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Non-driving related tasks in the context of Level 3 driving automation of passenger cars in traffic jams: A differentiation approach based on non-driving related tasks‘ characteristics

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Abstract

Driving automation systems of SAE Level 3 enable their users to engage in other non-driving related activities (SAE International, 2021), such as reading. Research indicates that non-driving related activities influence users' takeover behavior (Gold, Berisha, & Bengler, 2016). This thesis investigates how effects of non-driving related activities on takeover behavior and following manual driving behavior can be differentiated. The investigated differentiation approach is based on the psychological task switching paradigm that is applied to the context of Level 3 automated driving. The research questions address (1) which non-driving related activities users will engage in during a real Level 3 automated ride, (2) the overall effect size of non-driving related activities' influence on takeover behavior, and (3) how similarity in cognitive demands between a previous non-driving related activity and the driving task influence takeover behavior and following manual driving behavior.

Two Wizard-of-Oz studies and a meta-analysis were conducted to answer the research questions. Participants of the Wizard-of-Oz studies were told and assumed they were using a technical Level 3 driving automation system, while in fact a second driver was driving from the vehicle's rear. Participants' takeover behavior was assessed using quantitative metrics (e.g. accelerations, distances, time) and camera-based observation of participants' in-vehicle behavior. For the meta-analysis, takeover time was used as the indicator for takeover behavior.

Results show that higher similarity in cognitive demands of the non-driving related activity and the driving task benefits takeover time and time-to-collision (as an indicator for temporal and spatial distance to a forward collision). The effect sizes estimated in the meta-analysis also support a task switching based differentiation approach. Video analysis of participants' in-vehicle behavior during takeover indicates approaches for improvement of takeover procedures.

In summary, the differentiation approach based on task switching is able to differentiate between effects of non-driving related activities on takeover behavior and following manual driving behavior. The approach is not only applicable to standardized experimental tasks, but also applicable to natural activities. Differentiation is always relative and does not enable an absolute evaluation as "good/bad" or "suitable/unsuitable".

Zusammenfassung

Die Verwendung eines Automatisierungssystems nach SAE Level 3 (SAE International, 2021) ermöglicht es Nutzern erstmalig sich während der Fahrt mit fahrfremden Tätigkeiten zu beschäftigen, wie bspw. dem Lesen. Bisherige Forschung zeigt, dass fahrfremde Tätigkeiten das Übernahmeverhalten beeinflussen (Gold et al., 2016). In dieser Dissertation wird ein Ansatz zur Differenzierung von fahrfremden Tätigkeiten untersucht. Grundlage des Differenzierungsansatzes bildet das psychologische Task Switching Paradigma. Dieses wird auf die Übernahmesituation bei Level 3 Automatisierung angewendet. Die Forschungsfragen beziehen sich (1) auf die Art der fahrfremden Tätigkeiten, die Nutzer ausführen, (2) auf die allgemeine Effektgröße der Wirkung von fahrfremden Tätigkeiten auf das Übernahmeverhalten, und (3) auf die Wirkung von Ähnlichkeit der kognitiven Anforderungen zwischen einer fahrfremden Tätigkeit und der Fahraufgabe auf das Übernahmeverhalten und anschließende manuelle Fahrverhalten.

Zur Beantwortung der Forschungsfragen wurden zwei Wizard-of-Oz Studien und eine Metaanalyse durchgeführt. In den Studien wurde das Nutzerverhalten während einer Level 3 automatisierten Fahrt in einem Wizard-of-Oz Fahrzeug in Realfahrten untersucht. Während die Probanden auf dem Fahrersitz davon ausgingen, ein technisches Automatisierungssystem zu verwenden, fuhr tatsächlich ein zweiter Fahrer im Fond. Das Übernahmeverhalten der Probanden wurde gemessen mittels quantitativen, fahrbezogenen Maßen (z.B. zeitliche Komponenten, Beschleunigung, Abstände) als auch mittels kamerabasierter Beobachtung des Fahrerverhaltens im Fahrzeuginnenraum. In der Metaanalyse diente die Übernahmezeit als quantitatives Maß für das Übernahmeverhalten.

Die Ergebnisse zeigen, dass größere Ähnlichkeiten in den kognitiven Anforderungen der fahrfremden Tätigkeit und der Fahraufgabe zu Vorteilen in Übernahmezeit und Kollisionsnähe führen. Auch die Metaanalyse weist Effektstärken auf, die auf Basis des Task Switching Paradigmas angenommenen Teilprozesse unterstützen. Des Weiteren lassen sich aus der Beobachtung des Fahrzeuginnenraums Verbesserungsansätze für das fahrerseitige Übernahmeverhalten ableiten.

In der Gesamtschau erweist sich der untersuchte Ansatz zur Differenzierung von Effekten fahrfremder Tätigkeiten auf das Übernahmeverhalten und anschließende manuelle Fahrverhalten als nützlich. Dies gilt nicht nur für standardisierte Aufgaben im Experimentalkontext, sondern auch für nicht standardisierte, natürliche Tätigkeiten. Die Differenzierung ist stets relativ zu anderen fahrfremden Tätigkeiten und ermöglicht keine absolute Bewertung nach „gut / schlecht“ oder „geeignet / ungeeignet“.

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1. Introduction

With increasing sustained driving automation, the role for the person on the driver's seat changes. Today's driver assistance systems are categorized as Level 1 or Level 2 systems (SAE International, 2021). For systems of both levels, the driver is still responsible for the driving task so that she/he is not allowed to simultaneously engage in other non-driving related activities (Bundesanstalt für Straßenwesen, 2020). In contrast, a Level 3 system takes over the entire driving task when it is activated. Meanwhile, the person on the driver seat switches from a driver to a "fallback-ready user" (SAE International, 2021). That means she/he is relieved from driving, and can engage in non-driving related activities. Crucially, the Level 3 system has system limits (SAE International, 2021). When approaching these limits, the Level 3 system requests the user to continue driving (SAE International, 2021; UN Regulation No. 157, 2021). As a fallback-ready user, the person on the driver's seat is required to respond to this request by deactivating the system and continuing the ride as the driver again (SAE International, 2021; UN Regulation No. 157, 2021).

From a human factors perspective, this takeover situation is crucial for a safe design of Level 3 driving automation, and ultimately road safety. In this context, this dissertation addresses the effects of non-driving related activities that are performed during Level 3 automated driving phases, on following takeover behavior and subsequent manual driving behavior. Specifically, this thesis addresses Level 3 driving automation in traffic jams on highways. That is because at the beginning of this dissertation in 2018, announcements by OEMs and regulation activities suggested that the operational design domain of the first Level 3 driving automation systems will be traffic jams on highways. Respective systems are available today at the end of the dissertation. A first type approval for a vehicle equipped with a Level 3 driving automation system has recently been granted by the German Federal Motor Transport Authority (Kraftfahrt-Bundesamt, KBA, 2021).

This dissertation focuses on the moment of a system-initiated takeover in the context of Level 3 automated driving under normal/routine operation (SAE International, 2021). The aim is to find a differentiation approach for non-driving related activities based on their effects on subsequent takeover and driving behavior. This dissertation makes use of theories and empirical findings of task switching from cognitive psychological research to explain and predict takeover behavior and following manual driving behavior.

Chapter 2 explains SAE Level 3 driving automation including the relevant role for the human user in detail. Chapter 3 focuses on transitions from SAE Level 3 automated driving to manual driving. Chapter 4 addresses non-driving related activities during SAE Level 3 automated driving and how their effects on takeover and manual driving behavior are explained so far. This indicates a research gap for which chapter 5 offers a theoretical basis for differentiation between non-driving related activities. Chapter 6 summarizes the research questions of this dissertation. Chapter 7 provides an overview on general methodical decisions overarching this dissertation. Chapter 8 offers brief overviews on the two main publications included in this cumulative dissertation and an adjunct publication. Chapter 9 provides a general discussion on the dissertation with its implications on theory and practice, a methodical discussion, and an outlook on future research.

2. Level 3 automated driving

This dissertation follows definitions of the Society of Automotive Engineers International (SAE International) Standard J3016 (SAE J3016, 2021) and regulations on Level 3 automated driving provided by UN Regulation No. 157 (2021, UN R157). Furthermore, this dissertation focuses on system-initiated takeovers under routine/normal operation of SAE Level 3 driving automation functions, as defined by SAE J3016 (2021) and ISO TR 21959-1, in German road traffic.

This chapter provides the technical definition of SAE Level 3 automated driving (section 2.1), the human's responsibilities when using Level 3 driving automation functions in road traffic (section 2.2), and current regulation regarding operation of SAE Level 3 driving automation systems in German road traffic (section 2.3). The chapter focuses on the aspects that are relevant to the dissertation.

2.1. Technical definition of Level 3 automated driving

Generally, driving automation functions (SAE International, 2021; Shi, Gasser, Seeck, & Auerswald, 2020) can influence vehicle guidance (Donges, 1982, 2016) either

- indirectly by informing or warning the driver who then takes action on vehicle guidance eventually (Principle of Operation A),
- directly and on a sustained basis (Principle of Operation B), or
- directly and temporarily in accident-prone situations only (Principle of Operation C).

For sustained driving automation functions which correspond to Principle of Operation B (Shi et al., 2020), SAE J3016 (2021) provides a classification concept. Functions of Principle of Operation A or C are not within scope of SAE J3016. Consequently, SAE J3016 does not imply presence or absence of any of these Principle of Operation A or C functions. SAE J3016 defines six levels of sustained driving automation from Level 0 to Level 5. They are explained in the following with a focus on Level 3.

SAE Level 0 describes the absence of sustained driving automation functions. At this level, a human driver performs the entire dynamic driving task.

Functions of SAE Level 1 and Level 2 are available today as driver assistance systems. These functions support the driver in executing the dynamic driving task and operate on a sustained basis. Functions of SAE Level 1 can either support the lateral or longitudinal vehicle motion control. An example is adaptive cruise control (ACC). Functions of SAE Level 2 can support both lateral and longitudinal vehicle motion control. An example is the combination of adaptive cruise control and a lane-centering lane keeping assist (LKA). Both Level 1 and Level 2 functions can neither reliably detect the vehicle’s environment nor reliably react to it (SAE International, 2021). The human driver is required to monitor the environment, supervise the system and correct the system when needed.

In contrast to SAE Level 1 and Level 2 functions, SAE Level 3 functions execute the lateral and longitudinal vehicle motion control, and reliably perform the object and event detection and response (OEDR) within their respective operational design domain (ODD). Consequently, Level 3 driving automation functions execute the entire dynamic driving task on a sustained basis within their ODD. Outside their ODD, Level 3 systems cannot be activated. Conversely, when the system is active and the end of the ODD is approaching, Level 3 systems issue a timely request to intervene (see also chapter 2.2 on regulation) with the expectation that their fallback-ready human user will take over the driving task (SAE International, 2021).

Functions of SAE Level 4 execute the lateral and longitudinal vehicle motion control, reliably perform the OEDR and reliably achieve a minimal risk condition within their respective ODD. In contrast to Level 3, no fallback-ready user is expected. All occupants are passengers who are not required to contribute to driving at any time while the SAE Level 4 function is active.

Functions of SAE Level 5 are similar to Level 4, but have an “unlimited” (SAE International, 2021, p. 26) ODD. The “unlimited” ODD is defined as “on-road anywhere within its [refers to the vehicle operated by the Level 5 function] region of the world and under all road conditions in which a conventional vehicle can be reasonably operated by a typically skilled human driver." (SAE International, 2021, p. 32). Like SAE Level 4, all occupants are passengers who are not required to contribute to driving at any time while the SAE Level 5 function is active.

This dissertation focuses on "routine/normal ADS operation" as defined by SAE J3016:

"*Operation of a vehicle by an ADS [automated driving system] within its prescribed ODD [operational design domain], if any, while no DDT [dynamic driving task] performance-relevant system failure is occurring.*
NOTE: Routine/normal ADS operation includes vehicle responses to objects and events that are safety- and time-critical, as well as vehicle responses to the same that are not safety- and time-critical." (SAE International, 2021, p. 19)

2.2. New user role during SAE Level 3 automated driving

The German Federal Highway Research Institute (BASt) differentiates three roles for users of different driving automation systems. These roles are accompanied by different sets of responsibilities. In the following, first, an overview over all roles will be given. Next, the user role during Level 3 automated driving will explained in detail.

Table 1: Overview on users' roles in the context of sustained driving automation

Role of human	SAE Level of the driving automation system	Visualization
Driver role	SAE Levels 1 & 2	
(fallback-ready) User role	SAE Level 3	
Passenger role	SAE Levels 4 & 5	

Note. Figures for visualization by German Federal Highway Research Institute (Bundesanstalt für Straßenwesen, 2021).

From SAE Level 0 to Level 2, the human driver remains responsible for the driving task, irrespective of support provided by SAE Level 1 or Level 2 functions. Because functions of SAE Level 1 and Level 2 cannot provide reliable OEDR, drivers permanently need to monitor the environment, supervise the system and correct the system immediately if needed. Accordingly, recently published user communication concepts allocate the **driver role** to these three levels (Bundesanstalt für Straßenwesen, 2020; Shuttleworth, 2019) (see also Figure 1). Engagement in non-driving related activities might violate drivers' responsibilities and is secondary relative to performing the driving task. From a psychological perspective, if the driver engages in non-driving related activities, the situation can be described as multiple task performance (with driving task and non-driving related activity performed concurrently).

Driving automation functions of SAE Level 4 and Level 5 do not require a driver anymore. While the vehicle is operated by a SAE Level 4 or Level 5 function, any person inside the vehicle becomes a **passenger** and does not need to contribute to driving at any point in time. Users are familiar with the passenger role from public transportation, for example.

This dissertation focuses on SAE Level 3. Driving automation functions of SAE Level 3 introduce a new user role to road traffic. After the driver activates the Level 3 driving automation function, the Level 3 function performs the entire driving task including the OEDR, and the former driver is relieved from the driving task and becomes a **fallback-ready user** (Bundesanstalt für Straßenwesen, 2020; SAE International, 2021; Shuttleworth, 2019). The fallback-ready user may engage in other non-driving related activities, as long as she or he remains receptive to requests by the Level 3 driving automation function and other evident malfunctions that impair the performance of the dynamic driving task, e.g. burst tyre (§ 1b Abs. 2 StVG; SAE International, 2021). Upon such a request or malfunction, the fallback-ready user needs to take over the driving task again or achieve a minimal risk condition (SAE International, 2021).
In general (SAE International, 2021; ISO/TR 21959-1, 2020; §1b Abs. 2StVG), takeovers from the Level 3 system can be

- requested by the Level 3 system (system-initiated takeover), or
- voluntarily initiated by the user (driver-initiated takeover, also called "optional human-initiated transition" according to ISO/TR 21959-1) or
- necessary because of a technical malfunction that impairs performance of the dynamic driving task (failure-initiated takeover, also called "mandatory human-initiated transition" according to ISO/TR 21959-1).

This dissertation focuses on *system-initiated* takeovers under *routine/normal operation* (cf. section 3.26 in SAE International, 2021) of SAE Level 3 driving automation functions. The fallback-ready user's *receptivity* is a frequently misunderstood concept that shall be addressed separately in the following: SAE J3016 defines receptivity as "An aspect of consciousness characterized by a person's ability to reliably and appropriately focus his/her attention in response to a stimulus." (SAE International, 2021, p. 18). It should be highlighted that in the definition of "receptivity", a stimulus is premised that evokes an attentional response by a person. As such, "receptivity" is similar to the psychological concept of *exogenous (spatial) attention*, i.e. "attention to a given spatial location determined by "involuntary" mechanisms triggered by external stimuli (e.g., loud noise)" (Eysenck & Keane, 2010, p. 633). Besides exogenous attention, there is also *endogenous (spatial) attention*, i.e. "attention to a given spatial location determined by voluntary or goal-directed mechanisms" (Eysenck & Keane, 2010, p. 633). Receptivity is frequently misunderstood as a form of attention that is goal-directed rather than a "response to a stimulus" (SAE International, 2021, p. 18). That means receptivity is frequently misunderstood as endogenous attention rather than exogenous attention. Outside classification, exogenous attention also applies to specifications in § 1b Abs. 2 StVG. Attentional mechanisms are not the focus of this dissertation, and are described herein only to thoroughly describe the human user's role during Level 3 automated driving and the involved cognitive mechanisms.

A user who blocks his/her sensory systems from perceiving a system request or evident vehicle or system failures would violate his/her responsibility to remain receptive (e.g. see 5.1). For instance, a Level 3 system is very likely to use the user's auditory and visual sensory system to communicate a request to intervene. When the user closes his/her eyes for a long period of time, it is likely that the user will not be able to perceive the request to intervene. This may constitute a violation of the user role. Analogous to the normal/routine operation of the driving automation, this dissertation assumes compliant user behavior.

2.3. SAE Level 3 systems in German road traffic

Before referring to operation of SAE Level 3 systems in German road traffic, the difference between the concepts *function*, *system* and *vehicle* is explained briefly: The *vehicle* is the entity that may comprise multiple automation functions and systems that address different layers of the driving task as well as different Principles of Operation (see chapter 2.1; Shi et al., 2020). *Systems* are those bundles of functions that are offered to customers by automakers, e.g. "Autopilot" offered by the automaker Tesla. For classification purposes, a system is broken down into its functions that take effect on vehicle guidance, e.g. Autopilot includes i.a. a Principle of Operation B, Level 2 driving automation function with ACC and lane-centering LKA, and a Principle of Operation C emergency braking system. By describing the functions that constitute a system, the system can be described more accurate. As a consequence, classification concepts are applied to functions instead of systems or entire vehicles. For reasons of easier readability and notation, in the following, the system whose major component is a Level 3 driving automation function (e.g. "Drive Pilot" by Mercedes-Benz) will be referred to as "Level 3 system" instead of a "system comprising a Level 3 function".

