 and 2) led to an increase of traffic monitoring. However, on basis of Fig. 7-9 it cannot be separated whether the increase in traffic monitoring reflects a more intense monitoring during automated driving or the fact that more and more drivers switched to manual driving when approaching the system limit. To address this limitation, the percentage of traffic related glances was calculated for two different sections of automated driving in a subsequent analysis (Fig. 7-10). The first section (“pre”) was defined as the time span from the beginning of the

NDR-task until right before the take-over notification (0 to 120 s in Fig. 7-9). The second section ("post") referred to the time span from 120 s (take-over notification) until the system was deactivated by the driver or the take-over request was finally issued (variable duration). Results from a mixed ANOVA showed a significant increase in monitoring intensity from section "pre" to section "post" (F (1,33) = 27.39, p < .001, η^2_p = .45). In addition, there was a marginally significant interaction between HMI and time (F (2,33) = 2.61, p = .09, η^2_p = .14). The increase in monitoring frequency from "pre" to "post" tended to be larger for the adaptive HMIs that included the take-over notification compared to the Basic HMI.

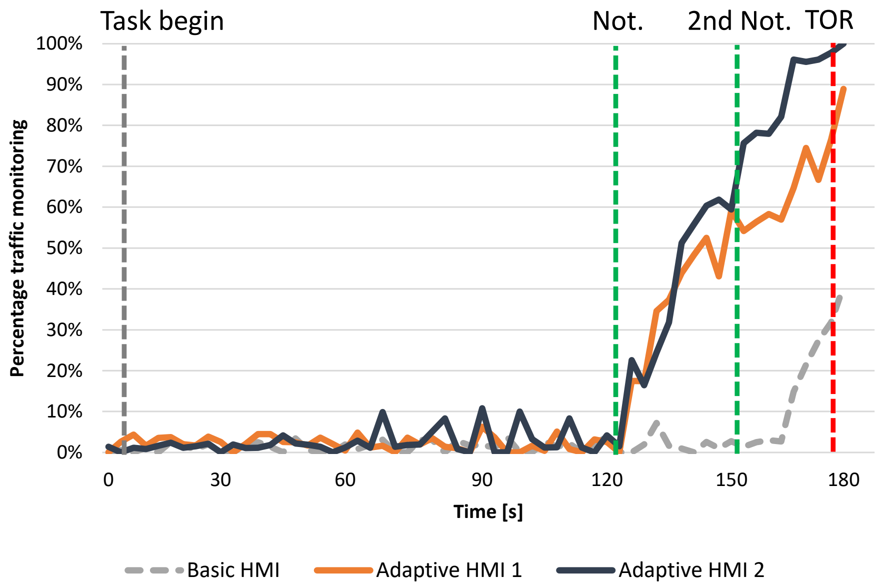

Fig. 7-9: Mean percentage of traffic monitoring (duration of windshield and mirror glances divided by time) in the broken down car scenario for the different HMI groups. In manual driving mode the value was set to 100%.

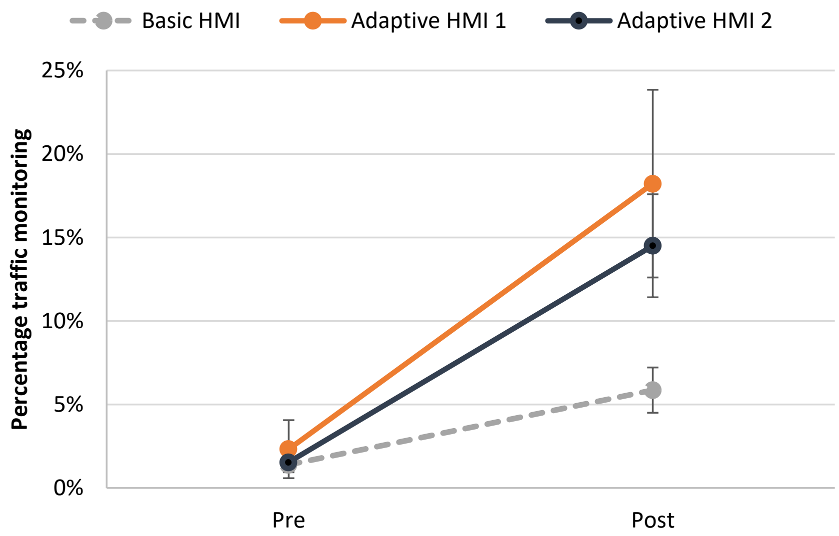

Fig. 7-10: Mean percentage of traffic monitoring for the sections „Pre" (from NDR-task begin until right before the take-over notification) and „Post" (from take-over notification until system deactivation or take-over request) in the scenario broken car/visual-manual task. Error bars represent the standard errors of the means.

7.4.3 Driver Behavior in Onboard-based Take-Over Situations

The data analysis of onboard-based take-over situations follows the structure used in the previous studies. First, drivers' self-regulation in terms of NDR-task disengagement is evaluated. Then, drivers' take-over performance is assessed under consideration of the different NDR-tasks (auditory-vocal and visual-manual handheld) and scenarios (narrow zone and broken down car).

NDR-task disengagement

For each of the four onboard-based take-over situations, it was descriptively analyzed how drivers dealt with the ongoing NDR-task after the take-over request was issued (Fig. 7-11). A distinction was made between three different behaviors: task interruption and no task resumption ("canceled" in Fig. 7-11), task interruption but resumption during manual driving ("interrupted"), and continuation of task interaction during take-over and manual driving ("continued"). Results showed that the visual-manual handheld task was overall strictly abandoned while the auditory-vocal task was only temporarily interrupted or even continued in about half of the cases (Fig. 7-11). This result was in line with subjective ratings given in the post drive questionnaire: 33 of 36 participants rated the visual-manual task as more impairing than the auditory-vocal task version. In addition, the subjectively perceived safety (rating scale from 0 [very low] to 15 [very high]) while performing the different tasks was 11.72 (SD = 2.43) for the auditory-vocal and 7.25 (SD = 3.10) for the visual-manual version.

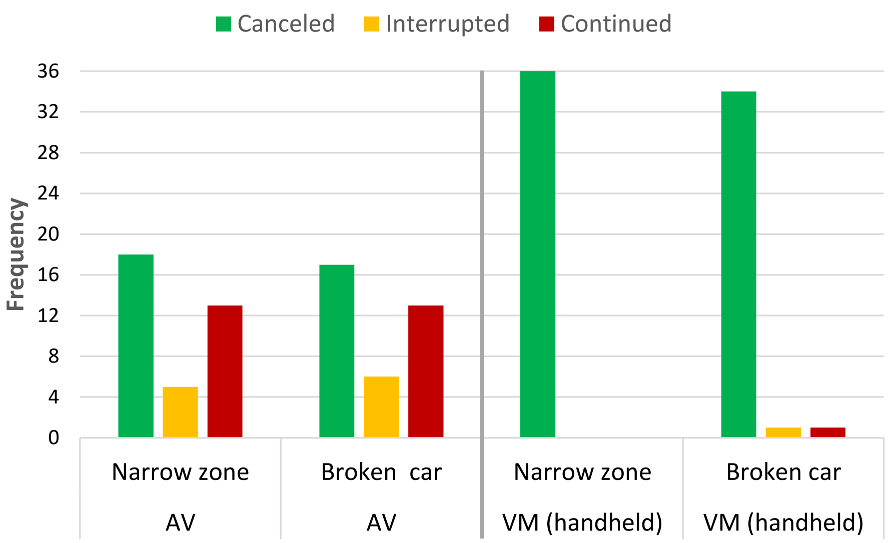

Fig. 7-11: Task disengagement in onboard based take-over situations. Depicted is the frequency of canceled, interrupted, and continued tasks for the different NDR-tasks (AV = auditory-vocal, VM = visual-manual).