While SAE Standard J3016 provides definitions of sustained driving automation, UN Regulation No. 157 provides international requirements for approval of Level 3 driving automation systems that are operated in road traffic. In this regard, UN Regulation No. 157 specifies more details in terms of the realization of Level 3 systems compared to SAE J3016. Type approval for Level 3 systems in Germany is based on UN Regulation No. 157, too. Aspects from this regulation that are relevant to this dissertation, are highlighted in the following. For further details, please see UN Regulation No. 157 (2021)[1].

UN Regulation No. 157 specifies where the Level 3 driving automation system can operate the vehicle, which is:

> *"on roads where pedestrians and cyclists are prohibited and which, by design, are equipped with a physical separation that divides the traffic moving in opposite directions and prevent traffic from cutting across the path of the vehicle. In a first step, the original text of this Regulation limits the operational speed to 60 km/h maximum and passenger cars (M 1 vehicles)."*

In Germany, these conditions are typically found on the highway ("Autobahn"). Considering the maximum vehicle speed of 60 kph, these conditions are typically found in traffic jams.

From a human factors perspective, the lead time with which the Level 3 system needs to issue a request to intervene is of great interest. UN Regulation No. 157 requires a Level 3 system to provide the fallback-ready user at least 10 seconds time for taking over the driving task after onset of the request to intervene. In case the user does not respond

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[1] available online: https://unece.org/sites/default/files/2021-03/R157e.pdf (lastly checked January 6th, 2023). Please note, this thesis is based on the 2021 version of UN Regulation No. 157 that was in preparation when this dissertation started. Recently, UN Regulation No. 157 was updated, now including a speed limit to 130 kph and lane changes (see: https://unece.org/sites/default/files/2022-05/ECE-TRANS-WP.29-2022-59r1e.pdf, lastly checked January 6th, 2023)

to the request to intervene, the system shall initiate a minimum risk maneuver earliest 10 seconds after the onset of the request to intervene. This is a major difference between the UN Regulation No. 157 and SAE J3016. Although UN Regulation No. 157 requires a minimal risk maneuver, this does not change the regulated Level 3 system into a SAE Level 4 system. The minimal risk maneuver required by UN Regulation No. 157 shall be executed after the Level 3 driving automation phase in case the expected takeover by the driver does not take place. In contrast, at no point in time, does a SAE Level 4 driving automation function expect a human driver to contribute to driving or to perform a minimal risk maneuver. Instead, by definition a SAE Level 4 function is capable of reliably achieving a minimal risk condition within its ODD. From the perspective of classification, the additional minimal risk maneuver required by UN Regulation No. 157 can be regarded as an additional Principle of Operation C function (Shi et al., 2020) outside the ODD of the SAE Level 3 function, but included in the same system. SAE J3016 refers to this "minimal risk maneuver" by UN Regulation No. 157 as a "failure mitigation strategy" (defined in section 3.11 of SAE J3016 (2021), see also section 8.6. ibidem). Based on UN Regulation No. 157, the worldwide first type approval for a vehicle equipped with a Level 3 system has recently been granted by the German Federal Motor Transport Authority (Kraftfahrt-Bundesamt, 2021).

Analogous to definitions by SAE J3016, in Germany, § 1b Abs. 2 StVG ("Straßenverkehrsgesetz", German road traffic act) requires the fallback-ready user to take over vehicle motion control in case of obvious circumstances that the driver must have detected and that hinder appropriate use of the automated driving function, e.g. burst tyre (see also chapter 2.2 on user role in Level 3).

3. Transition from Level 3 to Level 0

At the end of a Level 3 automated driving phase in traffic jams on the German Autobahn, the driving task is transferred from the Level 3 driving automation system back to the human driver. To ensure that this takeover proceeds safely, not only technical aspects related to the driving automation system need to be considered, but also human aspects.

3.1. Transition model for system-initiated takeovers

Marberger et al. (2018) first proposed a transition model that was later incorporated into ISO/TR 21959-1 (2020). ISO/TR 21959-1 differentiates two directions of transitions of vehicle motion control:

(1) transitions from the human driver to the driving automation system and

(2) transitions from the driving automation system to the human driver.

This dissertation addresses case (2) transitions of vehicle motion control from a driving automation system (specifically a Level 3 driving automation system) to manual driving. For this transition process, Figure 1 shows the transition model by ISO/TR 21959-1 applied to Level 3 automated driving. Definitions of the model's most relevant concepts for this dissertation are given in the following, and applied to Level 3 automated driving.

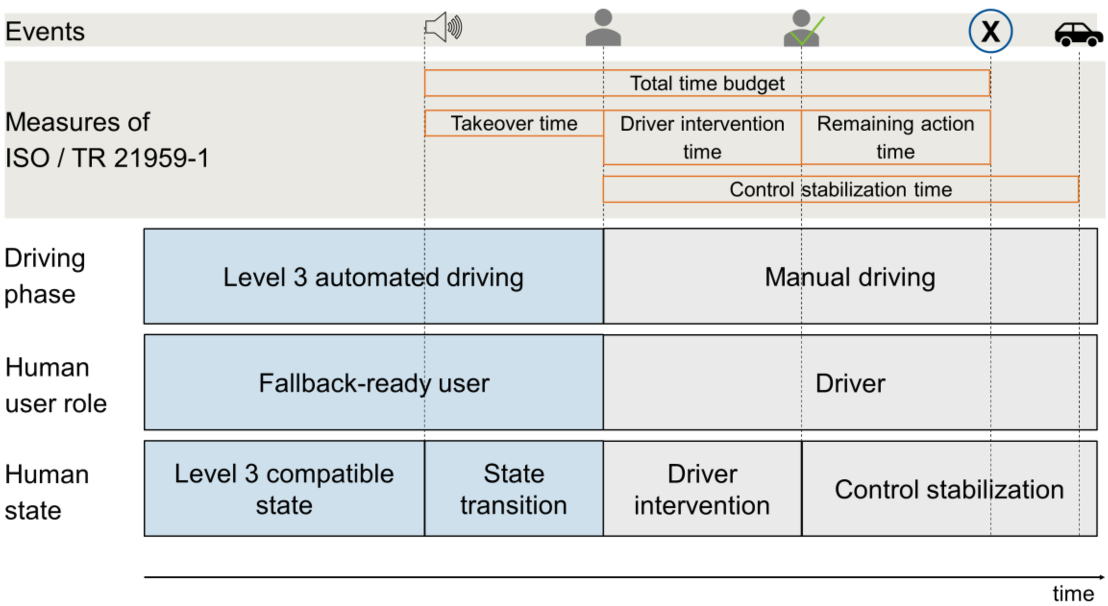

Figure 1: Transition model for system-initiated transitions from an automated driving phase to a manual driving phase ISO/TR 21959-1 (2020) applied to the takeover situation from Level 3 automated driving to manual driving. Legend for symbols: Level 3 driving automation system issues a request to intervene. user deactivates the system. driver completes a manoeuer. system limit of the Level 3 driving automation system. driver has fully stabilzed vehicle motion control.

The transition model (ISO/TR 21959-1, 2020) reflects different states for the driving automation system and the human driver or user over time. The transition model starts with an active Level 3 driving automation phase and assumes routine/normal operation. During this time the human user of the Level 3 system is in a state that is accepted by the automation system. When the system initiates a request to intervene, the driver state transition begins. The human user changes to the driver role upon deactivation of the driving automation system. Figure 2 depicts the driver state transition in further detail. The deactivation is carried out by "significant driver intervention to resume manual control" (ISO/TR 21959-1, 2020, p. 7) that is dependent on the respective system design (basic requirements are provided in UN Regulation No. 157). After the user deactivates the system, the post transition phase begins that is divided into a phase of driver intervention and a control stabilization phase. In experimental studies, the quality of the manual driving is frequently examined during the post transition phase (see also chapter 3.2, for quality measures related to takeover see also Table 3).

Besides measurement of driving quality, timing measures are included in the transition model. The *takeover time* (see also chapter 3.2, for operationalizations of takeover time see also Table 2) is the "time interval between onset of RtI [request to intervene] and user-initiated intervention or deactivation of an engaged automation function" (ISO/TR 21959-1, 2020, p.8). It is assumed that the *driver state transition* takes place during this time interval.

The driver state transition describes the "process of transforming the actual driver state (possibly affected by NDRA) to a target driver state suitable to effectively take-over manual control. This process can be analyzed on a sensory, motoric and cognitive level." (ISO/TR 21959-1, 2020, p. 7). For the thesis at hand, the "driver state" in Level 3 needs to be referred to as the user state since the human user does not perform the driving task anymore while the Level 3 system is active. The terminology is adapted accordingly in the following. In this dissertation, the "driver state transition" by Marberger et al. (2018) is applied to Level 3 automated driving. It describes the transition from a "current user state" to a "target driver state" (see Figure 2). In general, the driver and user state consists of the sensory, motoric and cognitive state, the arousal level and motivational conditions. According to the model (Marberger et al., 2018), the non-driving related activity performed during Level 3 automated driving influences the current user state. Requirements of the takeover situation influence the target driver state. Prior training, education and experience with the driving automation system influence both states and the transition process (Marberger et al., 2018).

This dissertation especially focuses on the user's and driver's cognitive state without fully excluding the sensory and motoric states. The arousal level and motivational conditions are outside the scope of this thesis.

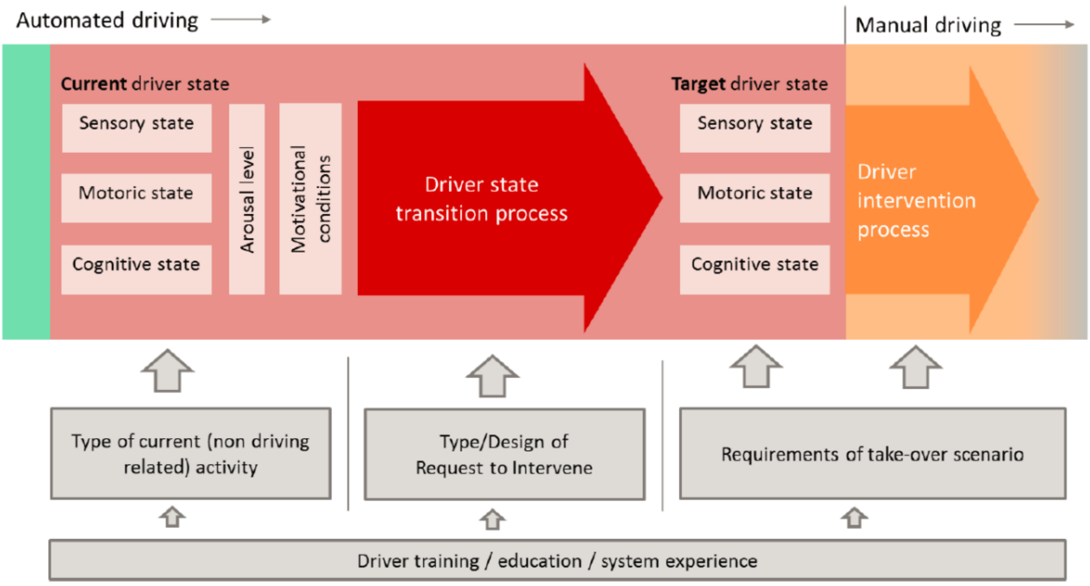

Figure 2: Driver state transition model for Level 3 automated driving (Marberger et al., 2018)

3.2. Current research on transitions

The moment the fallback-ready user takes over the driving task, she or he becomes the driver again, and affects road traffic. The relevance of the takeover situation for road safety has sparked intensive research on users' takeover behavior (for review see Jarosch, Gold, et al., 2019; for meta-analyses on effects of non-driving related tasks on takeover behavior see Weaver & DeLucia, 2020; B. Zhang, de Winter, Joost C F, Varotto, Happee, & Martens, 2019). To describe takeover behavior, different parameters are used that also depend on the experimental setup in which the takeover behavior was investigated. In the following the major experimental setups and parameters are described.

3.2.1. Parameters for takeover behavior

The term takeover behavior is chosen in this dissertation in order to distinguish it from the takeover performance. Both terms are commonly used. The term *takeover performance* has been associated with the degree to which a takeover has been successfully performed by the driver (Feldhütter, 2021). The evaluation of "success" requires a-priori defined pass-fail-criteria (Cao et al., 2021; Damböck, Farid, Tönert, & Bengler, 2012) to allow differentiation between "successful" and "not successful" takeovers. This dissertation does not focus on assessing the absolute success of takeover behavior. Rather this dissertation aims at differentiating non-driving related tasks based on their effects on takeover. This takes a relative perspective on takeover behavior which does not require defining "successful" and "not successful" takeovers. Therefore, in order to distance from the connotation of evaluating a takeover's "success", the term *takeover behavior* will be used instead of the term *takeover performance*.

Takeover behavior is usually described in terms of timing and quality (Gold, 2016). Typical **timing measures** are listed in Table 2. Usually, the onset of the Level 3 system's request to intervene marks the beginning of the timing measurement. The end of the driver takeover time measure is defined by the deactivation of the system (Marberger et al., 2018). The behavior that marks the deactivation of the Level 3 system is defined differently across studies. Table 2 shows the most commonly used timing measures and operationalizations.

Table 2: Definitions of timing measures

Interaction	**Definition**	**Studies**
Eyes on road	Coded via video labelling	Zeeb, Härtel, Buchner, & Schrauf, 2017
	Eye-tracking measured from start fame of request to intervene to end frame of first gaze to road center	Vogelpohl, Gehlmann, & Vollrath, 2020
	Via eye-tracking measured as first fixation of road center	Vogelpohl, Kühn, Hummel, Gehlert, & Vollrath, 2018
Hands on steering wheel	Steering wheel angle > 2°	Jarosch, Bellem, & Bengler, 2019; Louw, Merat, & Jamson, 2015
	First contact of hands with steering wheel via video labelling	Zeeb et al., 2017
	First touch of brake pedal	Jarosch, Bellem, & Bengler, 2019

Interaction	Definition	Studies
Foot on brake or acceleration pedal	Brake pedal >10°	Feldhütter, Hecht, Kalb, & Bengler, 2018; Gold et al., 2016; Jarosch, Kuhnt, Paradies, & Bengler, 2017; Körber, Gold, Lechner, & Bengler, 2016; Radlmayr, Brüch, Schmidt, Solbeck, & Wehner, 2018; Radlmayr, Fischer, & Bengler, 2018; Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Wan & Wu, 2018; Wintersberger, Riener, Schartmüller, Frison, & Weigl, 2018
Combinations of hands on steering wheel and feet on brake/acceleration pedal	Brake pedal >10° or steering wheel angle >2°	Feldhütter et al., 2018; Jarosch et al., 2017; Körber et al., 2016; Radlmayr et al., 2014; Radlmayr, Fischer, & Bengler, 2018; Wan & Wu, 2018
	Brake pedal > 10 % and 2° steering wheel angle	Gold et al., 2016; Gold, Damböck, Lorenz, & Bengler, 2013
	2° steering wheel angle or 5° brake/acceleration pedal	Wintersberger et al., 2018
	Hands on completely steering and interaction with either 5° steering wheel rotation or brake pedal (not further defined)	Yoon & Ji, 2019
	Deactivation of system by pulling levers or standardized brake pedal travel ≥10% or steering wheel angle velocity ≥10°/s	Zeeb et al., 2017
	Steering wheel turn or foot pedal press (without further definition)	Köhn, Gottlieb, Schermann, & Krcmar, 2019
	Deactivation of system by steering wheel button, braking pedal travel >10% or steering wheel angle >4°	Wandtner, Schömig, & Schmidt, 2018a
	Resume manual control by pedals, steering wheel or de-	Dogan, Honnêt, Masfrand, & Guillaume, 2019

Interaction	Definition	Studies
	/activation handle (without further definition)	

Another source of information are takeover quality measures, although not all studies that investigate takeover behavior, report quality measures. Typical **quality measures** are dependent on the respective takeover situation (see Table 3). For example, when the situation requires to evade an obstacle on the ego-lane by changing the lanes (Gold et al., 2016), it is of interest to describe both participants' lateral and longitudinal vehicle motion control. Assume the adjacent lanes are blocked by other traffic participants, then braking is the only maneuver left to avoid a collision (Wandtner et al., 2018a). In this case, to differentiate takeover quality, participants' longitudinal vehicle motion becomes more informative over lateral vehicle motion. Similarly, for a situation in which a vehicle is cutting in in front of the ego-vehicle and decelerates strongly (Zeeb et al., 2017), participants' longitudinal vehicle motion control may be of greater interest. In addition, the described situations all involve obstacles. In these cases, distances to the obstacle are informative regarding takeover quality (e.g. minimum time-to-collision). For situations without an obstacle (e.g. Zeeb et al., 2017), measures on distances are not informative. Generally, low maximum acceleration and large time-to-collision values are assumed to indicate safer takeover and driving behavior (Gold et al., 2016). Because takeover quality measures depend on the respective traffic situation, there is no established single general measure that is regarded suitable to evaluate takeover quality in any situation.

Table 3: Definitions of takeover quality measures

Information on	Measure	Studies
Participants' general reaction to request to intervene	Reaction type (e.g. steering only/ braking only/ steering and braking; stopping/ loss of control/ lane change; steering/ braking/ accident)	Jarosch & Bengler, 2019; Wang & Soffker, 2019; Zeeb et al., 2017
	Percentage of participants who checked the driving environment before starting a maneuver	Feldhütter et al., 2018
Collision avoidance / proximity of collision	Number of collisions	Radlmayr et al., 2014; Wandtner et al., 2018a; Wandtner, 2018; Wang & Soffker, 2019
	Minimum time-to-collision	Bourrelly et al., 2019; Dogan et al., 2019; Feldhütter et al., 2018; Gold et al., 2016; Radlmayr et al., 2014; Radlmayr, Fischer, & Bengler, 2018; Wandtner et al., 2018a
Longitudinal vehicle motion control	Minimum longitudinal acceleration / maximum deceleration	Feldhütter et al., 2018; Gold et al., 2016; Jarosch, Bellem, & Bengler, 2019; Radlmayr et al., 2014; Radlmayr, Fischer, & Bengler, 2018; Wandtner et al., 2018a; Wandtner, 2018
	Maximum longitudinal acceleration	Gold et al., 2016
	Standard deviation of speed in m/s	Dogan et al., 2019
	Minimum distance to lead vehicle in meters	Zeeb et al., 2017
	Minimum time gap to lead vehicle in seconds, minimum time headway between two vehicles	Dogan et al., 2019; Zeeb et al., 2017
Lateral vehicle motion control	Minimum lateral acceleration	Gold et al., 2016
	Maximum lateral acceleration	Feldhütter et al., 2018; Gold et al., 2016; Jarosch, Bellem, & Bengler, 2019
	Standard deviation of lateral position	Naujoks, Purucker, Wiedemann, & Marberger, 2019; Radlmayr, Fischer, & Bengler, 2018; Vogelpohl et al., 2018; Wandtner, Schömig, & Schmidt, 2018b
	Percentage of lane exceedances: Percentage of time slices, where at least one wheel was out of lane	Dogan et al., 2019
	Lane change speed in m/s	Dogan et al., 2019
	Standard deviation of steering wheel angle	Naujoks et al., 2019

Information on	Measure	Studies
Combination of lateral and longitudinal vehicle motion control	Maximum acceleration potential based on lateral and longitudinal accelerations	Gold et al., 2013; Wandtner et al., 2018b

3.2.2. Experimental setups to investigate human-machine-interaction

Studies investigating takeover behavior aim at drawing conclusions on future road traffic and road safety. To approximate the real traffic setting, driving simulators are mostly used (Weaver & DeLucia, 2020; B. Zhang et al., 2019). Simulated experimental setting provides participants with a physically safe environment which allows researchers to investigate experimental conditions irrespective of traffic situations' criticality. Furthermore, simulation enables, or at least facilitates, investigating conditions with low probability of occurrence in real traffic. At the same time, driving simulation leads to discussions on the validity of simulated rides as well as results and inferences drawn from application of driving simulation (Kaptein, Theeuwes, & van der Horst, 1996). Starting from fixed based driving simulators, several points of criticism have been addressed technically. For instance, missing vestibular feedback during the simulated ride is artificially added in motion-based driving simulators (e.g. used by Radlmayr et al., 2014). Virtual reality has been used (e.g. by Taheri, Matsushita, & Sasaki, 2017) to approximate a more realistic driving environment compared to screen-based projection of the driving environment (e.g. Köhn et al., 2019). Despite technological advancements in driving simulation, its inherent difference to real driving settings calls for validation studies (e.g. Bellem et al., 2017) on the one hand side. For others, this difference cannot be ruled out by validation studies and remains a point of discussion.

One aspect of the driving simulator setup that might be difficult to address even with advanced technological solutions is the participants' awareness of being physically safe irrespective of own actions. This may lead to behavior that is different from the on-road setting. As an alternative to driving simulators, the Wizard-of-Oz method has been used to provide participants with a real driving setting and at the same time investigating future automation technologies by simulating these specifically (Müller, Weinbeer, & Bengler, 2019). The Wizard-of-Oz method is realized by a second driver that simulates the driving automation system. The specific setup varies between studies. In some Wizard-of-Oz vehicles the second driver ("wizard driver") is seated in the passenger seat and operates the vehicle using control devices integrated into the armrest (Naujoks et al., 2019). Other researchers use a right-hand drive vehicle where the wizard driver operates the series driver's workspace while the participant is seated on the passenger seat on the left and operates dummy steering wheel and pedals (Scheiter, Linnemann, Herbst, & Bengler, 2020; Weinbeer et al., 2017). In another setup the wizard driver is hidden from participants and seated in the rear of the vehicle (Klamroth, Zerbe, & Marx, 2019).

Generally, the Wizard-of-Oz method provides participants a real driving situation, and as long as a cover story is provided, participants are likely to not notice that the automated driving system is simulated by the wizard driver. Therefore, the Wizard-of-Oz method may provide an experimental Level 3 automated driving setting of high external validity without exposing the participant to potential risks by untested driving automation systems. For this reason, in the studies conducted in this dissertation the Wizard-of-Oz method is applied.

Applying the Wizard-of-Oz method also has consequences for the measures used to describe takeover behavior. While generally, the commonly used measures can be assessed, some characteristics gain importance. For instance, when measuring participants' takeover time in the Wizard-of-Oz vehicle, it is important to not measure the time interval until actual deactivation of the system, but until the participant presses the button for deactivation. This is because it is the wizard driver who eventually deactivates the system after the participant presses the button for deactivation. If the time interval until actual deactivation is measured as the takeover time, the wizard driver's reaction time enters the takeover time measure as a confounding variable. Therefore, using the Wizard-of-Oz vehicle requires particular emphasis to measure takeover time as the time interval between the onset of the request to intervene and the driver action that deactivates the system (and not until actual system deactivation).

4. Non-driving related activities during Level 3 automated driving

While Level 3 automated driving functions perform the driving task, users may engage in other non-driving related activities (NDRAs). In the experimental context non-driving related *tasks* (NDRTs) have been used to infer effects of natural non-driving related activities on takeover behavior. In this dissertation, the term "task" is used for the experimental research context where participants are usually instructed to perform specific tasks for experimental purposes instead of performing natural activities by own choice. The term “activity” is used for the real world context where natural behavior throughout a Level 3 automated driving phase might not be limited to performance of a defined single task.

4.1. Non-driving related activities users choose to do

Before analyzing the effects of non-driving related activities on road safety, the range of potentially performed non-driving related activities is of interest. In Germany, automakers define the intended use of a given system which includes the range of non-driving related activities allowed for the user to perform while the system is active. This requires automakers to differentiate non-driving related activities in terms of their effects on road safety. The need to differentiate non-driving related activities’ effects on road safety strongly motivates research in this field. Researchers have investigated the range of non-driving related activities users would engage in by applying multiple-choice survey formats (Pfleging, Rang, & Broy, 2016; Schoettle & Sivak, 2014). Multiple choice formats require researchers to prepare a list of activities from which participants are asked to choose. Therefore, results from multiple-choice surveys cannot exclusively reflect the activities that users will engage in, but rather, are always mixed with researchers’ expectations. Another approach to investigate the range of potentially performed non-driving related activities is observing participants’ uninstructed behavior while they use Level 3 driving automation. Since Level 3 driving automation systems were not available yet, the method of observation has been applied in driving simulator studies (Hecht, Feldhütter, Draeger, & Bengler, 2020; Large, Burnett, Morris, Muthumani, & Matthias, 2017). Other researchers have prioritized users’ natural behavior over an accurate Level 3 driving automation setting by observing natural behavior of passengers in public transportation (Pfleging et al., 2016). However, from a user’s perspective, public transportation rather matches characteristics of SAE Level 4 or Level 5 driving automation because passengers are at no point in time required to contribute to driving or to remain fallback-ready. In contrast, SAE Level 3 driving automation functions require users to remain fallback-ready in order to be able to respond to both a system-initiated request to intervene and evident malfunctions with relevance to performance of the dynamic driving task (see chapter 2.2, § 1b Abs. 2 StVG, SAE International, 2021). This dissertation approaches the question of what users of Level 3 driving automation will do during automated driving, using the Wizard-of-Oz method to simulate Level 3 driving automation in a real driving setting. This may provide further insights into validity of existing results derived from the various methods (cf. publication 1: Shi & Frey, 2021).

4.2. Effects of non-driving related tasks on takeover behavior

Performing non-driving related activities during active Level 3 automated driving phases can influence takeover behavior directly and indirectly via effects on fallback-ready user's state.

Influences of non-driving related tasks on fallback-ready users' state have been investigated in dissertations by Wehlack (2019), Frey (2021) and Feldhütter (2021). Their research shows that during Level 3 automated driving, development of fatigue due to cognitive underload and monotony can be reduced by engaging in non-driving related activities. Monotonous non-driving related activities, however, can promote development of fatigue (Jarosch, Bellem, & Bengler, 2019). The fallback-ready user's state becomes relevant to road safety as soon as the user needs to take over the driving task again. Fatigued drivers are expected to show exacerbated takeover and driving behavior compared to drivers who are awake and attentive (Frey, 2021).

This dissertation's focus lies on the *direct influences* of non-driving related tasks on takeover behavior. These have been investigated in multiple studies that have been summarized in reviews (e.g. Jarosch, Gold, et al., 2019) and meta-analyses (Soares, Lobo, Ferreira, Cunha, & Couto, 2021; Weaver & DeLucia, 2020; B. Zhang et al., 2019). In summary, research shows that non-driving related tasks that are visually demanding or that require user's hands, prolong takeover time compared to non-visual and non-handheld non-driving related tasks (Weaver & DeLucia, 2020; B. Zhang et al., 2019).

4.3. Approaches to explain effects of non-driving related tasks

Jarosch, Gold, et al. (2019) categorize non-driving related tasks by their sensory (especially visual), motoric, cognitive, arousal and motivational characteristics (cf. Marberger et al.'s (2018) criteria for driver and user state, see chapter 3.1). The authors describe the range of literature per category and point out a very diverse range of literature, with non-driving related tasks seemingly having less pronounced effects on takeover than expected. Furthermore, the authors emphasize the methodological differences between the studies. Indeed, a meta-analysis by B. Zhang et al. (2019) shows that besides characteristics of non-driving related tasks, takeover time is influenced by factors such as urgency of the situation, prior experience of a takeover scenario, and the sensory modalities of a request to intervene. It should be noted that in this meta-analysis primary studies were included that investigated Level 2 *or* Level 3 driving automation. This can be deemed critical because Level 2 and Level 3 driving automation are associated with different roles for the in-vehicle human driver or user (see chapter 2.2). In a meta-analytical context, this problem is often referred to as the "apples and oranges problem" (e.g. Carpenter, 2020; Cortina, 2003).

Another approach to summarize effects of non-driving related tasks is found in a meta-analysis by Weaver and DeLucia (2020) which highlights the task switching paradigm underlying the Level 3 takeover situation. Interestingly, while acknowledging the task switching paradigm, Weaver and DeLucia (2020) use Wickens' multiple resources theory (2002, 2008) as their theoretical basis. According to Wickens (2002, p. 159) "Multiple resource theory is a theory of multiple task performance". Its application to a task switching situation can be challenged.

Human factors researchers in the automotive section traditionally come from manual (SAE Level 0) or assisted driving (SAE Level 1 and Level 2) settings, where the driving task always constitutes the primary task for the human driver (see Figure 3a). For these use cases, engagement in any non-driving related activity needs to be treated secondary compared to the driving task, as long as road safety is given priority. Wickens (2002) illustrates multiple task performance using a driving example where the human driver is in charge of the driving task:

> "*Driving along a crowded highway on a rainy evening, while trying to glance at the map and search the road side for the right turn off, the driver's cellular phone suddenly rings. The driver feels compelled to answer it and engage in conversation with the caller. Will the driver be successful?*" (Wickens, 2002, p. 159)

Against this background, it appears comprehensible to remain with the multiple task performance theory that has been successfully applied to secondary task engagement so far. With SAE Level 3, however, the role of the human driver changes fundamentally. After activation, the entire driving task is performed by the Level 3 system. This relieves the driver from the driving task and leads to a change in his or her role. As a fallback-ready user, she/he may perform non-driving related activities as their primary task while the system is active. Upon a request to intervene or upon noticeable failure, the user needs to take over the driving task again (see Figure 3b). This takeover situation has been described as a task switching setting by multiple authors (Hecht, Kratzert, & Bengler, 2020; Jaussein et al., 2021; Marberger et al., 2018; Naujoks et al., 2019; Weaver & DeLucia, 2020; Zeeb et al., 2017). Nevertheless, even in the context of Level 3 automated driving, "the predominantly used model (…) is Wicken's multiple resources theory"

(Jaussein et al., 2021, p. 14). Chapter 5 addresses this gap and describes this dissertation's theoretical basis as a suggestion to solve the outlined discrepancy.

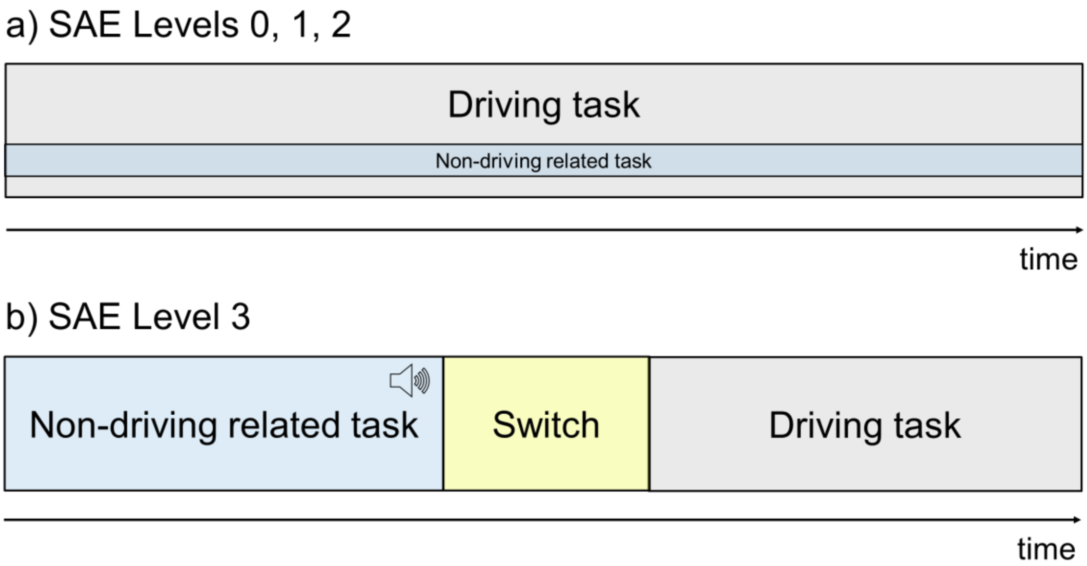

Figure 3: Performing non-driving related activities while driving. **a)** Level 0, 1 or 2 systems do not relieve the driver from driving. Performing non-driving related activities during SAE Level 0, 1, 2 leads to multiple task performance (the primary task is the driving task, and the non-driving related activity is the secondary task, given road safety is prioritized). **b)** Level 3 systems relieve the driver from driving. Performing non-driving related activities during SAE Level 3 leads to a task switching situation. Speaker symbol indicates a request to intervene issued by the Level 3 system.

5. Theoretical basis to differentiate non-driving related activities

In this chapter the gap outlined above in chapter 4.3 will be addressed first. Next, task switching theory from basic cognitive research is applied to the context of system-initiated takeovers in Level 3 automated driving. This forms the psychological theoretical basis of the dissertation.

5.1. Task switching and multiple task performance in current literature

On the one hand, researchers refer to the task switching paradigm to describe the psychological demands of the takeover situation in Level 3 automated driving (Hecht, Kratzert, & Bengler, 2020; Marberger et al., 2018; Naujoks et al., 2019; Zeeb et al., 2017). On the other hand, to explain and predict effects of non-driving related tasks on subsequent takeover and driving behavior, theories stemming from multiple task performance (e.g. Wickens, 2002) are still used (see chapter 4.2).

Multiple task performance theories, such as multiple resources theory by Wickens (2002, 2008), have been very useful to explain and predict effects of secondary task performance at previous levels of automation. As Figure 3 shows, for manual and assisted driving up to SAE Level 2, the driving task resides with the driver at all times, irrespective of potentially provided driving assistance by respective systems. In consequence, any engagement in non-driving related activities needs to be considered secondary relative to the primary driving task (see Figure 3a). SAE Level 3 changes this traditional driver role fundamentally. As described in chapter 2.2, in contrast to previous levels of driving automation, the former driver becomes a user who is relieved from the driving task when the system is active. Hence, engagement in non-driving related activities may become the user's primary activity (see Figure 3b). Nonetheless, SAE Level 3 systems will require the user to take over the driving task at the end of the system's domain. When the request to intervene is issued, the user needs to switch from the non-driving related activity to the driving task both physically and mentally. In cognitive psychological terms, the demands of this moment resemble those of a task switching paradigm (Hecht, Kratzert, & Bengler, 2020; Jaussein et al., 2021; Naujoks et al., 2019; Zeeb et al., 2017).

The task switching paradigm is characterized as follows: "In task-switching experiments, participants perform a discrete task on each trial. On some trials the task changes (switch trials), and on others it does not (repeat trials)." (Kiesel et al., 2010, p. 849). The major finding from research on task switching is the *switching cost* or *switch cost.* This cost refers to "increased reaction time and error rate on the trial following a switch of task." (Monsell & Driver, 2000, p. 16). In Level 3 automated driving, task switching takes place at the end of the Level 3 automated driving phase. Figure 4 compares the task switching trial of laboratory experiments to the task switching situation in Level 3 automated driving. Figure 5 depicts task switching in the course of a system-initiated transition from Level 3 automated driving to manual driving.