Take-over performance

Timing and quality metrics were considered to measure drivers' take-over performance in non-predictable onboard-based situations. A comparison was made between the different NDR-tasks (auditory-vocal vs. visual-manual handheld). The narrow zone and broken down car scenarios were analyzed separately due to the different requirements for the driver reaction.

For the analysis of the onboard-based *narrow zone scenario*, data from the three HMI groups was combined because similar warning concepts were used. An ANOVA revealed that drivers' hands-on steering wheel time was significantly higher for the visual-manual compared to the auditory-vocal task (F (1,35) = 25.20, p < .001, η^2_p = .42, see also Fig. 7-12). Also the take-over time (deactivation of the HAD system via braking, steering or button press) was significantly prolonged when engaged in the visual-manual task (F (1,35) = 4.39, p = .044, η^2_p = .11, Fig. 7-12).

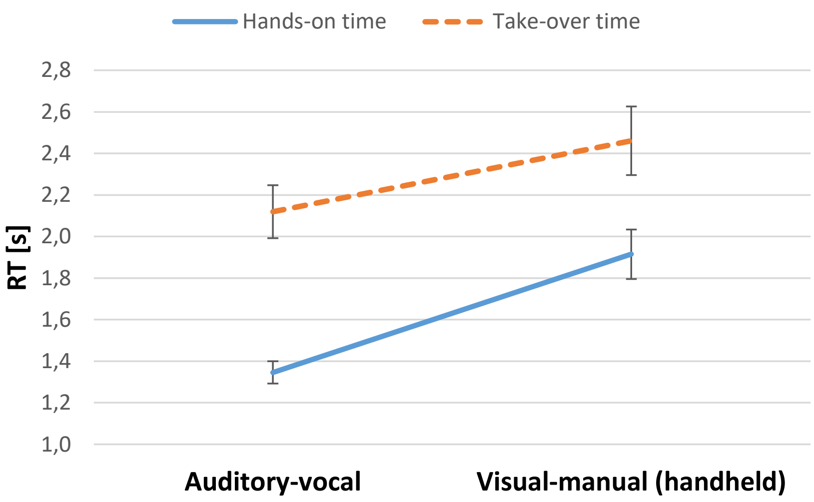

Fig. 7-12: Mean hands-on (blue line) and take-over times (orange line) for the different NDR-tasks in the narrow zone scenario. Error bars represent the standard errors of the means.

As the ego lane ended in the narrow zone, the time until finishing the required lane change (= vehicle's center on the left lane) was considered as well. For the auditory-vocal task, the lane change was finished after 5.51 seconds (SD = 0.65) on average and for the visual-manual task after 6.11 seconds (SD = 1.06). This difference was statistically significant (F (1,35) = 15.95, p < .001, η^2_p = .31). The same effect was found when assessing the distance in meter (measured from issuing the take-over request until the lane change was finished) instead of time (F (1,35) = 8.89, p = .005, η^2_p = .20). In addition to time-based metrics also aspects of take-over quality were assessed. Significant effects were found for maximum longitudinal decelerations (F (1,35) = 7.47, p = .010, η^2_p = .18), with higher values for the visual-manual task (M = 5.28 m/s^2, SD = 2.37) compared to the auditory-vocal task (M = 4.31, SD = 1.67). The maximum lateral acceleration was 2.05 m/s^2 (SD = 1.21) on average for the visual-manual and 1.87 m/s^2 (SD = 0.85) for the auditory-vocal task. However, this difference was not significant (F (1,35) = 0.89, p = .35, η^2_p = .03).

For the *broken down car scenario*, statistical analyses of take-over performance were limited to the Basic HMI and Adaptive HMI 1 groups. In the Adaptive HMI 2 group an automatic braking maneuver was applied when the driver was engaged in the visual-manual task. Thus, driver reactions were not fully comparable to the other groups and are separately discussed in the next paragraph. Fig. 7-13 depicts the combined data of the Basic and Adaptive HMI 1 groups concerning hands-on and take-over time. Similar to the narrow zone scenario, the visual-manual task was associated with significantly prolonged hands-on (F (1,20) = 6.88, p = .016, η^2_p = .26) and take-over times (F (1,21) = 6.66, p = .017, η^2_p = .24) compared to the auditory-vocal task.

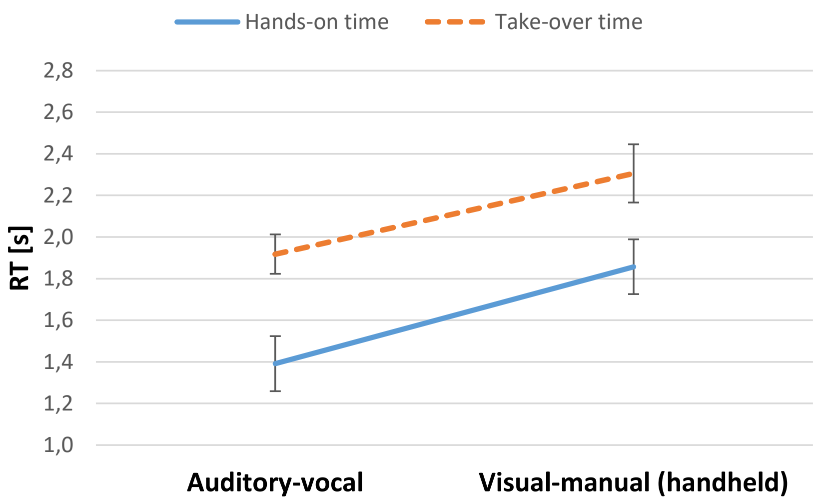

Fig. 7-13: Mean hands-on (blue line) and take-over times (orange line) for the different NDR-tasks in the broken down car scenario. Error bars represent the standard errors of the means.

However, some limitations need to be considered. There was a dropout in the number of valid cases due to the fact that three drivers already had their hands on the steering wheel when the take-over request was issued. Two of them even had deactivated the system beforehand.