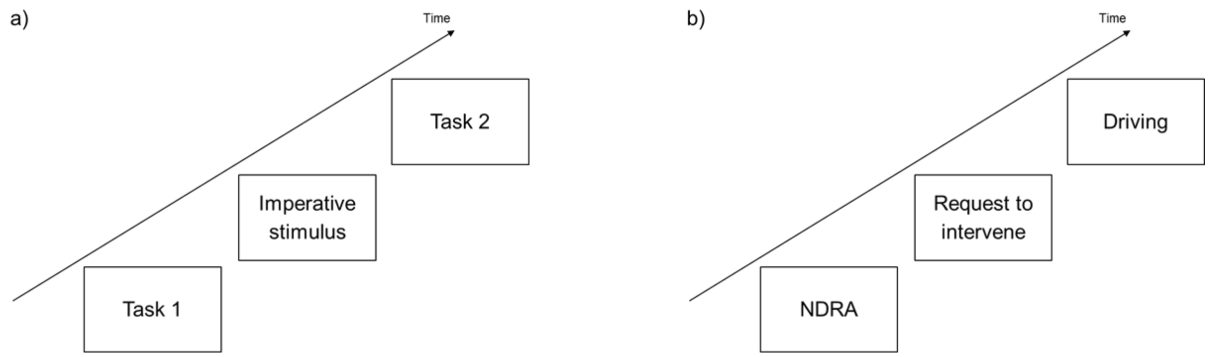

Figure 4: a) Schematic representation of a typical switching trial in a laboratory experiment. b) Schematic representation of switching in the context of takeover in Level 3 automated driving

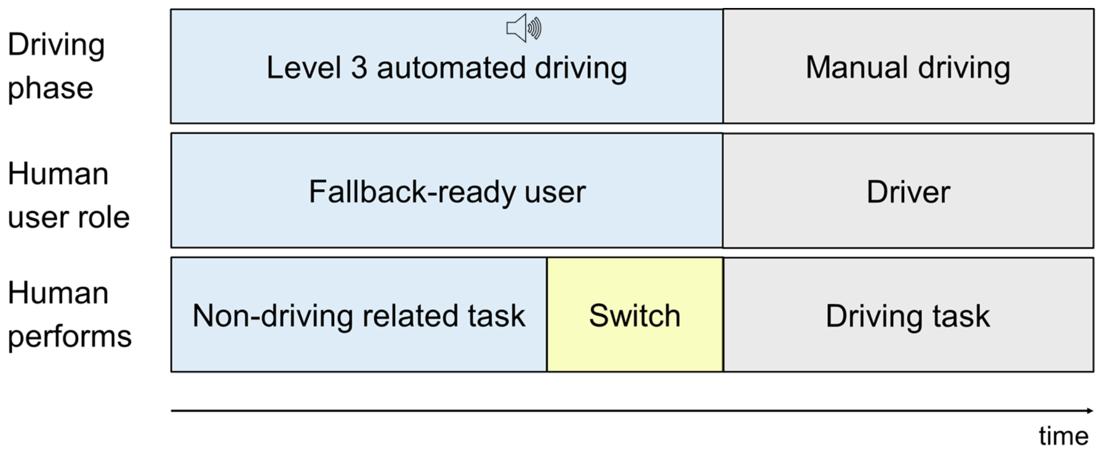

Figure 5: System-initiated transition process at the end of Level 3 automated driving in terms of human user roles and task switching. Speaker symbol marks the onset of the request to intervene. While the Level 3 system is active, the human is in the role of the fallback-ready user and may engage in non-driving related tasks. When the Level 3 system issues a request to intervene, the fallback-ready user needs to switch into the driver role. This is accompanied by switching from a non-driving related task to the driving task. After the fallback-ready user deactivated the Level 3 system, she/he continues the ride in the role of the driver.

In Level 3 automated driving, the non-driving related activity constitutes the first task and the non-driving related activity constitutes the second task. By definition and regulation, the fallback-ready user is required to resume manual control again after request by the system. Therefore, the second task is always the driving task, and only the first task (i.e. non-driving related activity chosen by the user) may vary. In the task switching paradigm an imperative stimulus calls for a switch of task or no switch. In Level 3 automated driving, the Level 3 system's request to intervene calls for switching from a non-driving related activity to the driving task. It should be highlighted that the user of a Level 3 driving automation system knows the second task in advance, i.e. the user is aware that she/he must switch to the driving task after perceiving the request to intervene, although the specific demands of the driving task depend on the respective driving situation at hand. In terms of task switching, this means the user can prepare for the switch in advance.

Literature usually draws on multiple task performance theories to explain and predict effects of non-driving related activities on following takeover behavior. Their potential, however, is limited and may conceal relevant confounding of experimental setups. For instance, in their meta-analyses, Weaver and DeLucia (2020) and B. Zhang et al. (2019) identify visual non-driving related tasks and non-driving related tasks that need to be held in the hands to increase takeover time (Weaver & DeLucia, 2020; B. Zhang et al., 2019). However, with regard to effects of visually demanding tasks, it needs to be noted that primary studies usually involve a task that requires the visual sensory system and a task that does not require the visual system (e.g. Gold et al., 2016; Wandtner et al., 2018a; Zeeb et al., 2017). For example, Wandtner et al. (2018a) investigated effects of different task modalities by using the same non-driving related task in different modalities. Participants were always provided with a sentence which they had to repeat. In the auditory condition, participants listened to the sentence, and had to repeat the question orally. In the visual condition, the sentence was presented in written format on a tablet computer, and participants had to read the sentence aloud. Results indicate numerically higher takeover times and larger times-to-collisions for the visual condition compared to the auditory condition (Wandtner et al., 2018a). This indicates that participants deactivated the system earlier and evaded a broken-down vehicle on the ego-lane with a greater distance. Referring back to the meta-analytical conclusion that visual demanding activities delay takeover, the actual manipulations in the primary studies need to be taken into account. Especially, if the aim is to draw inferences on the influence of non-driving related *activities* occurring in natural automated driving settings, comparing an experimental task that requires the visual sensory system, with another task that does not require the visual sensory system, is not sufficient for the following reasons: First, if the visual sensory system is not required for the instructed non-driving related task, it does not exclude the possibility that the visual system processes other stimuli that are not related to the instructed task, but e.g. related to the passing scenery. In consequence, participants still engage their visual sensory system on a non-driving related activity, although not on the instructed non-driving related task. Second, solely based on the aforementioned operationalization, it cannot be concluded that a task's visual demand *causes* an increase in takeover time. Rather, the alternative explanation that visual perception of the driving environment during Level 3 automated driving phase *accelerates or facilitates* takeover upon a request to intervene cannot be ruled out. This alternative explanation is salient when task switching theory is applied instead of multiple task performance theory. In order to draw inferences on the consequences of a non-driving related task's visual demand, the alternative explanation needs to be excluded in the experimental design. For instance, participants need to be prevented from visually perceiving the driving environment in both conditions and not only in the condition involving the "visually demanding" non-driving related task. This could be achieved by the occlusion method for example (ISO 16673, 2017). Occlusion prevents participants from visually perceiving driving related stimuli before the request to intervene. In this case, the task's visual demand can be argued to cause a delay, instead of prior visual perception of the driving environment being an advantage for takeover. Hence, the alternative explanation of facilitation by prior perception of the driving environment would be excluded. However, to the author's knowledge this was not set as a criterion in the respective meta-analysis. Therefore, the overall conclusion on a task's visual demands needs to be treated with caution (Weaver & DeLucia, 2020; B. Zhang et al., 2019).

Referring back to the experimental setup of preventing participants' visual perception generally suggested above, this setup is only suggested for experimental purposes and to disentangle different theories since a solid theoretical basis benefits drawing informed inferences in practice. Considering practical requirements, a user who blocks his/her sensory systems from perceiving a request by the system would violate his/her responsibilities as the fallback-ready user (see chapter 2.2).

5.2. Task switching in takeover situations at SAE Level 3

A task switching approach to the takeover situation at the end of a Level 3 automated driving phase may increment insights into effects of non-driving related tasks on following takeover and manual driving behavior. This dissertation applies theories and empirical findings from task switching and modality shifting research to the field of Level 3 driving automation. The aim is to extend currently explainable and predictable effects of non-driving related activities on takeover and manual driving behavior. First, the switch cost (as defined in chapter 5.1) will be transferred to the Level 3 automated driving context. Next, a recognized task switching theory to explain switch costs will be presented (see 5.2.1.2) and applied to Level 3 automated driving (see 5.2.3).

5.2.1. Switch costs in Level 3 automated driving

As defined in chapter 5.1, switch costs describe a relative performance decrement in terms of reaction time and error rates when two consecutively performed tasks are different (switch trial) compared to same (repeat trial). Basic psychological research further indicates that switch costs can be reduced when switching between similar tasks compared to switching between dissimilar tasks (Arrington, Altmann, & Carr, 2003). This finding is applied to effects of non-driving related activities on takeover behavior in the context of Level 3 automated driving.

In Level 3 automated driving, it is by definition not possible for the human driver to perform the driving task before and after the request to intervene[2]. That is because Level 3 driving automation systems perform the entire driving task within their operational design domain. That means, before the request to intervene, the human user is excluded from the driving task, and after the request, she/he is required to perform the driving task. Thereby, the takeover situation always represents a switch trial. Yet, research on non-driving related tasks' effects on takeover suggests differences among "switch trials" in terms of following takeover behavior. This gives rise to the assumption that the "switch trials" in Level 3 automated driving are not a homogenous group of trials, but can be further differentiated.

In fact, there is basic psychological research on "similarity effects in task switching" where "task similarity was defined as shared attentional control settings (Experiment 1) or shared response modality (Experiment 2)" (Arrington et al., 2003, p. 786). At the same time, the Arrington et al. (2003) note that "the construct of similarity in cognitive psychology is controversial and has been defined in various ways" (Arrington et al., 2003, p. 783). Their results show reduced switch costs for switches between similar tasks compared to switches between dissimilar tasks, which suggests "facilitation of task switching when tasks are similar" (Arrington et al., 2003, p. 784).

5.2.1.1. Similarity between tasks

To assess similarity between a non-driving related activity and driving task, in the context of this dissertation, the working memory theory by Baddeley is used (Baddeley & Hitch, 1974; Repovs & Baddeley, 2006). Baddeley's working memory theory suggests modality-specific cognitive modules for maintaining and processing information (Baddeley & Hitch, 1974; Repovs & Baddeley, 2006): The phonological loop holds and processes auditory information, the visuo-spatial sketchpad holds and processes visual and spatial information. Later research, however, suggests that the visuo-spatial sketchpad might

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[2] This refers to driving the ego-vehicle on the road in the real world. In a virtual reality, the user could engage in a driving game during the automated driving phase, unrelated to the ego-vehicle.

consist of two modules processing visual and spatial information separately, instead of one module that processes both visual and spatial information (Klauer & Zhao, 2004; Logie & van der Meulen, 2009; Smith & Jonides, 1997). The working memory components postulated in Baddeley's working memory theory constitute the criteria to describe similarity in cognitive demands between the non-driving related activity and the driving task. Visual and spatial demands are coded separately after considering the aforementioned research. When the non-driving related activity and the driving task involve the same working memory components, they are regarded as similar in terms of their cognitive demands.

5.2.1.2. Considering modalities: Modality shifting effect

Choosing a modality-specific working memory model as the basis for assessing similarity between tasks takes into account another line of research that shows costs associated with modality shifting without changing the task (Spence, Nicholls, & Driver, 2001). Originally, Spence et al. (2001) investigated effects of expecting a target in the wrong modality. As a seminal secondary finding of their experiment, they found the modality shifting effect in their control condition. Spence et al. (2001) observed faster reaction times when the current and the preceding targets were presented in the same modality compared to different modalities (cf. Table 3 in Spence et al., 2001, p. 333). The modality shifting effect was found for targets of any modality (visual, auditory, tactile). The study by Spence et al. (2001) initiated a notable amount of research on the modality shifting effect replicating the effect in various samples and under various conditions (Gondan, Lange, Rösler, & Röder, 2004; Pecher, Zeelenberg, & Barsalou, 2004; Poole, Miles, Gowen, & Poliakoff, 2021; M. Zhang, Wu, & Wang, 2021). The modality shifting effect was not only found on a perceptual level for targets presented in different sensory modalities (e.g. target presented in auditory, tactile or visual modality, Spence et al., 2001). It was also found on a conceptual level (Pecher et al., 2004) for targets that are all presented visual-verbally as written words, but differ in conceptual modality (e.g. sweet candy, green leaves, Pecher et al., 2004).

5.2.2. The stage model of executive control for task switching

Literature on effects of non-driving related tasks on takeover behavior in the context of Level 3 automated driving usually cites Monsell (2003), if any, when referring to task switching (Weaver & DeLucia, 2020; Zeeb et al., 2017). In task switching research, two theoretical approaches have traditionally competed to explain task switching phenomena: the task-set reconfiguration approach by Rogers and Monsell (1995) and the task set inertia approach by Allport, Styles, and Hsieh (1994). Referring to Monsell (2003) only, might therefore turn a blind eye on the competing approach. Since there is evidence for both approaches, more recent theories tried to integrate the two competing approaches. With over 950 citations in Web of Science, Rubinstein, Meyer, and Evans (2001) proposed and established a *stage model of executive control for task switching*. This model assumes two processes: executive control processes and task processes.

Task processes involve those cognitive, perceptual and motoric processes that are needed to work on a task. They take place whenever working on a task. Hence, task processes are not specific to task switching paradigm. They are further differentiated into the three stages of *stimulus identification*, *response selection*, and *movement production*. At the stage of *stimulus identification*, a task's stimulus characteristics are perceptually encoded and made accessible for the next stage of response selection (involving declarative working memory). At the stage of *response selection*, the previously encoded characteristics are translated into abstract motoric codes (involving procedural working memory) for the next step of generating a motoric response. At the stage of *movement production*, the abstract motoric codes are translated into motor instructions to execute a movement in response to the perceived stimulus.

Executive control processes are specific to switching and include the two stages *goal shifting* and *rule activation*. They enable task switching. At the stage of *goal shifting*, goals are updated according to the present and upcoming tasks. This includes updating both declarative and procedural working memory contents. At the second stage of *rule activation*, rules for response selection for past tasks are deactivated, and the rules for response selection for the present task are activated. The stage of rule activation is assumed to take place after goal shifting has been completed, and after stimulus identification of the current task. After the stage of rule activation is completed, the response selection stage takes place.

Rubinstein et al. (2001) emphasize that "The model's component stages, including both executive control and task processes, are strictly successive. Each stage starts only after its predecessors have finished." (Rubinstein et al., 2001, p. 772). Figure 6 depicts the temporal sequence of the assumed processes. For the application of executive control processes to the takeover situation in the next chapter, it is important to further note that Rubinstein et al. (2001) explicitly state: "goal shifting may occur before stimulus identification starts for the next task" (Rubinstein et al., 2001, p. 771). In this case, goal shifting constitutes an "endogenous control process" (Rubinstein et al., 2001, p. 771). Preconditions for this to happen are (1) response-stimulus interval is long and (2) prior information about the next task is available. Both is given in the takeover situation at Level 3. (1) The response-stimulus interval refers to the time between the response to the first task until the stimulus of the next task is presented (Rubinstein et al., 2001). This applies to Level 3 driving automation because the driving task is known to be the next task. Regarding the response-stimulus interval, the Level 3 system is required to provide at least 10 seconds lead time for takeover. In addition, the user can disengage from the non-driving related activity on own accord any time. Thereby, the time between the last response to the non-driving related activity and the stimulus identification of the upcoming driving task can be considered long, especially compared to usual laboratory experiments on task switching who use response stimulus times in milliseconds range (e.g. Rogers & Monsell, 1995). Precondition (2) refers to prior information on the upcoming task. This is also given in Level 3 automated driving because the user is always aware that she/he needs to switch to the driving task upon request by the system.

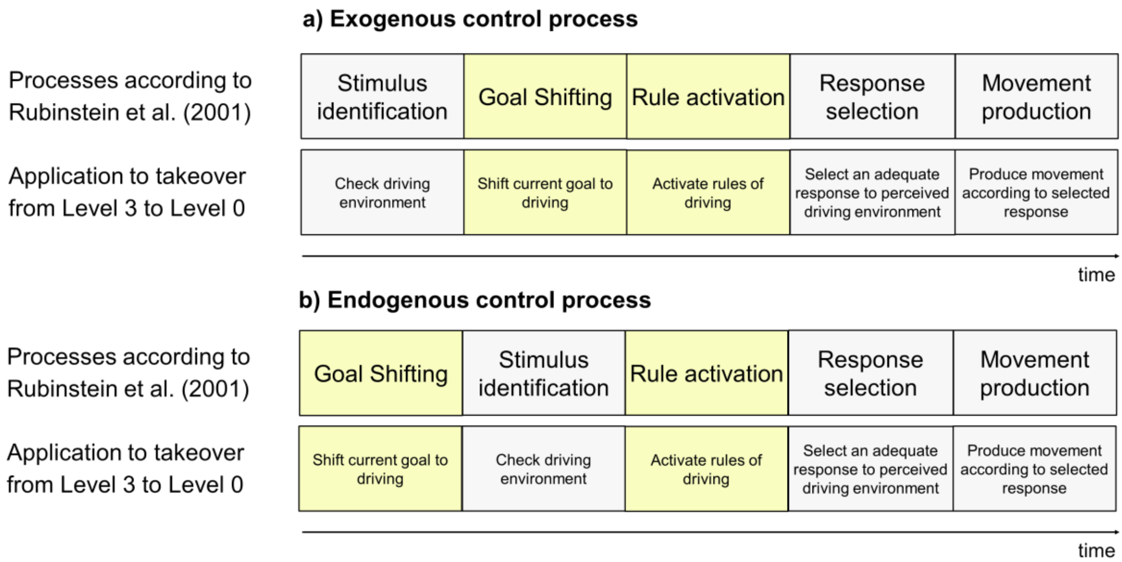

Figure 6: Schematic of temporal sequence of task and executive control processes suggested by the stage model of executive control for task switching (Rubinstein et al., 2001). Processes are applied to the process of takeover from SAE Level 3 automated driving to Level 0 manual driving. Task processes related to driving are colored in grey, executive control processes are colored in yellow. During Level 3 automated driving, the sequence depicted in a) may occur when switching to the driving task is triggered by a system request to intervene. The sequence depicted in b) may occur when users switch of their own accord.

5.2.3. Applying the stage model of executive control for task switching to takeover situations in Level 3 automated driving

In this chapter, the stage model of executive control for task switching (Rubinstein et al., 2001) is applied to system-initiated takeover situation in Level 3 automated driving. Figure 7 maps the task processes and executive control processes suggested by Rubinstein et al. (2001) to the takeover situation in Level 3 automated driving.

Task processes take place whenever the user engages in a specific task. In the Level 3 driving automation context, task processes take place when the user engages in the non-driving related task during Level 3 automated driving, and when the driver engages in the driving task after Level 3 automated driving. For example, when the user plays Tetris (= non-driving related task), then stimulus identification refers to the process of recognizing the currently descending geometric shape (e.g. “It’s an L-shaped tetromino!”). In the next stage of response selection, the goal and rules of Tetris are considered. Response selection refers to the process of deciding whether and where to move the L-shape tetromino and whether and how to rotate it. Finally, the stage of movement production refers to executing the movement required to realize the previously decided response.

Human performs	Non-driving related task	Switch	Driving task
Processes of the Stage Model of Executive Control for Task Switching	<u>Task Processes</u> • Stimulus identification • Response selection • Movement production	<u>Executive control processes</u> • Goal shifting • Rule activaiton	<u>Task processes</u> • Stimulus identification • Response selection • Movement production

Figure 7: Processes of the stage model of executive control for task switching (Rubinstein et al., 2001) applied to switching from a non-driving related task performed during Level 3 automated driving to manual driving.

Executive control processes are specific to switching from one task to the next task. With the onset of the request to intervene of a Level 3 system, the user needs to switch from the non-driving related task to the driving task. As explained in chapter 5.2.2, the stage of goal shifting can take place even before the stage of stimulus identification for the following task (Rubinstein et al., 2001). For example, even while playing Tetris, the user may mentally prepare for the driving task. If the user was not playing Tetris, but listening to an audiobook, relevant information for the subsequent driving task can be perceived before onset of the request to intervene. Compared to playing Tetris, this allows for earlier stimulus identification related to the upcoming driving task. In the audiobook example, stimulus identification related to driving is possible to occur earlier because the non-driving related task does not engage the visual sensory modality. In a next step, based on the observed driving environment even response selection can take place before the request to intervene. As a consequence, only the motor reaction needs to be performed after the request to intervene is issued (= movement production). Compared to the Tetris example, earlier stimulus identification and response selection related to the upcoming driving task may constitute an advantage for the audiobook example regarding the takeover process. This is hypothesized to result in faster responses (e.g. lower takeover time) and possibly less "erroneous" responses (e.g. less hazardous behavior with larger minimum time-to-collision, lower maximum accelerations) to the request to intervene. Potentially, the influence of non-driving related tasks also extends to the manual driving behavior after takeover is performed.

6. Research questions and hypotheses

The following three research questions structure this dissertation:

(1) What activities do users engage in during Level 3 automated driving in a real ride?

(2) What are the overall effect sizes for differences in takeover time between non-driving related tasks based on task switching and modality shifting?

(3) Does similarity between modalities involved in the non-driving related task and the driving task influence takeover behavior and subsequent manual driving behavior in a real ride?

This chapter presents how the research questions were deducted. The research questions are addressed in separate publications. Two publications are included as main publications for this cumulative dissertation (Shi & Bengler, 2022a; Shi & Frey, 2021) and one is added as adjunct publication (Shi & Bengler, 2022b) to provide the full context of the conducted research.

Chapter 7 describes the methods generally applied throughout this thesis. Chapter 8 provides one-page summaries of the main publications and a brief summary of the adjunct publication.

6.1. RQ 1: Non-driving related activities

To investigate effects of non-driving related activities on road safety, a first step is to investigate which non-driving related activities will be performed by future users (see chapter 4.1). Existing studies have investigated the range of activities using multiple-choice surveys and observations (Pfleging et al., 2016; Schoettle & Sivak, 2014). Multiple choice formats are inherently confounded with researchers' expectation since a list of activities needs to be provided to the participants. On the other hand, studies applying the method of observations were conducted in driving simulators (Hecht, Feldhütter, et al., 2020) or public transportation (Pfleging et al., 2016). Driving simulators provide a Level 3 driving automation context, but the experimental situation may counteract natural behavior. Observations in public transportation allow observation of natural behavior, but the respective situations do not mirror the specific demands of Level 3 driving automation (see chapter 4.1). This thesis contributes to existing studies and provides further insights into validity of previous results by implementing a Wizard-of-Oz approach. The Wizard-of-Oz method provides a Level 3 driving automation setting, and from participants' perspective, might reduce salience of being observed because participants are seated in and drive a real vehicle instead of being seated in a driving simulator in a laboratory.

➔ RQ 1: What activities do users engage in during Level 3 automated driving in a real ride?

Results show that users are likely to engage in reading activities, to watch the outside and to use their smartphones. Different methods provide insight into different aspects of engagement in non-driving related activities, e.g. assessing different types of activity, assessing duration of engagement in a specific activity (Shi & Frey, 2021).

6.2. RQ 2: Overall effect sizes

Much research has been conducted on the question of how non-driving related tasks affect following takeover behavior. The individual studies seem inconclusive and previous meta-analyses were based on Wickens' multiple resources theory. This thesis contributes to meta-analyses in this field by applying task switching theory. Since many single studies have been performed on influences of non-driving related tasks on takeover behavior, effect sizes can be estimated based on task switching.

➔ RQ 2: What are the overall effect sizes for differences in takeover time between non-driving related tasks based on task switching and modality shifting?

Based on psychological research on switch costs, it is assumed that takeover times are lower and takeover quality is higher following non-driving related activities that allow for task processes related to driving to take place earlier compared to non-driving related activities that do not allow for these processes to take place earlier. Resulting effect sizes suggest takeover times are faster after non-driving related tasks that allow for stimulus identification and movement production (= task processes related to driving) to take place earlier, i.e. before the system's request to intervene. Largest effect sizes were found for physical switching and smaller effect sizes for cognitive switching (Shi & Bengler, 2022b).

6.3. RQ 3: Influence of similarity

The conducted meta-analysis points toward the possibility that task switching theory has the potential to differentiate between non-driving related tasks. To investigate whether task switching assumptions can cause differences in takeover behavior and following manual driving behavior in a real world driving setting an experimental study is conducted.

➔ RQ 3: Does similarity in cognitive processes that are involved in the non-driving related task and the driving task, influence takeover behavior and subsequent manual driving behavior in a real ride?

Results show cognitive switch costs in accordance to predictions by the applied task switching theory (Shi & Bengler, 2022a). After experimental manipulation of the cognitive similarity between the non-driving related activity and the driving task, higher similarity facilitates takeover: Takeover times are significantly lower after a non-driving related activity that is similar to the driving task in cognitive demands compared to non-driving related activities that are less similar. In addition, subsequent manual driving behavior seems less collision prone (Shi & Bengler, 2022a).

7. Methods

This chapter describes the methods that are generally applied in this dissertation. A detailed description of operationalization and methods is found in the respective publications.

7.1. Wizard-of-Oz method

When the studies included in this dissertation were conducted, Level 3 driving automation systems were not available yet. To allow researching human factors issues related to Level 3 automated driving without exposing participants to unknown risks of technical systems under development, the Wizard-of-Oz method was used in the studies.

The Wizard-of-Oz vehicle of BASt was used in all studies. It is based on a Volkswagen Caddy Maxi (year of manufacture: 2013) with automatic transmission and 140 HP. Figure 8 shows the schematic setup of the Wizard-of-Oz vehicles used in all studies of this dissertation. In the vehicle rear, additional steering control elements are implemented. The participant is seated in the usual driver's seat, and is unaware of the second driver in the vehicle rear. The participant is instructed to activate and deactivate the Level 3 driving automation system by pressing a button on the steering wheel. Participants are informed about the system limits, and that they are provided with lead time to react to the request to intervene. In fact, when participants activate the Level 3 driving automation system, the second driver ("wizard driver") takes over the driving task, and simulates the driving automation system. When a pre-defined system limit is reached, the wizard driver issues a request to intervene and continues the driving task until the participant presses the button to deactivate the driving automation system. Figure 9 depicts the human-machine-interface used to transfer vehicle motion control between the two drivers.

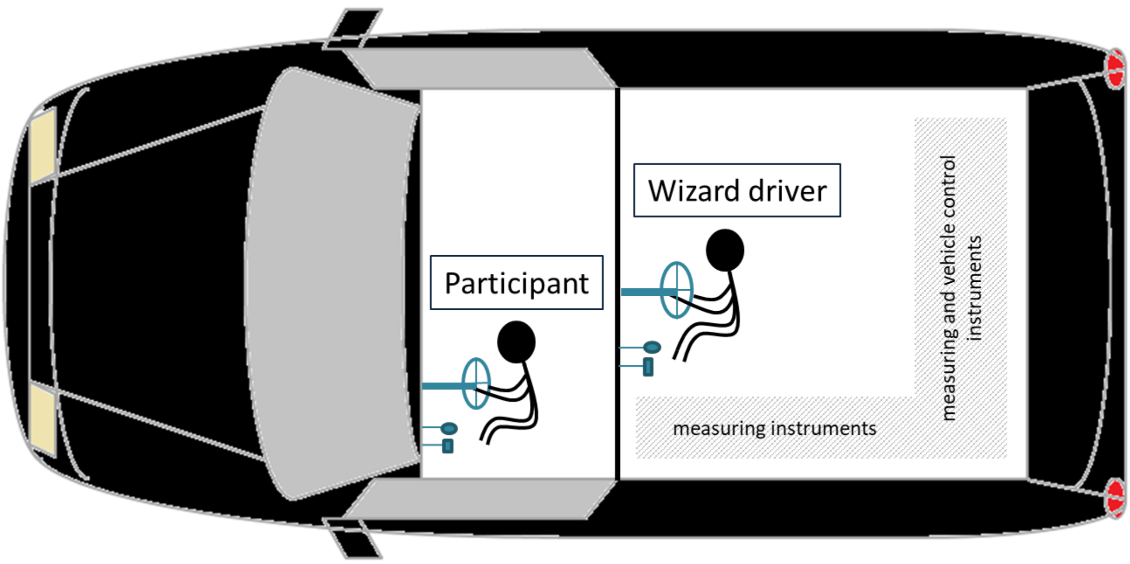

Figure 8: Schematic setup of the Wizard-of-Oz vehicle used. Figure originally published by Shi and Frey (2021), licensed under CC-BY-NC-ND 4.0 (https://creativecommons.org/licenses/by-nc-nd/4.0/), no changes were made.

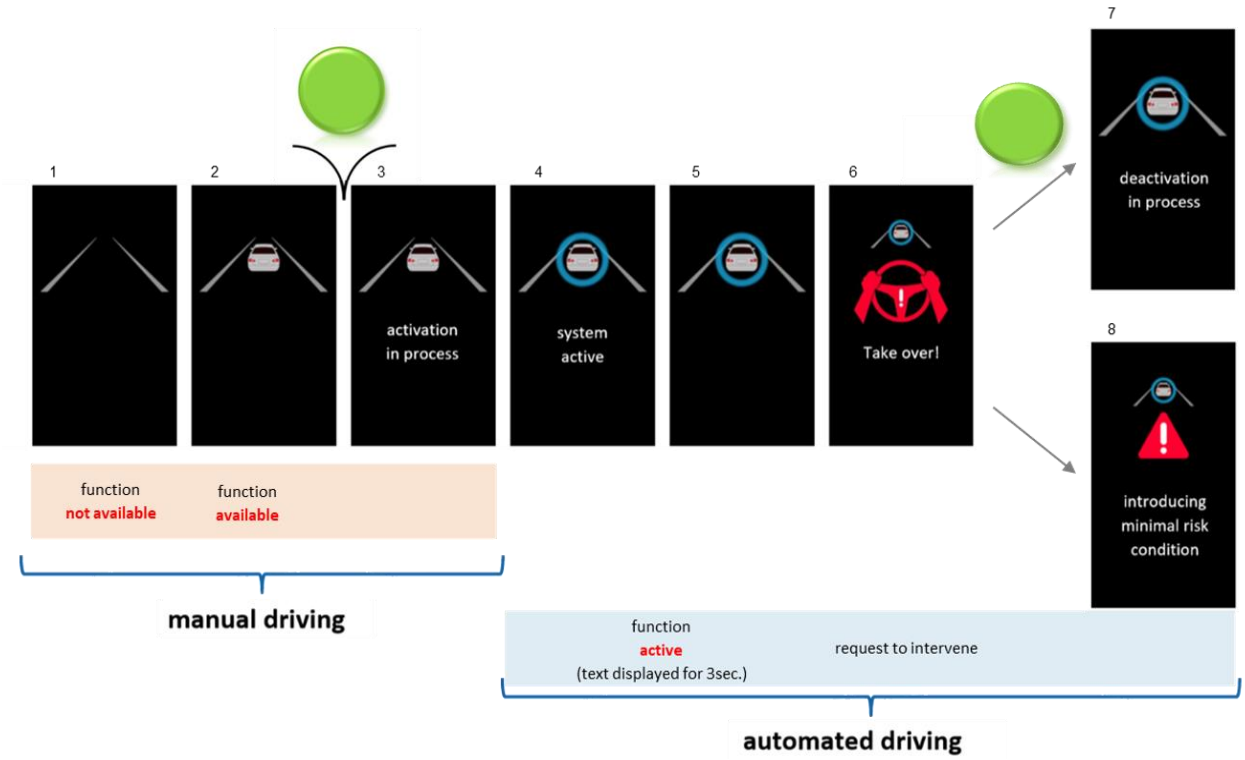

Figure 9: Human-machine-interface of the Level 3 driving automation system in the Wizard-of-Oz vehicle. The numbered displays show the sequence of Level 3 activation and deactivation processes. Displays 1- 7 show the sequence for a regular activation/deactivation process. Display 8 shows the HMI in case a minimal risk maneuver was necessary. The green button indicates required button press by the participant to activate or deactivate the driving automation system. Any verbal information was presented in German language, and is only translated here. Figure originally published by Shi and Bengler (2022a), licensed under CC-BY 4.0 (https://creativecommons.org/licenses/by/4.0/), no changes were made.

7.2. Non-driving related activities

Compared to previous literature, this thesis focuses more strongly on the practical setting, and therefore, differentiates between non-driving related tasks and non-driving related activities (see chapter 4). In this thesis, the term non-driving related *activity* is used to describe any activity that users naturally choose to engage in when using Level 3 automated driving usually in road traffic. The term non-driving related *task* is used in this thesis to refer to experimental settings where an experimenter instructs participants to engage in a specific task as a non-driving related activity during the experimental Level 3 automated driving phase.

This dissertation aims at inferences on the level of natural non-driving related activities. Therefore, in this doctoral thesis natural non-driving related activities are directly investigated rather than standardized tasks typically implemented in experimental settings. The experimental non-driving related tasks of the study reported in publication 2 (Shi & Bengler, 2022a) are therefore chosen after considering the results on non-driving related activities reported in publication 1 (Shi & Frey, 2021). This allows a stronger test of the theoretical assumptions. In the end, the investigated theoretical framework shall be applicable to the real world application of Level 3 driving automation including the engagement in non-driving related activities. As study 1 shows, it is unlikely for users to engage in standardized tasks usually implemented in experiments (Shi & Frey, 2021). Compared to standardized tasks, demands of natural activities are more diverse. Considering the aim of this dissertation, the suggested theoretical framework should be able to differentiate effects of non-driving related activities in the real world. The capacity of the theoretical framework should not be limited to differentiation between effects of standardized tasks that specifically and exclusively manipulate cognitive demands of interest. Therefore, non-driving related activities are chosen as experimental tasks in publication 2 (Shi & Bengler, 2022a).

For a similar reason, the theoretical framework in general does not focus on the specific demands of non-driving related tasks to explain their effects. Rather, the theoretical framework considers the relevant context of task switching in which the activities (driving and non-driving related activity) take place. When the context of task switching is taken into account, the first and the second task cannot be regarded separately anymore. Additionally, in this context, standardized tasks are unlikely to occur as publication 1 indicates (Shi & Frey, 2021).

8. Overview on publications

This chapter provides summaries of the publications included in this cumulative dissertation.

8.1. Main publication 1: What users are likely to engage in

The publication entitled "Non-driving related tasks during Level 3 automated driving phases - Measuring what users will be likely to do" is published in the APA journal Technology, Mind, and Behavior (Shi & Frey, 2021). It addresses research question 1: "What activities do users engage in during Level 3 automated driving in a real ride?".

The study address gaps in the current literature as outlined in chapter 4.1. Two methods are applied to investigate what activities users engage in during Level 3 automated driving: In study 1, participants provide self-report on non-driving related activities they would engage in (instead of previously applied multiple-choice questions; Pfleging et al., 2016; Schoettle & Sivak, 2014). Specifically, participants first experienced Level 3 automated driving in a real ride on the German Autobahn using the Wizard-of-Oz vehicle. After that, participants listed three to five activities they would perform if the system was available on their own vehicle. In study 2, participants directly engaged in non-driving related activities during Level 3 automated driving on a test track (instead of engaging in non-driving related tasks in a driving simulator; Hecht, Feldhütter, et al., 2020; Large et al., 2017). Engagement in non-driving related activities was analyzed based on video recordings.

The two methods yield complementary information on engagement in non-driving related activities. On the one hand, when participants list potential non-driving related activities, rarely performed tasks can be revealed. These might remain hidden when observing participants since the range of activities that is observed, is strongly dependent on the duration of the experiment. For example, when asked what activities participants would perform (study 1), approx. 15% stated to eat or drink during Level 3 automated driving. In study 2, observation shows that the duration rate of all eating and drinking activities taken together constitute below 1% of the total duration of engagements in non-driving related activities.

On the other hand, information on the duration or frequency with which an activity is performed cannot be obtained by naming, but by observation. For example, for gazes to the outside, a total duration rate of 5.90% was found, and an engagement rate of 38.89%. The engagement rate indicates that 38.89% of all engagements to non-driving related activities refer to gazes to the outside. These two metrics together indicate that participants frequently looked outside, but the total time of looking outside was comparatively low.