These behaviors only occurred in the scenario where drivers were performing the visual-manual task. Due to errors in the scenario implementation the participant's car drove slower than intended when approaching the situation, which might have caught drivers' attention. When the take-over request was issued, the average speed was only 108.95 km/h (SD = 2.74, range 98.52 to 111.0), representing an average time to collision of 6.61 seconds instead of the intended 6.0 seconds. Because of these technical shortcomings, quality metrics of vehicle dynamics (e.g. minimum accelerations) cannot be equally compared between the experimental conditions. However, it should be noted that overall three collisions occurred for the visual-manual task and two collisions for the auditory-vocal task.

Lastly, drivers' take-over behavior in reaction to the automatic braking application was descriptively analyzed (Fig. 7-14). This system behavior was only implemented in Adaptive HMI 2 for the presumed worst case situation (= broken down car scenario while performing the visual-manual task).

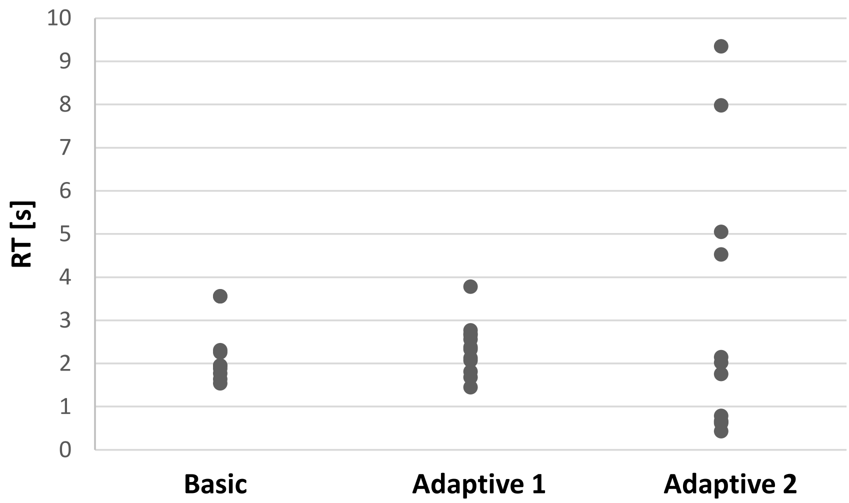

Fig. 7-14: Take-over time for the different HMI groups in the broken down car scenario with visual-manual task. Depicted are the individual take-over times of all drivers, i.e. each dot represents one participant.

A remarkable result was the high variability in drivers' take-over time when being supported by the automatic braking (Fig. 7-14). When comparing the response times of Adaptive HMI 2 to the other HMI groups, it seems that the automatic braking facilitated a fast reaction for the majority of drivers. However, an opposite effect was found for one third (four drivers) of the participants in the Adaptive HMI 2 group. In these cases drivers showed particularly slow take-over times. When interpreting this result, it should be noted that 3 of these 4 drivers showed a quick gaze and hands-on reaction but decided to let the system perform the braking maneuver without their intervention. However, one driver only made a single control glance and continued NDR-task interaction during the automatic braking maneuver. After the drive, 5 of the 12 participants with Adaptive HMI 2 could remember the automatic braking. In many cases, drivers applied the brakes quickly and, therefore, did not note the automatic braking maneuver.

7.4.4 Usability, Acceptance, and Trust Ratings

After finishing the test drive, participants were asked to evaluate several HMI characteristics. To assess overall usability, the System Usability Scale (SUS; Brooke, 1996) was used. Following the criteria provided by Bangor, Kortum, and Miller (2009), results indicated an overall “excellent“ usability with scores in the top quartile of the reference distribution. The average score on a scale from 0 to 100 was 84.38 (SD = 10.67) for the Basic HMI, 89.38 (SD = 9.72) for the Adaptive HMI 1 and 87.71 (SD = 8.43) for the Adaptive HMI 2. The ratings did not significantly differ between the HMI groups (F (2,35) = 0.84, p = .443, η^2_p = .05).

In addition, self-developed items were used that were created on basis of the pre-study requirement analysis (chapter 7.1). For example, mode awareness was assessed using the statement “It is always obvious whether the system is engaged or not”. All items were answered on a five point Likert scale ranging from “strongly disagree” (-2) to “strongly agree” (+2). Regardless of the HMI group, for most items strong or very strong agreement was found (Fig. 7-15). Descriptively inspected, lower agreement ratings occurred for the Basic HMI in the last four questions (Fig. 7-15). For the item “Awareness of system limits” (complete statement: “I am well informed about situations the system cannot handle on its own.”) the difference between HMI groups was statistically significant (F (2,35) = 4.42, p = .020, η^2_p = .21).

In addition, drivers rated the perceived usefulness of the main HMI elements. On a scale from 1 (“very low”) to 15 (“very high”) the main status indication was rated with 10.34 (SD = 3.43), the preview screen with 12.64 (SD = 2.37) and the representation of the surrounding traffic situation (only Adaptive HMI 1 and 2) with 11.13 (SD = 3.08).

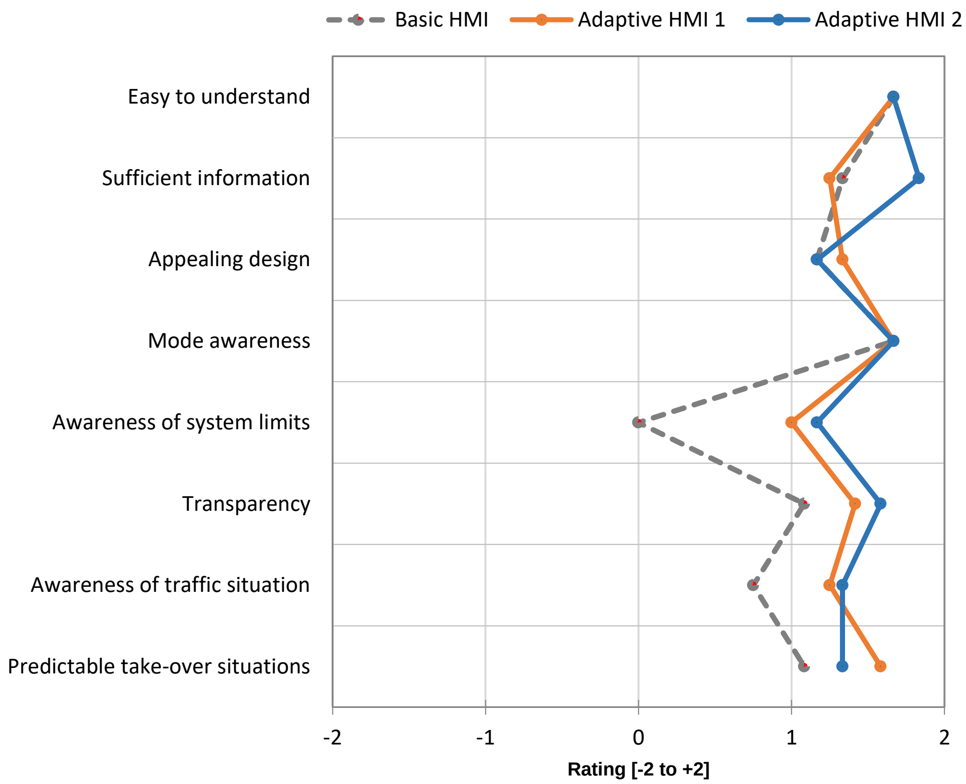

Fig. 7-15: HMI evaluation based on requirement analysis. Mean values are depicted for each HMI group.