8.2. Main publication 2: Experiment on cognitive similarity effects

The publication entitled “Non-driving related tasks' effects on takeover and manual driving behavior in a real driving setting: A differentiation approach based on task switching and modality shifting” is published in the journal Accident Analysis and Prevention (Shi & Bengler, 2022a). It addresses research question 3: “Does similarity in cognitive processes that are involved in the non-driving related task and the driving task, influence takeover behavior and subsequent manual driving behavior in a real ride?”.

The study uses the Wizard-of-Oz method on a test track to simulate Level 3 automated driving in a traffic jam (see chapter 7). An additional lead vehicle simulated a traffic jam. The traffic jam was standardized. That means every participant experienced the same traffic jam in each condition. Each participant performed three blocks. Each block represents one condition, and included a different non-driving related task. The non-driving related tasks were selected to reflect different degrees of similarity to the driving task. Moreover, they should be close to natural activities users of Level 3 systems would actually engage in (rf. main publication 1; Shi & Frey, 2021). The three non-driving related tasks are playing Tetris, reading and typing a summary of the text, and watching a documentary film. Each block ended with a system-initiated takeover. At the end of the third block, participants were confronted with a balloon car that became visible only after the lead vehicle cut out in short distance to the balloon car. Takeover time, accelerations and time-to-collision (TTC) relative to the static balloon car were measured.

Results are in accordance with the applied task switching theory: Higher similarity between the non-driving related task and the driving task was accompanied by lower takeover times and numerically higher TTCs. Higher TTCs indicate that participants evaded the balloon car in greater distance. There were no differences in accelerations between the non-driving related tasks. The results contradict the previous notion of using multiple task performance theory as a theoretical basis to explain effects of non-driving related tasks on takeover and driving behavior. Multiple task performance theory would expect performance decrements when two tasks require same cognitive processes or resources (e.g. Wickens, 2008).

8.3. Adjunct publication: Meta-analysis

The publication entitled “Overall effects of non-driving related activities’ characteristics on takeover performance in the context of SAE Level 3: A meta-analysis” is published in the conference proceedings of AHFE 2022 (Shi & Bengler, 2022b). It addresses research question 3: “What are the overall effect sizes for differences in takeover time between non-driving related tasks based on task switching and modality shifting?”.

A meta-analysis was conducted to examine if the current range of literature provides support for the assumption that effects of non-driving related activities are based on task switching theory. Four effect sizes were calculated for the difference between (1) engagement in an active non-driving related task vs. monitoring task, (2) a task that needs to be put away vs. does not need to be put away before takeover, (3) a task that requires the visual sensory system vs. does not require the visual sensory system, and (4) non-driving related tasks involve different similarities to the driving task. The effect sizes indicate early task processes: (1) and (3) show influences of early visual perception of the driving environment, (2) represents the influence of early motoric preparation for the driving task. The last effect size (4) indicates differences in switch costs of non-driving related tasks.

The meta-analysis was performed using R version 4.1.0 and the robumeta package (Fisher & Tipton, 2015). An intercept-only model was used to calculate average effect sizes. Robust variance estimation methods were used because the effect size estimates violated assumptions of traditional meta-analytic methods, such as assumption of independent effect sizes and independent sampling errors. In addition, the covariance structure underlying effect sizes was unknown (Shi & Bengler, 2022b).

The results indicate large effect sizes for (1) engagement in an active task compared to a monitoring task, and for (2) physical switching (need to put away the task). (3) Engaging in a task that requires the visual sensory system yielded a medium effect size. This effect size is in accordance with both multiple task performance theory and task switching theory. The experiment reported in Shi and Bengler (2022a), however, disentangles the two theories. A small effect size was found for (4) cognitive similarity. It should be noted that the primary studies did not intentionally manipulate cognitive similarity. Since the meta-analysis can only analyze existing data, this effect size, though small, was interpreted as a promising starting point for further experimental investigation on the theoretical basis.

9. General Discussion

This general discussion first addresses the three research questions that structure this thesis (section 9.1). Next, the implications for theory (section 9.2) and practice (section 9.3) are discussed. Afterwards, the methods applied in this dissertation are discussed (section 9.4) and an outlook on future research is given (section 9.5).

9.1. Answers to the research questions

This chapter summarizes the answers to the initially posed research questions. For detailed report on results, please refer to the original publications (Shi & Bengler, 2022a, 2022b; Shi & Frey, 2021).

9.1.1. Answer to RQ 1

What activities do users engage in during Level 3 automated driving in a real ride?

This research question is addressed in publication 1 in further detail (Shi & Frey, 2021). This section summarizes the key results in light of research question 1. Different measures were used to assess engagement in non-driving related activities. In study 1, each participant stated three to five non-driving related activities. Naming rate served as an indicator for engagement in non-driving related activities. In study 2, non-driving related activities were identified by observing participants in-vehicle behavior. Engagement rate and total duration rate of engagement per observed non-driving activity served as indicators for engagement in non-driving related activities. Naming rate reflects non-driving related activities users engage in intentionally. The two metrics based on observation do not provide information on intention. Therefore, they can reveal non-driving activities that users would not state of their own accord. Furthermore, they inform about eventual behavior (duration and frequency of engagement). Based on naming rate, reading seems to be the most likely non-driving related activity followed by using the smartphone, and eating and drinking. Based on engagement rate, steady gazes to the outside are performed most frequently. However, their total duration rate is rather low, indicating frequent but brief gazes to the outside. Considering total duration rate, smartphone use (without phone calls) and reading seem to be most likely. Taken together, based on publication 1, users seem to prefer to engage in reading activities, to use their smartphones, to look at the environment, and to eat or drink. The results from the Wizard-of-Oz studies match previous findings from driving simulator studies, such as Hecht, Feldhütter, et al. (2020). Furthermore, results indicate a discrepancy between tasks investigated in experimental context and activities that users of Level 3 driving automation would naturally engage in. Previous research on effects of non-driving related tasks shows a strong weight on standardized tasks. These have the advantage of high internal validity, but are not expected to be performed in real driving settings which is shown in publication 1 (Shi & Frey, 2021).

9.1.2. Answer to RQ 2

What are the overall effect sizes for differences in takeover time between non-driving related tasks based on task switching and modality shifting?

This research question is addressed in the adjunct publication in further detail (Shi & Bengler, 2022b). This section summarizes the key results in light of research question 2. The effect sizes reported by Shi and Bengler (2022b) are estimated and interpreted based on task switching theory by Rubinstein et al. (2001). The effect sizes indicate a benefit for takeover after non-driving related tasks that allow the user to visually perceive the driving environment, and to physically prepare for the driving task. This relates to the stage of stimulus identification (visual perception) and movement production (physical preparation of the driving task) in Rubinstein et al.'s (2001) theory. The effect size for cognitive similarity between a non-driving related activity and the driving task is interpreted to indicate that non-driving related tasks similar to the driving task are followed by lower takeover times compared to non-driving related tasks that are less similar to the driving task. These effect sizes are in line with previous meta-analyses that find increases in takeover time due to handheld tasks and visually demanding non-driving related tasks (Weaver & DeLucia, 2020; B. Zhang et al., 2019). Since meta-analyses provide effect sizes that describe the effects found in previous studies, causal inferences cannot be drawn. To further disentangle competing theories and to allow inference on causal effects, an experimental study is needed that contrasts predictions of both theories. A first experimental study is provided in publication 2 (Shi & Bengler, 2022a).

9.1.3. Answer to RQ 3

Does similarity in cognitive processes that are involved in the non-driving related task and the driving task, influence takeover behavior and subsequent manual driving behavior in a real ride?

This research question is addressed in publication 2 in further detail (Shi & Bengler, 2022a). This section summarizes the key results in light of research question 3. In this study, three natural non-driving related activities were selected as experimental tasks based on their similarity to the driving task and considering task switching theory (Rubinstein et al., 2001). The task switching approach predicts shorter takeover times and higher takeover quality after non-driving related activities that are similar to the driving task in terms of cognitive demand. In contrast, a multiple task performance approach would predict the opposite pattern of results: A non-driving related activity that competes for cognitive resources with the driving task should be followed by impaired takeover behavior compared to a non-driving related activity that does not compete for resources. If multiple task performance theory applies, results should indicate longer takeover times and worse takeover and manual driving behavior after non-driving related activities that require the same cognitive resources as the driving task.

The observed takeover behavior and following manual driving behavior are in accordance with predictions of the task switching theory approach, and contradict predictions of multiple task performance theories: Compared to low similarity, high similarity between a non-driving related activity and the following driving task in terms of cognitive demands was accompanied by faster takeover times. Furthermore, high similarity is also accompanied by numerically less critical manual driving behavior following takeover. These results support a task switching based approach to differentiate non-driving related activities. Furthermore, the task switching based approach appears applicable to natural non-driving related activities.

Besides this main finding, video analysis indicates that users of Level 3 systems are prone to poor in-vehicle behavior when requested to take over the driving task although they received thorough one-on-one instruction before the experimental ride. This observation emphasizes the importance to clearly communicate users' responsibilities (see also section 9.3.4).

9.2. Implications for theory

In this thesis, task switching theory is applied to the takeover situation in Level 3 automated driving (see chapter 5.2). This extends previous literature that applied multiple task performance theory to non-driving related tasks' effects on subsequent takeover behavior. This dissertation proposes an alternative approach by following theory and empirical findings from research on the task switching paradigm. In this chapter these initial theoretical assumptions are discussed based on the experimental results of this dissertation.

9.2.1. The takeover situation in Level 3 automated driving from a task switching perspective

While task switching has already been acknowledged as the psychological paradigm underlying the takeover situation (Hecht, Kratzert, & Bengler, 2020; Naujoks et al., 2019; Weaver & DeLucia, 2020; Zeeb et al., 2017), multiple task performance theories have been applied still (e.g. Weaver & DeLucia, 2020). This dissertation strictly applies theory and empirical findings from task switching to takeover situations in Level 3. The aim is to find an approach to systematically differentiate non-driving related activities regarding their effects on takeover and subsequent manual driving behavior. The theory postulated in this thesis is thoroughly investigated. This dissertation thereby extends the theoretical basis applied to non-driving related activities' effects by adding a task switching perspective.

The task switching based theoretical framework assumes that takeover behavior (takeover time and takeover quality) is influenced by task processes and executive control processes (Rubinstein et al., 2001) as well as similarity between the non-driving related activity and the driving task in terms of cognitive similarity (Arrington et al., 2003). Both assumptions were addressed in this thesis, and are discussed in the following.

Applying the stage model of executive control for task switching (Rubinstein et al., 2001) to effects of non-driving related activities in Level 3 driving automation

Task processes consist of the stages of stimulus identification, response selection and movement production. Thus, they encompass perceptual, cognitive and motoric attributes of the non-driving related activity. Executive control processes consist of the stages of goal shifting and rule activation (Rubinstein et al., 2001). The temporal sequence of the stages can be influenced by characteristics of the non-driving related activity. As shown in the meta-analysis, non-driving related activities that involve users' hands prolong takeover time compared to other activities that do not require users' hands (Shi & Bengler, 2022b). In terms of the task switching theory, this relates to the stage of movement production for driving. Preceding non-driving related activities that do not require the users' hands, allow earlier production of movement related to driving compared to non-driving related activities that require users' hands. Similarly, the meta-analysis indicates that non-driving related activities that require the users' visual sensory system prolong takeover time compared to other activities that do not require the users' sensory system, and compared to monitoring tasks that require the user to visually perceive driving relevant stimuli (Shi & Bengler, 2022b). In terms of the task switching theory, this relates to the stage of stimulus identification for driving. Driving related stimulus identification can occur earlier when the non-driving related activity does not require the visual sensory system. The stage of response selection follows the stage of stimulus identification (Rubinstein et al., 2001). However, to be able to select adequate responses, executive control processes need to take place in between. It is therefore assumed that early stimulus identification related to driving also allows response selection related to driving to occur earlier, including the executive control processes. In the meta-analysis the executive control processes are not represented. This is because these processes are specific to task switching. Primary literature, however, is conducted based on assumptions of multiple task performance theory (e.g. Zeeb et al., 2017). Therefore, the temporal sequence of executive control processes has not been experimentally manipulated, so that it cannot be considered in a meta-analysis.

Regarding the influence of early task processes, this dissertation shows that early task processes reduce takeover time over non-driving related tasks that do not allow for early task processes. Notably, the respective effect sizes are large with effects sizes between d = .326 and d = .663 (Shi & Bengler, 2022b).

Similarity in cognitive demands between non-driving related activity and driving task

To investigate effects of similarity in cognitive demands, it is necessary to keep constant effects of task processes and executive control processes. The added task switching perspective allows to apply a more specific theoretical background, and thereby, allows a more specific prediction of non-driving related activities' effects.

Second, by applying task switching theory, differentiation of non-driving related activities is not based on an isolated single main feature. This allows to go beyond distinguishing experimental tasks that demand specific resources by experimenters' deliberate manipulation (e.g. SuRT, n-back task, Radlmayr, Fischer, & Bengler, 2018). Instead, natural activities with multiple cognitive demands can be differentiated (as indicated by publication 2, Shi & Bengler, 2022a). Moreover, the suggested differentiation approach contextualizes non-driving related tasks' effects into the specific setting of Level 3 driving automation. Differentiation is based on the similarity in cognitive demands between a previous non-driving related task and the subsequent driving task. That means effects on takeover behavior are influenced by both the non-driving related task and the driving task. Switching to the driving task is a precondition given by the context of Level 3 driving automation. Thus, takeover behavior can be substantially modulated by the characteristics of the preceding non-driving related task.

Third, this dissertation provides first empirical support for a task switching based differentiation approach for non-driving related activities (see section 5.2). The proposed differentiation approach assumes that effects of non-driving related tasks on takeover behavior and manual driving behavior occur within an applied setting following the task switching paradigm. Relevant characteristics for the task switching paradigm are two consecutively performed tasks and an imperative stimulus that calls for a switch or no switch (see Figure 4 in section 5.1). In the Level 3 driving automation setting, the non-driving related activity constitutes the first task, the driving task constitutes the second task and the system's request to intervene constitutes the imperative stimulus that calls for a task switch. The main research finding on the task switching paradigm is the switch cost which represents a decreased performance in switch trials (= first and second tasks are different tasks) compared to repeat trials (= same task is performed twice) (Kiesel et al., 2010; Monsell & Driver, 2000). Furthermore, basic cognitive research shows that for switch trials, the size of switch costs is smaller when two tasks are similar compared to when two tasks are dissimilar (Arrington et al., 2003). A recognized theory for task switching is the stage model of executive control for task switching by Rubinstein et al. (2001). According to this theory, task processes and executive control processes take place in the course of task switching. Stimulus identification, response selection and movement production are task processes, and take place when working on a specific task (whether in the context of task switching or not). Goal shifting and rule activation are executive control processes, and take place when switching from one task to another. Executive control processes are therefore specific to the task switching paradigm. Applying the empirical findings of switch costs (Arrington et al., 2003) and the task switching theory by Rubinstein et al. (2001) to Level 3 driving automation suggests:

a) Takeover times are lower and takeover quality is higher when the previously performed *non-driving related activity allows task processes (perceptual, cognitive or motoric) related to driving to take place earlier,* compared to non-driving related activities that do not allow for these processes to take place earlier.

b) Takeover times are lower and takeover quality is higher when the previously performed *non-driving related activity is similar to the driving task in terms of cognitive demands,* compared to non-driving related activities that are less similar to the driving task in terms of cognitive demands.

Publication 2 and the adjunct publication refer to these assumptions (Shi & Bengler, 2022a, 2022b).

Regarding assumption a), task processes include “stimulus identification, response selection and movement production” (Rubinstein et al., 2001, p. 770). The conducted meta-analysis shows largest effects on takeover times when task processes related to the driving task can take place earlier: Takeover times are faster after non-driving related tasks that allow for stimulus identification and movement production (Rubinstein et al., 2001) to take place before the system’s request to intervene (Shi & Bengler, 2022b). This effect is also found in previous meta-analyses that indicate faster takeover times after non-driving related tasks that do not occupy the users’ hands or visual sensory system (Weaver & DeLucia, 2020; B. Zhang et al., 2019).

Regarding assumption b), the experimental study conducted in this dissertation shows that compared to lower similarity, high similarity in cognitive demands between the non-driving related activity and the driving task leads to faster takeover (Shi & Bengler, 2022a).

9.2.2. Implications for basic cognitive research

In the context of task switching, basic cognitive psychological research indicates that similarity compared to dissimilarity between two tasks reduces switch costs (Arrington et al., 2003). Applying this finding to Level 3 automated driving results in the assumption that non-driving related activities similar to the following driving task reduce switch costs (seen in higher takeover times and worse takeover quality) compared to non-driving related activities that are dissimilar to the following driving task. The body of basic research that addresses the question how different degrees of similarity between two tasks affect switch costs, is rather small compared to other lines of research related to task switching. This dissertation highlights the practical relevance of basic research on cognitive similarity between tasks. Additionally, as Arrington et al. (2003) note “the construct of similarity in cognitive psychology is controversial and has been defined in various ways” (p. 783). This dissertation emphasizes the value of such basic research, and at the same time, contributes to it by indicating that working memory components appear to be a suitable means to assess similarity between tasks in practice.

9.3. Implications for practice

In addition to the theoretical implications, the differentiation approach suggested in this dissertation can be diversely applied in practice (see 9.3.1). In Germany, a Level 3 driving automation system needs to conform to UN Regulation No. 157. The takeover times observed in this dissertation are discussed in light of UN Regulation No. 157 (see 9.3.2). Furthermore, this dissertation focuses on the use of Level 3 driving automation systems in traffic jams on the German Autobahn and integrates the observed in-vehicle driving behavior into this particular operational design domain (see 9.3.3). Finally, implications for communication of automated driving to users are discussed (see 9.3.4).

9.3.1. Potential applications of the suggested differentiation approach

Identify non-driving related activities for Level 3 system use

Currently, in Germany, there are no additional limitations by public authorities regarding non-driving related activities when using SAE Level 3 systems. Automakers decide which non-driving related activities can be performed in accordance with the respective Level 3 driving automation system. In this context, the proposed differentiation approach contributes to the range of research that may serve as a basis to draw conclusions on suitable non-driving related activities. In practice, identifying non-driving related activities that potentially deteriorate fallback-ready users' takeover behavior or following manual driving behavior necessitates to consider all possible non-driving related activities. Since with reasonable time and effort not all activities can be investigated experimentally, this dissertation draws on psychological theories for differentiation (in the sense of Kurt Lewin's famous citation of a business man saying "there is nothing as practical as a good theory" (Lewin, 1943, p. 118)). The suggested differentiation approach can help to identify non-driving related activities that potentially deteriorate fallback-ready users' takeover behavior or following manual driving behavior: According to the suggested differentiation approach, in a first step, it should be sorted out whether the non-driving related activities in question allow for *task processes related to driving* to take place early (see section 9.2.1 hypothesis a). It is advantageous when task processes related to driving (stimulus identification, response selection, movement production) can take place earlier. If they cannot take place earlier, takeover behavior and following manual driving behavior are likely deteriorated (see main publication 2 and adjunct publication; Shi & Bengler, 2022a, 2022b).

For instance, listening to an audiobook allows task processes related to driving to take place earlier because the fallback-ready user can visually perceive the driving environment, and select and prepare a response to the perceived driving environment before the onset of the request to intervene. This constitutes an advantage over other non-driving related activities (such as reading) that do not allow for stimulus identification, response selection and/or movement production to take place before the onset of the request to intervene.

In a next step, the *similarity* between cognitive demands of the non-driving related activity and the following driving task should be assessed (see section 9.2.1 hypothesis b). It is advantageous when the non-driving related activity and the driving task are similar in terms of cognitive demands. If they are not similar, the takeover behavior and following manual driving behavior are likely deteriorated (see publication 2; Shi & Bengler, 2022a).

For instance, in publication 2 (Shi & Bengler, 2022a), playing Tetris (high similarity to the driving task in terms of cognitive demands) was followed by fast takeover and numerically lower time-to-collision than the other two non-driving related activities (with lower similarity to the driving task in terms of cognitive demands).

Prevent negative effects of non-driving related activities on road safety

In case the differentiation approach points out negative effects of non-driving related activities on following takeover, it also allows to derive measures to counteract or prevent these. This may be of interest in the course of deciding on characteristics of the human-machine-interaction between the Level 3 system and its user. The task switching theory underlying the differentiation approach (Rubinstein et al., 2001) provides starting points to generate such measures. For instance, if the negative impact is predicted because task processes and executive control processes cannot take place earlier, this could be fostered by design of the human-machine-interaction.

An example related to the stage of stimulus identification is the “request to monitor” examined by Hasegawa, Wu, and Kihara (2022). Their “request to monitor” asks users “to stop a non-driving-related activity approximately one minute (54.5 s to be exact) before the impending transition and monitor the traffic situation until the [request to intervene]” (Hasegawa et al., 2022, p. 5). Encouraging the fallback-ready user to observe the driving environment before the request to intervene allows stimulus identification, response selection and potential movement production (= task processes according to Rubinstein et al. (2001)) related to the following driving task to take place earlier. Specifically, the “request to monitor” (Hasegawa et al., 2022) encourages the fallback-ready user to visually perceive the driving environment (= stimulus identification according to Rubinstein et al. (2001)), which allows the fallback-ready user to mentally select suitable actions in response to the perceived driving environment (e.g. mental decision for overtaking maneuver; corresponds to response selection according to Rubinstein et al. (2001)), and finally prepare respective movements (e.g. moving hands to steering wheel and feet to pedals; corresponds to movement production according to Rubinstein et al. (2001)).

Another example related to the stage of movement production is to integrate non-driving related activities into the vehicle's entertainment system so that the users does not need to hold additional items in their hands. In case the non-driving related activity cannot be integrated directly, the vehicle's interior could be designed to facilitate removing the item quickly and safely. The aim is to facilitate the stage of movement production related to driving.

Irrespective of which stage is addressed, in case the human-machine-interaction is adapted, this may change the fallback-ready user's activity before takeover. Therefore, it is suggested to re-estimate effects of non-driving related activities after changes in the human-machine-interaction.

Evaluate the specified non-driving related activities for Level 3 system use

The differentiation approach may also serve as a basis to evaluate the range of non-driving related activities previously defined suitable for a specific Level 3 driving automation system. Aside from automakers, this may be of interest to consumer protection. The criteria of the differentiation approach may contribute to respective future evaluation methods. The development of such methods remains for future research.

9.3.2. Observed takeover times in the context of UN Regulation No. 157

UN Regulation No. 157 (2021) provides provisions for the international approval of Level 3 driving automation systems. It requires a Level 3 system to provide the fallback-ready user with at least 10 seconds time for taking over the driving task. The takeover times measured in the study reported in main publication 2 (Shi & Bengler, 2022a) are mostly covered by the stated time span of 10 seconds. The takeover times of five of 38 participants (corresponding 13.16%) exceeded 10 seconds. Regarding road safety, it is highly advantageous that the UN regulation demands a minimum risk maneuver in case the user did not take over the driving task, even though the technical definition by SAE J3016 (2021) does not require so.

UN Regulation No. 157 currently limits the maximum automation speed to 60 kph. It is intended to raise this limit to 130 kph in the near future. The experiment reported in main publication 2 was conducted on the basis of the current regulation. Consequently, the interpretation of results should not unconditionally be transferred to a speed limit of 130 kph. There is no indication to assume that the theoretical background and the proposed differentiation approach will not apply at a higher speed limit. However, for the observed driving behavior reported in publication 2 (Shi & Bengler, 2022a), experimental characteristics need to be considered when transferring them to a higher speed limit: First, the experiment implemented a simulated driving automation system with a maximum automation speed of 60 kph. When raising the maximum automation speed to 130 kph, the travelled distance after completed takeover is expected to be greater. In terms of collision with the balloon car, this may lead to lower time-to-collision values ceteris paribus. Second, during the takeover processes, 46.4% of observable participants in the experiment showed some kind of poor in-vehicle behavior after takeover from Level 3 automated driving. These include “moving the driver’s seat back to driving position, switching off the interior light in the dark” (Shi & Bengler, 2022a, p. 11) after takeover, and “not looking at all to the adjacent lane when evading the balloon car” (Shi & Bengler, 2022a, p. 11). When raising the maximum automation speed to 130 kph, these behaviors may have a stronger impact on manual driving behavior after completed takeover due to the reduced time for corrective interventions. Consequently, in addition to the reduced time-to-collision (TTC), manual driving behavior might be more erratic which may reflect in more extreme maximum and minimum lateral and longitudinal acceleration measures.

9.3.3. Driving behavior in the context of German specifics for traffic jams on the Autobahn

This dissertation focuses on the Level 3 systems regulated by UN Regulation No. 157 (2021) that operate in traffic jams on highways. For traffic jams on German highways, the German Road Traffic Regulations (“Straßenverkehrsordnung”, StVO) allow some specifics. Generally, on German roads overtaking is allowed on the left only (§5 Abs. 1 StVO). However, for traffic jam situations on highways, §7 Abs.1 S.1 StVO allows a deviation that is further specified in §7 Abs.2 and Abs. 2a StVO:

> *“(2) If the density of traffic has resulted in queues of vehicles in the lanes of one carriageway, traffic on the right (nearside lane, middle lane) may move faster than traffic on the left (offside lane, middle lane). (2a) If, on a carriageway for one direction of traffic, a vehicle queue has formed and come to a standstill or is moving at low speed in the left-hand lane, vehicles may overtake this queue on the right at a slightly higher speed and with the utmost care.”*

Overtaking on a highway’s right lane is allowed when a queue has not developed on all lanes of a carriageway (König, Dauer, Hartung, Jagusch, & Hentschel, 2021, p. 640). According to König et al. (2021), preconditions are:

- Traffic on the left lane is at standstill or driving at a speed below 60 kph.

- In case of standstill on the left lane, vehicles on the right lane may drive at a maximum speed of 20 kph
- In case of moving traffic on the left lane, vehicles on the right lane may drive maximum 20 kph faster than vehicles on the left lane, up to a speed of 80 kph.
- Overtaking with utmost care

For the user of a Level 3 driving automation system, the possibility of overtaking on the right lane has no impact if she/he is driving on the right lane and is aware of this exception. However, overtaking on the right is usually not allowed outside this specific traffic situation. In case the user of the Level 3 system is not driving on the right lane, other traffic participants might overtake her/him on the right lane up to a speed of 80 kph. Furthermore, other traffic participants may overtake on the left lane without speed limitation (if traffic signs do not indicate a speed limit). These specifics add complexity to takeovers during a dissolving traffic jam (= first Level 3 driving automation systems' limit) on the German Autobahn.

Given human judgment processes (Kahneman, 2003), it can be argued that overtaking on the right is initially not intuitive for many drivers, and the realization that it is allowed in the current situation may be delayed. This is because according to the dual-process model of judgement, there may be a conflict between "system 1" and "system 2" in this situation (Kahneman, 2003). Judgment of the situation may be first dominated by system 1 which operates "typically fast, automatic, effortless, associative, implicit (not available to introspection)" (Kahneman, 2003, p. 698) and is "governed by habit and are therefore difficult to control or modify" (Kahneman, 2003, p. 698). Since the first judgement is "governed by habit" (Kahneman, 2003, p. 698), it can be assumed that most drivers would assume overtaking on the right is not allowed. In contrast to system 1, "[t]he operations of System 2 are slower, serial, effortful, more likely to be consciously monitored and deliberately controlled; [..] relatively flexible and potentially rule governed." (Kahneman, 2003, p. 698). Since system 2 operates slower than system 1, revised judgement based on system 2 may be delayed. As a result, it can be assumed that drivers will initially assume overtaking on the right is not allowed, and only with delay, realize that in the present situation it is allowed[3].

In the experimental study of this dissertation, participants' in-vehicle takeover behavior was observed (Shi & Bengler, 2022a). Many participants did not check the surroundings

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[3] For overtaking on the right in traffic jams on the German Autobahn, a sequence of a video report about the first Level 3 driving automation system gives an example of how the slower system 2 overrules an initial quick judgement (Motoreport, 2022).

and/or presence of other traffic participants after takeover and before conducting a lane change (Shi & Bengler, 2022a). Taken together, both the specifics of the traffic jam situation outlined above, and the observation that many participants do not properly watch their surroundings, raise the importance to safeguard the moment of takeover in dissolving traffic jams on the German Autobahn. Communication of intended system use appears to gain importance outside and inside the vehicle before and/or during system use.

9.3.4. Communication of intended system use

In line with previous research, participants in this dissertation's studies stated or directly showed behaviors that deviate from their responsibilities as fallback-ready users (Shi & Bengler, 2022a; Shi & Frey, 2021). The observations from this dissertation's Wizard-of-Oz studies highlight the need to clearly communicate users' responsibilities in the context of Level 3.

For instance, in study 1 of publication 1 (Shi & Frey, 2021), five of 39 participants indicated sleeping as a potential non-driving related activity during Level 3 automated driving phases. Notably, just before answering, participants experienced Level 3 driving automation on a German highway in real traffic. In study 2 of this publication, sleeping was not observed (Shi & Frey, 2021). This may have different reasons, such as a too short observation period, reactivity to the experimental situation (e.g. being observed, excitement to use an automated driving function), generally low prevalence of sleeping, or the possibility to be injured in case of an accident. In a physically safe driving simulator environment, Hecht, Feldhütter, et al. (2020) could observe one participant (of $n = 20$) sleeping. In conclusion, based on these studies, sleeping may be generally low prevalent, yet, indicates potential misuse of Level 3 driving automation systems that jeopardizes road safety at the moment of takeover at the latest.

In addition to sleeping as a violation of fallback-ready users' role, in publication 2, participants showed poor in-vehicle behavior during the takeover process and the following manual driving phase in 46.4% of evaluable videos (Shi & Bengler, 2022a). The reported case analysis in main publication 2 exemplifies the relevance of these behaviors when they accumulate (Shi & Bengler, 2022a). As outlined in the discussion section of publication 2, the participants were individually instructed on how to use the Level 3 driving automation system just before the experimental ride of one-hour duration. Outside an experimental setting, users of Level 3 driving automation systems are likely to receive less detailed instruction before starting their journey.

In this regard, recently, the United Nations Economic Commission for Europe (UNECE) WP.1 published a "resolution on safety considerations for activities other than driving undertaken by drivers" that is applicable to Level 3 automated driving (UNECE, 2022). The resolution provides recommendations for different stakeholders (drivers, manufacturers, contracting parties) and also for the design of the automated driving system to ensure both vehicle safety and road safety. These recommendations explicitly include driver information and education. Manufacturers "should (…) inform and educate drivers about the safe use and limitations of automated driving systems" (UNECE, 2022, p. 2) and "contracting parties are encouraged to (…) consider appropriate domestic measures focusing on driver education and driver testing to ensure that drivers have the skills and knowledge necessary to manage the demands of new technologies" (UNECE, 2022, p. 3). For these measures to take effect, drivers are recommended to "familiarize themselves with how to operate the vehicle and the requirements regarding activities other than driving" (UNECE, 2022, p. 2). Furthermore, during automated driving phases, "drivers should (…) maintain physical and mental ability to safely take over dynamic control of the vehicle [and] (…) refrain from activities other than driving if those activities impede the take-over of dynamic control when a transition demand is issued" (UNECE, 2022, p. 2).

The studies of this thesis hint at the importance for communicating intended system use (Shi & Bengler, 2022a; Shi & Frey, 2021).

9.4. Methodical discussion

In this dissertation, a differentiation approach based on task switching was investigated. Throughout this dissertation methodical decision were made. First, the task switching based differentiation approach requires operationalization of the key concepts (see 9.4.1). Second, investigating non-driving related activities in the context of Level 3 driving automation requires to provide Level 3 automated driving to participants. Since Level 3 driving automation systems were not available at the time of this dissertation, it was not feasible to conduct studies with technical Level 3 systems in real driving settings. To bypass the unavailable driving automation systems and make investigation in real driving settings possible, Wizard-of-Oz vehicles are the state-of-the-art method to simulate respective driving automation systems in real traffic or on test tracks. The application of the Wizard-of-Oz method is discussed in section 9.4.2. Third, the aim of this dissertation is to differentiate effects of natural non-driving related activities rather than experimental tasks. The use of natural activities as experimental tasks is discussed in section 9.4.3. The last section 9.4.4 discusses whether the differentiation approach is suitable to differentiate between natural non-driving related activities' effects. These overarching methodical decisions are discussed in the following.

9.4.1. Operationalization of key components of the proposed differentiation framework

To investigate the theoretical framework, its theoretical constructs require operationalization. The operationalization of the framework's key components is discussed in the following.

The central component of the framework is the *switch cost*. In basic psychology, this metric describes the difference in performance on switch trials and repeat trials with increased error rates and higher reaction times in switch trials than in repeat trials (Kiesel et al., 2010; Monsell & Driver, 2000). In the Level 3 driving automation setting of this thesis, the switch costs refer to increased takeover times and reduced takeover quality in response to a request to intervene by the automation system.

In the laboratory setting, a *repeat trial* consists of one task that is performed two times consecutively. A *switch trial* consists of two different tasks performed consecutively. By definition of Level 3 driving automation, it is not possible for the person on the driver's seat to drive the ego-vehicle before and after the request to intervene. This is because when the Level 3 driving automation system is active, it performs the entire driving task and thereby, excludes the human user from the driving task. However, when the system is switched off (upon system request or by the user's own accord), the user performs the driving task again. Thereby, the takeover situation in the context of Level 3 driving automation always represents a *switch trial*.

The theoretical framework suggested in this dissertation argues that similarity between the non-driving related activity and the driving task can reduce switch costs in the takeover situation. This is based on previous research that shows differences in takeover behavior after different non-driving related tasks (Gold et al., 2016; Wandtner et al., 2018a). This gives rise to the assumption that "switch trials" are not a homogenous group of trials, but can be further differentiated. In fact, there is basic psychological research on "similarity effects in task switching" (Arrington et al., 2003, p. 781) where "task similarity was defined as shared attentional control settings (Experiment 1) or shared response modality (Experiment 2)" (Arrington et al., 2003, p. 786). However, at the same time, "the construct of similarity in cognitive psychology is controversial and has been defined in various ways" (Arrington et al., 2003, p. 783). Arrington et al.'s (2003) results show reduced switch costs compared to switching between dissimilar tasks. In the context of this dissertation, the shared working memory components (Baddeley & Hitch, 1974; Repovs & Baddeley, 2006) define the cognitive similarity between the non-driving related activity and the driving task. This decision is based on the notion that task switching engages the working memory (e.g. Rubinstein et al., 2001). Baddeley's working memory theory (Baddeley & Hitch, 1974; Repovs & Baddeley, 2006) suggests modality-specific cognitive modules for maintaining and processing information. For instance, the phonological loop holds and processes auditory information, the visuo-spatial sketchpad holds and processes visual and spatial information. Later research, however, suggests that the visuo-spatial sketchpad might consist of two modules processing visual and spatial information separately, instead of one module that processes both visual and spatial information (Klauer & Zhao, 2004; Logie & van der Meulen, 2009; Smith & Jonides, 1997). The cognitive processing modules postulated in Baddeley's working memory theory constitute the criteria for describing similarity in cognitive demands between two tasks in task switching. Visual and spatial demands are coded separately after considering the aforementioned research. This coding of cognitive demands was applied to existing literature on effects of non-driving related tasks (cf. meta-analysis, Shi & Bengler, 2022b). In a next step, the coding of cognitive demands was applied to select non-driving related tasks for experimental purposes (cf. main publication 2, Shi & Bengler, 2022a). The experimental manipulation based on this coding reveals effects on takeover behavior that are in accordance with task switching theory (Shi & Bengler, 2022a).