The rating scale by van der Laan, Heino, and de Waard (1997) was used to assess drivers' acceptance of the HMI concepts. Descriptively inspected, the adaptive HMI versions resulted in slightly higher ratings in both subscales (Fig. 7-16). However, differences were not significant (Usefulness: F (2,35) = 2.06, p = .144, η^2_p = .11; Satisfying: F (2,35) = 0.68, p = .51, η^2_p = .04).

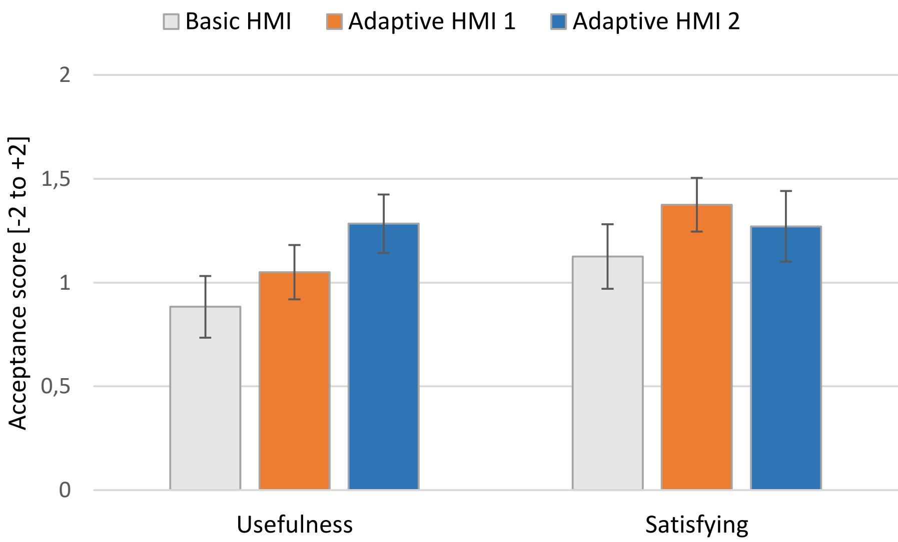

Fig. 7-16: Acceptance ratings (van der Laan et al., 1997) for the three HMI concepts (each: n = 12). Depicted are the mean values for the two subscales "Usefulness" and "Satisfying" with standard errors.

At the end of the experiment, drivers rated their trust in automation on a scale from 0 to 100 %. The average score was 79.17 % (SD = 15.64) for the Basic HMI group, 86.67 % (SD = 9.85) for Adaptive HMI 1 and 85.00 % (SD = 11.68) for Adaptive HMI 2. There was no significant difference between the HMI groups (F (2,35) = 1.176, p = .32, η^2_p = .07).

Subsequent to the test drive, the experimenter presented the other, not experienced display versions. In a forced choice, 27 of the 36 participants preferred the cluster display of the adaptive HMIs and even 32 the center stack concept of the Adaptive HMIs.

7.5 Discussion

The main goal of the present study was to gain further understanding of drivers' self-regulation and take-over performance when dealing with NDR-tasks and, particularly, to evaluate the impact of different HMI concepts on these variables.

First, the analysis of time critical onboard-based situations provided a valuable replication of the effects of NDR-task modalities on take-over performance and extended the findings of Study 2 and 3 to a new take-over situation. In the newly introduced narrow-zone scenario, drivers showed significant decrements in take-over performance when being engaged in the visual-manual (handheld) task compared to the auditory-vocal task. This included timing aspects (hands-on and take-over time) as well as quality metrics (higher accelerations, delayed lane change). It is important to note that these differences were found although the auditory-vocal task was increased in its cognitive demand compared to Study 2 and 3, reflected in the mental demand dimension of the NASA TLX (Fig. 7-4). However, the comparable number of collisions for the visual-manual and auditory-vocal task in the current study (3 vs. 2 collisions) might be interpreted in the sense that the cognitive component should not be neglected (see also Study 3). In this context, it should be considered that drivers tended to maintain their engagement in the auditory-vocal task even throughout take-over situations. Thus, drivers might possibly underestimate the distraction potential of the auditory-vocal task in comparison to the visual-manual task. The latter task was strictly canceled in take-over situations.

A newly introduced concept for highly critical take-over situations was an automatic braking application that was triggered simultaneously with the take-over request. This concept was implemented in Adaptive HMI 2 and executed in the onboard-based broken down car scenario when engaged in the visual-manual task. All but one driver showed a quick hands-on reaction. However, 4 of 12 drivers let the system perform the maneuver without their intervention and one driver even continued NDR-task engagement throughout the automatic braking maneuver. Hence, the effects of the automatic braking application are ambiguous. The braking maneuver was immediately applied and strong enough to prevent a collision with the broken down car. Thus, the situation was under control even if the drivers did not take over control quickly. However, as the driver is considered as the fallback level in highly automated driving, it would be desirable that the driver does not fully rely on the automatic maneuver. It might be more promising to use a staged warning concept to prevent complacency, i.e. beginning with an urgent take-over request (possibly with a brake jerk) and only applying the automatic emergency maneuver in the very last second to prevent a collision.

The server-based take-over situations, which could be anticipated with a comfortable lead time, allowed for an investigation of drivers' self-regulation over a larger time span. An interesting finding was that, although the system limit became visible 2.5 minutes in advance, drivers disengaged from the NDR-task not before reaching the 1 minute position. At this point in time the take-over notification was issued in the adaptive HMI groups. Results indicate a high effectiveness of the notification concept. Descriptive analyses found that drivers in the adaptive HMI groups increased their monitoring frequency after the notification, released themselves earlier from the NDR-task and switched faster to manual driving than the participants with the basic HMI. With the additional notification after 30 seconds (implemented in Adaptive HMI 2 when still engaged in the visual-manual task) all drivers took over vehicle control notably before the critical take-over request (lead time = 6 seconds) would have been issued. Similar to the onboard-based scenarios, the visual-manual task was canceled more strictly compared to the auditory-vocal task. The majority of drivers continued the auditory-vocal task when they received the take-over notification. In several cases the task was even further processed after the drivers had switched to manual driving.

In addition to the effects of the different HMI versions on driver behavior, also the subjective evaluations were of interest. All HMI versions showed very high usability, with the adaptive HMIs being only descriptively better. Participants' answers of the self-designed items suggest that the pre-defined requirements were mainly fulfilled by all HMI variants. However, the awareness of system limits was rated significantly higher for the adaptive HMIs than for the basic HMI. Acceptance ratings and trust in automation were also slightly (but not significantly) higher for the adaptive HMIs. The two adaptive HMI versions showed very similar subjective ratings in all discussed measures.

The drivers also rated the perceived usefulness of the different HMI elements. The preview screen was rated as particularly useful, but also the representation of the surrounding traffic situation (Adaptive HMIs) was appreciated by the drivers. In this context, it should be noted that the adaptive HMIs had, on a descriptive level, also higher ratings in transparency and drivers' awareness of the current traffic situation. Thus, if technically feasible, a graphical representation of the driving environment might provide advantages (see also Hergeth, 2016).

When considering objective and subjective data, it seems that the adaptive HMI concepts were overall beneficial compared to the Basic HMI. While there were only slight benefits in the subjective evaluations, the adaptive HMI concepts clearly supported NDR-task disengagement and monitoring behavior in server-based take-over situations. Based on the results of the current study, an explicit announcement of upcoming system limits (take-over notification) is highly recommended. This is in line with a study by van der Heiden, Iqbal, and Janssen (2017) where a pre-alert was also beneficial in terms of gaze behavior, NDR-task disengagement and take-over performance compared to a control group.

In addition, it should be noted that with a second notification (implemented in Adaptive HMI 2) all drivers in the current study took back vehicle control before the take-over request would have been issued. The second notification was adaptive to drivers' NDR-task engagement, namely it was only issued if the driver was still performing the visual-manual task. Further research should confirm if this driver-adaptive aspect is crucial, or if an unspecific second notification might lead to similar results without the need for a driver state monitoring system. In a study by Merat et al. (2014), predictable transitions with a regular time interval were associated with better driver performance compared to an adaptive concept based on drivers' glance behavior. In addition, cognitively demanding tasks might be distracting as well (e.g. Radlmayr et al., 2014; Study 3 of this thesis, chapter 6) and are hard to detect with current driver state monitoring systems. However, as static concepts will likely lead to an overall increased number of warnings, potential acceptance issues should also be considered in future studies.

Finally, some limitations of the current study should be taken into account. First, the study was conducted in a driving simulator, which might limit the transferability to real world driving. However, it can be assumed that the relative comparisons between experimental conditions are not affected in driving simulator settings ("relative validity"; Blaauw, 1982). Nevertheless, there might be changes over time in self-regulatory behavior and HMI evaluation when drivers become more familiar with the system, which could not be detected in the current study. It would be interesting for further research to investigate such long term effects, including the potential occurrence of complacency or system misuse (c.f. chapter 2.1.3).

7.6 Conclusion

This last study of the thesis focused on self-regulation and driver performance in predictable as well as non-predictable take-over situations in the context of highly automated driving. In addition, the impact of three different HMI concepts on these variables was assessed.

First, the study replicated the effects of NDR-task modalities on self-regulation and driver performance in non-predictable take-over situations and extended the results to the newly introduced narrow-zone scenario. This supports the generalizability of previous finding of Study 2 and 3.

Another emphasis of the study were the predictable server-based take-over situations, which provided a comfortable lead time for the driver. Drivers' self-regulation when nearing such situations was analyzed in detail. Overall, the adaptive HMI concepts including an explicit prealert ("notification") were beneficial in terms of NDR-task disengagement, monitoring behavior and timing of system deactivation.

Subjective ratings indicated a very good user experience for all HMI concepts. However, there were slight advantages for the adaptive HMI concepts that also included a graphical representation of the traffic situation. The findings of Study 4 might help to define requirements and possible implementations of comprehensive HMI concepts for future highly automated driving systems.

8 Synopsis & Discussion

The main goal of this thesis was to systematically investigate the impact of different NDR-tasks on take-over performance in highly automated driving. Of particular interest also was the role of drivers' self-regulation when dealing with NDR-tasks and how drivers can be supported by the HMI concept. Multiple resource theory was used as framework of this thesis (Fig. 8-1), under consideration of specific aspects of highly automated driving (c.f. chapter 3).

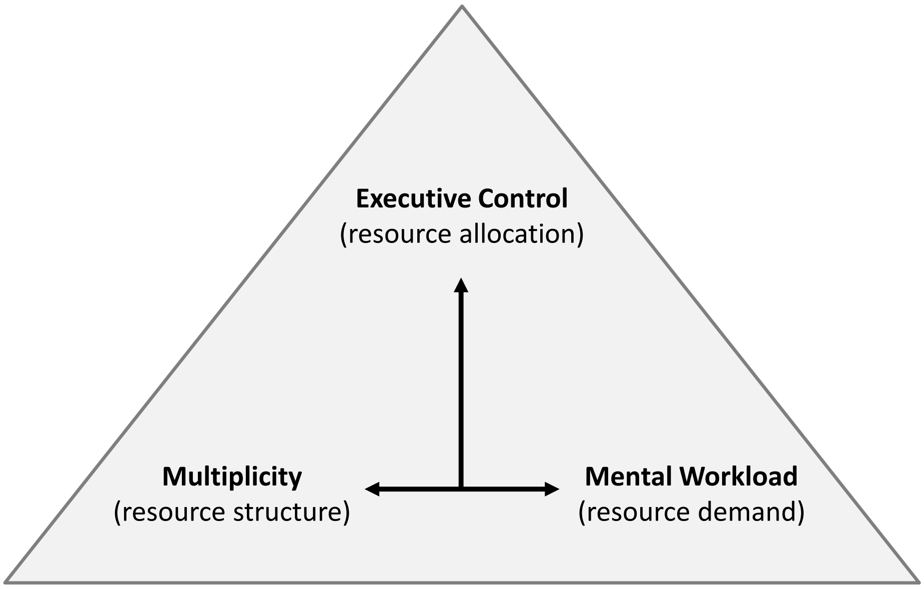

Fig. 8-1: Architecture of multiple resource theory (adapted from Wickens et al., 2013).

The first three simulator studies focused on the different components of multiple resource theory's architecture: resource structure, resource demand, and resource allocation (self-regulation). Based on the findings and an additional requirement analysis, different HMI concepts were developed and evaluated in Study 4.

8.1 Effects of Resource Structure (Multiplicity)

As discussed in chapter 3.1, multiple resource theory predicts performance decrements if two or more tasks require the same type of mental resources. This thesis focused on the impact of NDR-task modalities as they are main predictors for the amount of distraction in manual (e.g. Dingus et al., 2011; Louw et al., 2013) and partially automated driving (Spiessl & Hussmann, 2011). For this purpose, a model task was developed that enabled different stimulus and response modalities whilst keeping the task itself as constant as possible. In line with multiple resource theory, results of Study 2 to 4 indicated that visual-manual NDR-tasks, particularly when performed handheld, lead to the greatest interferences with the also visual-manual task of taking back vehicle control. Study 2 showed that take-over performance with an auditory-vocal task was comparable to a baseline without any task. Hence, it was used as the new baseline condition in Study 3 and 4, where the difference to the visual-manual handheld task was replicated and extended to other take-over situations.

All studies showed that the visual-manual handheld task particularly delayed the time until the hands were back at the steering wheel. Effects were also found for the even more safety critical take-over or brake response time, as well as quality metrics (e.g. min. TTC, accelerations, and number of collisions). According to Zeeb et al. (2015), the hands-on reaction can be considered as being mostly reflexive in nature. Thus, it can be assumed that mainly the motoric/effector interference led to delays in the hands-on time. The fact that also the non-reflexive take-over time was affected by the visual-manual (handheld) task might have two reasons. First, the visual task component might have delayed the perceptional processes needed to regain situation awareness which is the prerequisite to decide for the appropriate take-over maneuver. This assumption is supported by the fact that in Study 2 also the visual-vocal and visual-manual (mounted) tasks tended to delay the take-over time. Similar findings were obtained for the mounted texting task in Study 1. The second reason might be that for the handheld version of the task an additional cognitive demand arises, namely where to dispose the tablet computer. This could interfere with the also cognitive task of deciding for an appropriate take-over reaction (see also cognitive bottleneck theory; Pashler, 1994).

Although several effects of NDR-task modalities were found across the studies, it should be considered that some differences were relatively small in absolute numbers. For the take-over time (broken down car situation, time budget = 6 s) differences between mean values of visual-manual (handheld) and auditory-vocal task were 0.45 s (Study 2), 0.2 s (Study 3), and 0.38 s (Study 4). Given a vehicle speed of 120 km/h and comparable decelerations, this reflects an additional braking distance of 11.33 m for the visual-manual (handheld) task. For critical situations, as considered in this thesis, this can still make the difference for collision avoidance or mitigation. In addition, the difference was much higher for first contact with the situation (see Appendix, chapter 11.1) and when considering quantiles of the distribution in addition to the mean. Differences in the take-over time regarding 90 %-percentiles of visual-manual (handheld) and auditory-vocal task were 1.30 s (Study 2), 0.52 s (Study 3), and 1.81 s (Study 4).

8.2 Effects of Resource Demand (Mental Workload)

Besides the effects of resource overlap, multiple resource theory also suggests that task interference increases when a high amount of mental workload is required (= resource demand). This aspect was mainly addressed in Study 3 of this thesis. For this purpose, two versions of the visual-manual (handheld) task were implemented. The only difference was their cognitive demand in terms of task difficulty (repeating vs. alphabetizing given sentences).

Compared to a low demanding auditory-vocal task, hands-on times were significantly delayed for both versions of the visual-manual task. Mental workload had no influence on this first driver reaction as there were no differences between the two visual-manual tasks (low vs. high workload). Together with the results of Study 2, this finding further supports the hypothesis that mainly the motoric task component (i.e. occupation of hands) determines the hands-on time, with only small impact of cognitive distraction.

However, it seemed that visual-manual as well as additional cognitive load had an impact on the even more safety relevant take-over time. As discussed in section 8.1, visual distraction might mainly delay the perceptual processes in a take-over situation. Additional cognitive task demand might interfere with regaining situation awareness and also with decision making regarding the required take-over maneuver. However, it should be noted that in this study effects on take-over time were only marginally significant. In absolute numbers, the mean take-over time for the visual-manual task with low cognitive load was 2.24 s vs. 2.52 s for the high workload task. For both tasks, the 90 %-percentile was 4.0 s. Overall, the effects of task modalities / occupation of hands (section 8.1) seem to be slightly greater than the impact of cognitive load. However, this interpretation has to be viewed with caution, given the small sample size of Study 3. Further research is necessary to confirm this assumption and to generalize it to other sets of NDR-tasks as well as take-over scenarios.

8.3 Resource Allocation (Executive Control, Self-Regulation)

Drivers' self-regulation regarding NDR-tasks processing and take-over behavior was a relevant topic in all studies of this thesis. The results of Study 1 indicated the need to distinguish between different aspects of self-regulation, as suggested by Tab. 3-1. On the planning/decision level, drivers showed mostly appropriate self-regulation. When participants had the choice, they preferred NDR-task engagement in sections of highly automated compared to manual driving. In addition, when a preview display was present, drivers accepted less tasks prior to upcoming take-over situations. These results indicate that strategic and tactical self-regulatory behavior, as reported for manual driving (Wandtner et al., 2016; Schömig & Metz, 2013), also takes place in the context of highly automated driving. However, for the highly motivating task used in Study 1 (including a reward system) the absolute number of accepted tasks was still relatively high. Further research should address drivers' task management strategies for other kind of NDR-tasks and motivational conditions.

The other main class of self-regulation, namely NDR-task disengagement in take-over situations (control level in Tab. 3-1), was addressed in all studies of this thesis. The tasks associated with the highest impairments in take-over performance were also the tasks that were strictly canceled in critical take-over situations (Study 2 to 4). It can be assumed that drivers were overall aware of the current task demands and adapted their behavior accordingly. In particular, visual-manual tasks were perceived as highly risky (reflected in subjective ratings of perceived safety and workload) and these tasks were immediately canceled in reaction to a take-over request. This behavior can be considered as appropriate in terms of traffic safety.

In contrast, the fact that drivers tended to continue auditory-vocal tasks even throughout take-over situations allows for different interpretations. First, low demanding auditory-vocal tasks (as the task used in Study 2 and 3) are usually associated with only moderate risk increases compared to baseline (c.f. Dingus et al., 2016; Young 2014). Such kind of tasks (e.g. hands free cell phone or passenger conversations) are also not banned for manual driving. These aspects and the fact that take-over performance was not impaired in comparison to baseline (Study 2) are arguments to consider drivers' persistence in the auditory-vocal task as rather uncritical. However, in Study 4 a more difficult version of the task was used (also reflected in NASA TLX ratings) and still a substantial number of drivers persisted in the task during take-over. In addition, Study 3 found no adaptations of drivers' task disengagement regarding scenario criticality or cognitive workload. Further research is necessary to determine under which circumstances drivers might underestimate the risk associated with specific NDR-tasks and if countermeasures in terms of lockout approaches (Study 2) or legislation are required. Study 1, for instance, also showed that task pacing might be a crucial factor: For a system paced texting task, the level of task persistence tended to be higher than for the self-paced texting tasks used in Study 2 to 4. However, it has to be considered that also the take-over scenarios differed between these studies.

Study 4 showed that drivers' task disengagement is also highly influenced by the HMI concept. Drivers made use of a preview screen depicting the remaining distance to a system limit. However, without an explicit take-over notification (warning chime and speech output) a remarkably high number of drivers was still engaged in the task when the system limit was reached. Thus, drivers seem to benefit from explicit and staged warning concepts that support their self-regulatory behavior. Specific advantages of driver adaptive warning concepts need to be critically examined in further research (see also chapter 7.5).

8.4 Limitations

Some limitations have to be considered when interpreting the research findings of this thesis. Study specific limitations have been discussed in the related chapters. General limitations are outlined in the following.

First, all studies were conducted in a driving simulator, which might limit the transferability to real world driving. However, even if the absolute values might differ to the real world, relative comparisons between highly standardized experimental conditions are usually not compromised in driving simulator settings (providing "relative validity"; Blaauw, 1982).

Another limitation arises from the experimental designs applied in this thesis. Given the limitations in sample size, within-subject or mixed designs were used. On the one hand, the advantage of within-subject factors is that inter-individual variance can be controlled. On the other hand, learning effects have to be considered, although the order of experimental conditions was counterbalanced. It can be assumed that take-over reactions become faster and better with repetition (see first contact analysis in Study 2, chapter 5.4; Gold, 2016; Körber et al., 2016). Hence, the reported mean values for timing and quality metrics might underestimate the effects for new and completely unexpected take-over situations.

Finally, the participant samples of this thesis were limited to young and mid age drivers. The transferability of certain results to other age groups and different amounts of driving experience has to be confirmed in further research. However, results of studies by Petermann-Stock et al. (2013) and Körber et al. (2016) suggest that older drivers are able to cope with critical take-over situations as well as younger drivers, although their modus operandi might differ.

9 Conclusion

From a human factors perspective, level 3 automated driving (SAE International, 2014) can be considered as a promising but also very challenging step on the way to fully automated vehicles. Apart from technical challenges, psychological aspects are crucial for the development and evaluation of such systems. Bainbridge's (1983) "ironies of automation" seem to be particularly relevant for this intermediate level of automation, where the driver is relieved from continuous vehicle guidance/supervision, but required to be the fallback level when system limits occur and a take-over request is issued. An important aspect for human performance in such situations is the driver state that is highly influenced by the interaction with NDR-tasks.

This thesis systematically investigated the impact of NDR-task engagement on take-over performance in the context of highly automated driving systems. It could be shown that the architecture of multiple resource theory (Wickens, 2008; chapter 3.1 of this thesis) provides a useful general framework for psychological research in this field, including the components of resource structure, resource demand, and resource allocation (self-regulation). The experimental studies within this thesis showed that particularly visual-manual NDR-tasks with high motoric load (i.e. occupation of hands) were detrimental for drivers' take-over performance. Even though more research is certainly needed, a high amount of mental workload seems to further deteriorate drivers' ability to take over quickly and accurately.

Specific stages of human information processing were considered to explain these effects. It can be assumed that the hands-on steering wheel reaction is mainly reflexive in nature and primarily affected by an effector conflict when the hands are occupied (see also Zeeb et al., 2015; Ruscio, Ciceri, & Biassoni, 2015). Visual distraction can delay the perception of the current driving situation, and as serially achieved, also the resumption of situation awareness and decision making in terms of the required take-over maneuver. High mental workload, induced by the NDR-task, might directly interfere with the cognitive processes of regaining situation awareness and decision making. However, more fine-grained experimental settings, e.g. similar to the approach used by Levy et al. (2006) would be needed to verify these assumptions. In addition, NDR-task characteristics beyond information processing demands should be considered in further research. Task-switching research indicates that motivational conditions, already invested effort, and interruptibility might be relevant dimensions (Lee, 2014). In addition, the impact of the take-over scenario (e.g. criticality and complexity) and possible interactions should not be neglected.

Besides aspects of resource structure and resource demand, the role of resource allocation or self-regulation was also addressed in this thesis. As framework, a three level model of self-regulation was introduced (chapter 3.1.3). Study 1 showed that drivers adapted their decision to engage in NDR-tasks to the current driving mode as well as to the occurrence of predictable take-over situations (planning/decision level). NDR-task disengagement (control level) was subject to research in all four studies of this thesis. Overall, drivers seemed to be aware of the NDR-task specific amount of distraction. The tasks with the highest impairments of take-over performance were also strictly canceled in critical take-over situations. On the other side, system paced tasks seem to foster task perseverance (Study 1). In addition, there was a tendency to persist in auditory-vocal tasks, even when the mental demand of the task was rather high.

Several practical implications arise from the findings of this thesis. First, the reported performance decrements associated with specific types of NDR-tasks might help policy makers and regulators to decide for allowed and prohibited tasks during highly automated driving. However, there is already a high prevalence of distracting NDR-tasks in manual driving (Dingus et al., 2016; UDRIVE, 2017) even when they are illegal. Furthermore, drivers are likely to increase the frequency of task interactions in higher automation levels (see chapter 2.2.3). Thus, besides legal restrictions there is a clear need for well-matched technical solutions and HMI concepts to increase traffic safety.

Some possible requirements for future HMI concepts can be derived from the findings of this thesis. An overall goal should be to account for drivers' self-regulatory behavior and strive to facilitate it with the HMI strategy. Study 1 and 4 demonstrated that providing a preview of upcoming take-over situations can be beneficial in terms of NDR-task engagement as well as disengagement. However, without an explicit pre-alert (take-over notification) a high number of drivers was still engaged in the task when the system limit was reached. Hence, drivers seem to benefit from explicit and staged warning concepts that facilitate their self-regulatory behavior. It should be noted that these concepts are only applicable for predictable and planned transitions to manual driving (e.g. enabled by the usage of dynamic map data and car-to-x communication).

In urgent take-over situations, task lockout approaches might be implemented to support the driver. These approaches are applicable when the vehicle's infotainment system or coupled devices are used. Study 2 showed that such an HMI concept can speed up drivers' hands-on reaction. Based on this study, acceptance problems are unlikely to occur, at least for highly critical take-over situations. The technological advances in driver state monitoring systems might also allow for task adaptive HMI concepts when non-coupled devices are used or everyday tasks as interacting with passengers or reaching for objects are carried out.

Nevertheless, when the driver is not able to respond timely to an urgent take-over request, an automatic emergency maneuver should be executed. The simulator studies of this thesis showed that time budgets of six or eight seconds are not always sufficient for the driver to prevent a collision in critical take-over scenarios. Hence, it would be beneficial if the driver is not the only available fallback level in such time-critical situations.

Automated driving has been considered to increase comfort, driving efficiency, and traffic safety. However, it is still a long way to go until these goals might finally be achieved. It is the hope of the author that this thesis might provide a contribution to our understanding of human factors challenges associated with highly automated driving, as well as providing new pieces to the puzzle to leverage the potential of automated driving for future mobility.

10 References

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11 Appendix

11.1 Study 2: Additional Results

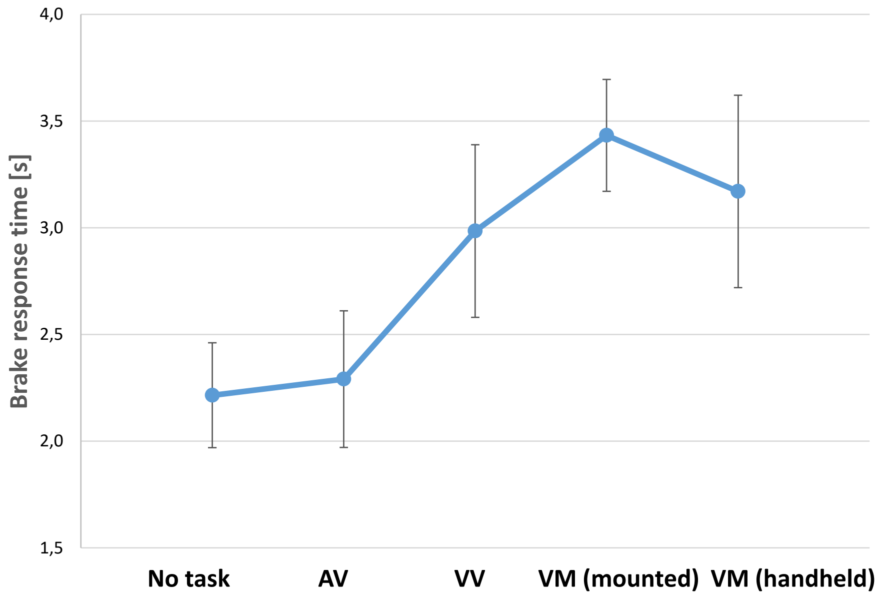

Fig. A1: Brake response time for first contact with the take-over situation (N = 6 for each NDR-task; AV = auditory-vocal, VV = visual-vocal, VM = visual-manual). Error bars represent the standard errors of the means.

11.2 Study 4: Additional Results

Focus groups: The following tables depict participants' information needs for the different system states (system available, system active, planned take-over, unplanned take-over). Overall, four focus groups were performed (two with experts, N = 5 and N = 6; two with non-experts, N = 3 and N = 2). For each information unit it is indicated how many of the groups agreed on this aspect. The order of information units in the tables reflects the rankings created by the participants at the end of each focus group.

Tab. A1: Information needs for "System available – ready to engage".

Information unit	No. of expert groups	No. of non-expert groups
Status information: system available	2	2
Estimated HAD duration / distance	2	2
Estimated system confidence	1	2
Information how the system can be activated	2	0
Onboard sensors: e.g. lead car and lane markings	1	1
Estimated travel speed for upcoming HAD section	1	0

Tab. A2: Information needs for “System active – regular driving“.

Information unit	No. of expert groups	No. of non-expert groups
Estimated HAD duration / distance	2	2
Status information: system available	2	1
Graphical representation of driving situation	2	1
Planned maneuvers	2	1
System confidence	1	1
Information how the system can be deactivated	1	0
Only speed indication, r.p.m. not needed in HAD	1	0
Deviation from target speed	0	1

Tab. A3: Information needs for “Planned take-over (Take-over notification)”.

Information unit	No. of expert groups	No. of non-expert groups
Early communication of upcoming take-over situation	2	2
Reason for the need to take back vehicle control	2	2
Distance / time left until take-over situation is reached	1	2
If possible: maneuver recommendation	2	0
Estimated duration / distance of manual driving section	1	1

Tab. A4: Information needs for “Unplanned take-over (Take-over request)”.

Information unit	No. of expert groups	No. of non-expert groups
Multimodal and urgent warning	2	2
Reason for the need to take back vehicle control	2	1
If possible: maneuver recommendation	2	1
System-initiated speed reduction	2	1
Escalating warning intensity over time	2	0

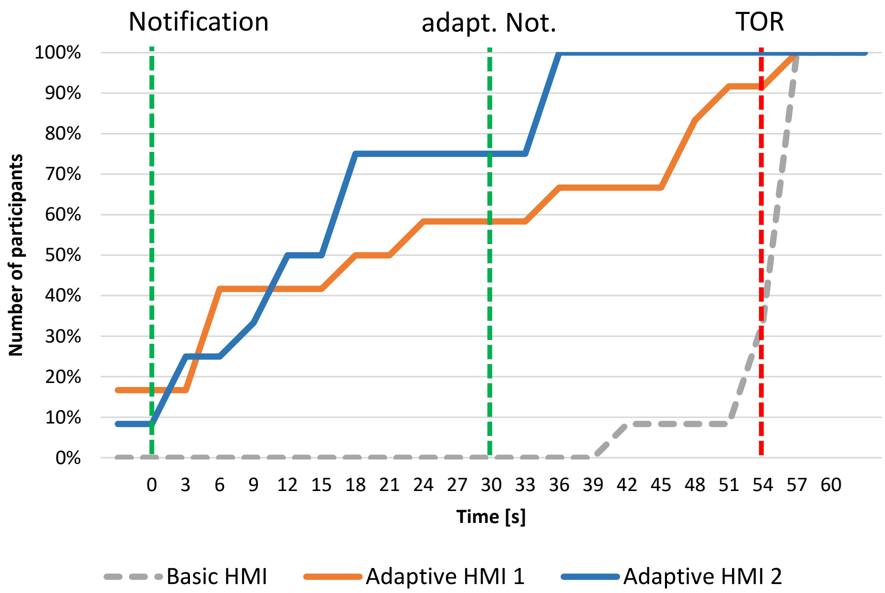

Fig. A2: Disengagement from the visual-manual task in the server-based narrow zone scenario.

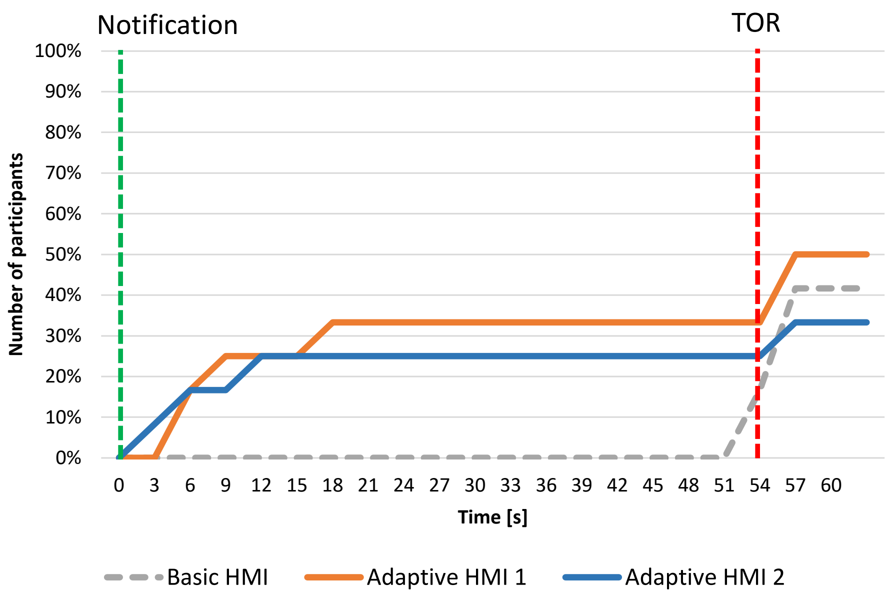

Fig. A3: Disengagement from the auditory-vocal task in the server-based narrow zone scenario.