Another line of research also encourages the choice of a modality-specific working memory model as the basis for assessing similarity between tasks. Research shows modality shifting effects both on a perceptual level (Spence et al., 2001) and on a conceptual level (Pecher et al., 2004). The modality shifting effect describes the costs in performance on a task when the target stimulus is presented in a different modality as the preceding target compared to when the target is presented in the same modality as the preceding target. This effect is found for targets presented in different sensory modalities (e.g. target presented in auditory, tactile or visual modality, Spence et al., 2001) and for targets that are all presented visual-verbally, but differ in conceptual modality (e.g. sweet candy, green leaves, Pecher et al., 2004).

9.4.2. Application of the Wizard-of-Oz method

At the beginning of this dissertation, Level 3 driving automation systems were not available yet. Most studies that investigated Level 3 automated driving were conducted in driving simulators. One added value of this dissertation is its focus on real driving settings by using a Wizard-of-Oz vehicle and natural non-driving related activities. The Wizard-of-Oz vehicle is the state-of-the-art method to simulate driving automation in a real ride both on test tracks and in real traffic. The method allows to investigate Level 3 driving automation without exposing participants to risks of untested technical systems, and moreover, allows to provide participants with a real driving experience. This section discusses how the Wizard-of-Oz vehicle was used as an experimental method in main publications 1 and 2 (Shi & Bengler, 2022a; Shi & Frey, 2021).

In this dissertation, the Wizard-of-Oz method simulates Level 3 driving automation. Participants are instructed to activate and deactivate a driving automation by pressing a button on the steering wheel. In fact, a second driver in the vehicle rear drives while the participant believes a driving automation system performs the driving task. Compared to driving simulator studies, studies using Wizard-of-Oz vehicles are rare for different reasons (e.g. high costs, high safety requirements for conducting studies, natural driving environment provides a less controllable experimental environment than simulated driving environment). The fact that a human driver imitates a driving automation system, however, gives rise to new points of discussion, summarized by Müller et al. (2019). On the one hand, it can be argued that by providing a real driving situation to participants, the method inherently involves higher external validity compared to driving simulation. However, to make use of this benefit, Müller et al. (2019) point out several quality criteria for the use of Wizard-of-Oz vehicles in studies on automated driving. Specifically, test quality criteria are applied to the Wizard-of-Oz method, i.e. objectivity, reliability and validity. In the discussion section of main publication 1, these criteria are thoroughly addressed referring to the two studies reported therein. In essence, the discussion applies to the Wizard-of-Oz study reported in main publication 2, too. In the following, the use of the Wizard-of-Oz vehicle throughout this dissertation will be discussed concisely along the criteria suggested by Müller et al. (2019).

If the Wizard-of-Oz method is **objectively** applied, results are independent from the person acting as a wizard driver. If objectivity is not given, results depend on the wizard driver. For instance, differences in the wizard drivers' driving styles may contribute to differences in study results. For all studies in this dissertation, the wizard drivers followed an instructed driving style (Shi & Bengler, 2022a; Shi & Frey, 2021) including issuing requests to intervene at pre-defined locations. The instruction standardizes the wizard driver's driving style and "system limits" so that it can be replicated by other wizard drivers. Environmental conditions, including weather and road conditions, surrounding road users in real traffic and their driving styles, are beyond the experimenter's control, and may influence the wizard driver's driving situationally. Prior instruction may at least reduce effects of environmental conditions.

If the Wizard-of-Oz method is **reliably** applied, the wizard driver's driving style can be replicated by other wizard drivers. The instructions on the driving style outlined above, allow for replication by other trained wizard drivers. In each of the conducted studies, one trained wizard driver acted as the wizard driver for all participants. The respective wizard driver was required to take sufficient breaks in order to reduce intraindividual differences in the wizard driver's driving style and to prevent errors due to inattention or fatigue. This procedure supports both reliability and objectivity.

If the Wizard-of-Oz method is **validly** applied, (1) participants believe they are using a technical Level 3 driving automation system and (2) performance of the Level 3 driving automation simulated by the wizard driver resembles the performance of a technical Level 3 driving automation system. Regarding the first aspect, participants were asked how they thought the driving automation works before they were debriefed. No participant thought a second driver was driving the vehicle from the rear. From this, and from statistical analysis of the standardized trust questionnaires, it can be derived that participants did trust the driving automation system. The second validity aspect refers to the comparison of wizard driver's performance to the performance of a technical Level 3 driving automation system. However, technical Level 3 systems operating in the investigated traffic situations are not available yet at the time of this dissertation. Therefore, a conclusion on the second validity aspect cannot be reached.

In summary, the Wizard-of-Oz method has been applied as objectively, reliably and validly as possible. Environmental conditions are beyond the researcher's control, and comparison of the wizard driver's performance to a technical Level 3 system operating in the respective domains is not possible due to not yet available Level 3 systems.

9.4.3. Natural activities as experimental non-driving related tasks

This dissertation focuses on real driving settings. At the beginning of this dissertation, research on non-driving related activities' effects on takeover behavior was mostly conducted in driving simulators and implemented standardized tasks as non-driving related activities. Standardized tasks allow for controlled manipulation of specific mental processes. Their effects on takeover behavior were usually investigated in driving simulator settings which allow to control the driving environment (e.g. Radlmayr et al., 2014). Later studies moved towards implementing more natural Level 3 driving automation situations by either applying natural activities as the non-driving related activity in their studies (e.g. Dogan et al., 2019), or by implementing real driving situations outside simulation (e.g. Naujoks et al., 2019). The previous chapter 9.4.2 discussed the use of a Wizard-of-Oz vehicle to provide more natural driving experience. This chapter discusses the use of natural non-driving related activities as experimental tasks.

Publication 1 indicates that there is a gap between the tasks used in experimental studies and the activities that users would engage in during Level 3 automated driving (Shi & Frey, 2021). For this reason, natural activities were chosen as experimental tasks in publication 2 (Shi & Bengler, 2022a). The aim of this dissertation is to find a differentiation approach that can be applied in practice where activities do differ in multiple regards. Therefore, using natural non-driving related activities rather than standardized tasks is a stronger test of the suggested differentiation approach compared to using standardized tasks. Furthermore, irrespective of whether standardized tasks or natural activities are implemented in the experiment, it requires multiple replications to confirm validity of a proposed approach (see section 9.5 for an Outlook on future research). In this regard, the study reported in main publication 2 provides a promising starting point that supports the proposed differentiation approach and contradicts differentiation based on commonly applied theories of multiple task performance. Indications for future research are provided in section 9.5.

It can be argued, however, that natural non-driving related activities may not be suited as experimental tasks because they likely differ in more characteristics than those that are in the study's focus.

For instance, apart from the manipulated difference, another difference could be related to the allocation of attention. As outlined in the introduction chapter 2.2, endogenous attention refers to the voluntary allocation of attention, and exogenous attention refers to stimulus-triggered allocation of attention (Eysenck & Keane, 2010; Wentura & Frings, 2013). Watching a film and playing Tetris can be argued to involve exogenous attention to a greater extent compared to reading and typing a summary. Reading and typing a summary on the other hand might involve a greater extent of endogenous attention allocation compared to the other two non-driving related activities. The assumption is based on the moving visual stimuli when playing Tetris and watching a film, whereas for reading stimuli remain static and may be less likely to capture attention. These assumed differences in exogenous and endogenous attention allocation, however, do not coincide with the empirically found differences in takeover behavior. Here, playing Tetris leads to shorter takeover times and numerically larger times-to-collision. Therefore, the observed differences in takeover behavior and manual driving behavior cannot be explained by differences in endogenous or exogenous attention allocation.

9.4.4. Potential and limitations of the suggested differentiation approach

Extending the focus on standardized tasks to include natural activities

When differentiating between non-driving related activities' effects on takeover or manual driving behavior, some authors specifically distinguish between standardized tasks and natural non-driving related activities (Naujoks, Befelein, Wiedemann, & Neukum, 2017). Not considering differences between standardized tasks and natural activities in this context, may to some degree lead to circular reasoning: Primary literature uses standardized tasks because they pose a clearly defined single primary demand on the participant. This allows researchers to investigate the influence of the specifically manipulated task characteristic. Differentiation approaches build on the range of the aforementioned primary literature, and argue that they are suitable because they can differentiate between effects found in primary literature. This reasoning maintains a perspective on non-driving related tasks that focuses on one main demand or sensory modality. To expand this perspective, differentiation approaches might more strongly take account of the original practical problem of operating Level 3 driving automation systems in road traffic. For example, differentiation approaches could more strongly consider characteristics of the original automated driving setting, thereby taking into account the weight of standardized tasks in primary literature outlined earlier. In this regard, the proposed differentiation approach takes no account of whether an activity is a standardized task or a natural activity (Shi & Frey, 2021). The differentiation approach is applicable to both because it is based on the involved cognitive processes, and respective psychological theories and empirical findings from the task switching paradigm (see chapter 9.2 for theoretical discussion on the differentiation approach). The suggested differentiation approach takes practical issues into account by contextualizing the performance of non-driving related activities into Level 3 automated driving.

Type I and type II errors based on the suggested differentiation approach

Results of this dissertation indicate that differentiation between non-driving related activities is possible based on the proposed task switching approach. Publication 2 finds differences between playing Tetris and the two other non-driving related tasks watching a documentary film and reading and typing a summary (Shi & Bengler, 2022a). However, no difference was found between the latter two tasks. This may raise the question to what degree differentiation is possible. A power analysis was conducted to estimate the probability of revealing a difference between the latter two tasks if there was a true effect. With a total sample of $n = 36$ and a within-subjects design ($r = .588$), the effect of size $d = .07$ could be found with a power of $1 - \beta = .11$. This indicates both (1) that the difference in takeover times between watching a film and reading and typing is rather small with an effect size of $d = .07$, following convention by Cohen (1988), and (2) that it was unlikely (power of .11) for a potential effect of this size ($d = .07$) to reach significance in the analysis[4].

Based on the theoretical approach, a difference between the two tasks “watching a documentary film” and “reading and typing” was expected because their similarity to the driving task is not the same. On the one hand side, the effect size can be interpreted to indicate comparably small practical relevance of differences between the two tasks “watching a documentary film” and “reading and typing”. This would acknowledge a theoretical difference (as shown in the existent effect size) that is yet of low practical relevance (as mirrored by the small size of the effect). On the other side, it can be argued that the experimental test scenario was not suitable to unveil the theoretically assumed difference (false negative). However, participants’ TTC-values indicate that the experimental test scenario was a very critical event (Shi & Bengler, 2022a). Median TTC values for each condition vary between 1 sec. (watching a film) and 2 sec. (playing Tetris). Literature suggests a minimum TTC-value of 1 sec. for near-miss situations (Hayward, 1972). That means it is expected that for TTC-values below 1 sec. “a crash will occur because there is not enough time for avoidance” (Hayward, 1972, p. 27). Therefore, it can be argued that the test scenario with the balloon car represents a very critical event.

A true negative decision would further corroborate the suggested differentiation approach since no practically relevant difference needed to be detected. A false negative decision would suggest additional adaptations of the differentiation approach. Based on a single study, it cannot be concluded whether the decision was true or false negative.

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[4] It would require a total sample of $n > 1200$ for an effect size of $d = .07$ to reach significance with a power of $\beta = .80$.

Further research is required to conclude on this question. In addition, the result raises the question of what level of detail a differentiation approach must be able to depict differences between non-driving related activities. For now, it appears that the suggested differentiation approach is more prone to overestimate differences between non-driving related activities (type I error) than to neglect them (type II error). That means, based on the suggested differentiation approach, it seems more likely to predict differences in takeover behavior than to neglect differences. For the purpose at hand, however, it is more expedient to commit such a type I error than a type II error. That means, it is more expedient for a prediction to overestimate empirical differences, rather than for a prediction to not detect or underestimate an empirical difference.

Relative comparisons instead of categories

The differentiation approach suggested here provides insights into effects of non-driving related activities on takeover behavior and following manual driving behavior. The differentiation approach points out relative effects of non-driving related activities. That means the effects of two or more non-driving related activities on takeover behavior and manual driving behavior are compared. On this basis, a non-driving related activity cannot be evaluated or categorized in absolute terms as “good vs. bad” or “suitable vs. unsuitable”. Such categorization is not the aim of the differentiation approach. Categorizing non-driving related activities as “good/bad” or “suitable/unsuitable” would require additional information on the human-machine-interaction design of the system. As outlined in chapters 9.3.1 and 9.5.3, whether the predicted effects of non-driving related activities indeed eventually occur in road traffic, also depends on potential measures implemented to counteract the predicted negative impacts. In this context, the proposed differentiation approach offers multiple forms of applications (see chapters 9.3.1 and 9.5.3). Categorization of non-driving related activities is not the aim of this dissertation. Rather the aim of this dissertation is to find a differentiation approach that can differentiate effects not only in experimental setups but also in natural automated driving environments. For this, the suggested approach accounts well for empirical data and provides a promising basis for future replication and further research.

9.5. Outlook on future research

9.5.1. Similarity between tasks

In basic psychology, there is no consensus on how to assess two tasks' similarity in terms of cognitive demands yet (Arrington et al., 2003). In this thesis, Baddeley's working memory theory (Baddeley & Hitch, 1974; Repovs & Baddeley, 2006) was applied in order to describe a task's demands. In addition, similarity between two tasks is assessed by comparing the resulting demand profiles of the two tasks. In this doctoral thesis, this approach has been used for the first time to describe non-driving related tasks. In the context of non-driving related activities in Level 3 automated driving, future research could apply the method to further non-driving related activities and in different operational design domains of the Level 3 automated driving system. In the context of describing two tasks' similarity, this thesis hints towards the practical demand for such a method and points towards the possibility to apply Baddeley's working memory theory (Baddeley & Hitch, 1974; Repovs & Baddeley, 2006) for this purpose. Future research can investigate its applicability in other research fields outside automated driving. Lastly, future research could estimate this method's inter-rater reliability by examining different researchers' congruence on a given task's demand profile.

9.5.2. Task switching paradigm in Level 3 driving automation

This thesis provides first indication that task switching theory may be useful in explaining effects of non-driving related activities on takeover and following driving behavior. Since this dissertation provides first research activities in this regard, the theoretical framework needs to be further corroborated by future research.

As described in chapter 9.4.3, there are different methodical approaches to investigate the theoretical framework. Standardized tasks have been mostly applied in standardized settings. Currently, it can be criticized that the natural non-driving related activities that have been used as experimental tasks in publication 2 (Shi & Bengler, 2022a), may differ in other regards, too. To rule out alternative explanations further research is required. For instance, to address the concern that natural activities may differ in other regards, too, future research could apply standardized tasks to corroborate the findings of this dissertation. Another possibility is to choose a different set of natural non-driving related activities to randomize confounding factors over multiple studies.

One major finding of this dissertation is that the results reported in main publication 2 are in line with task switching theory, while contradicting predictions of multiple task performance theories. This poses a new stance because multiple task performance theory has been regarded as the underlying theoretical framework so far (e.g. Weaver & DeLucia, 2020). Based on this dissertation, the new assumption is that task switching theory is applicable to SAE Level 3.

9.5.3. HMI solutions to support switching to the driving task

Recently, multiple research projects focus on adaptions of the human-machine-interaction to facilitate and foster takeover behavior, e.g. project HADRIAN funded by European Union's Horizon 2020 research and innovation program, projects @city and STADT:up funded by the German Federal Ministry for Economic Affairs and Climate Action, Human Factors project funded by Japanese Cross-ministerial Strategic Innovation Promotion Program SIP Automated Driving for Universal Services (SIP-adus). Adaptations of the HMI are one means to guide the in-vehicle driver's or user's attention, and to communicate information that is currently relevant. These research activities share the aim to support users of Level 3 driving automation during the takeover process. From this dissertation, indications can be deduced regarding which cognitive processes can be specifically addressed by interaction design to help users during the course of takeover from SAE Level 3 to Level 0. For instance, the "request to monitor" investigated by Hasegawa et al. (2022) allows task processes related to the driving task to take place before the request to intervene. In this case, the user is requested to visually perceive the driving environment before the request to intervene. Based on the differentiation approach suggested in this thesis, the "request to monitor" as an HMI element is expected to reduce takeover time and improve takeover behavior. In this sense, HMI solutions for improving takeover behavior can be derived from the differentiation approach.

This dissertation's focus lies on the newly developed theoretical approach based on task switching. Focusing on this approach does not imply to ignore the explanatory potential of other promising theoretical approaches. For instance, it can be argued that when the "request to monitor" precedes the request to intervene, users' takeover behavior can be explained by cued response. In this sense, the "request to monitor" might serve as a cue for following takeover. As such, the "request to monitor" might pre-activate behavioral responses to the request to intervene.

10. Summary

Based on extensive literature review on effects of non-driving related activities on takeover behavior, it was observed that task switching is the acknowledged underlying psychological paradigm to takeover situations in Level 3 automated driving (Hecht, Kratzert, & Bengler, 2020; Naujoks et al., 2019; Weaver & DeLucia, 2020; Zeeb et al., 2017). At the same time, effects of non-driving related activities on following takeover behavior and manual driving behavior are explained using theories of multiple task performance (Jaussein et al., 2021; Weaver & DeLucia, 2020). Furthermore, it was observed that both primary literature and secondary literature try to describe non-driving related tasks based on one single main feature (e.g. visual task SuRT; Radlmayr, Fischer, & Bengler, 2018) or at maximum two features (e.g. visual and handheld task; Wandtner et al., 2018a). Three research questions were derived from the literature and the observations:

(1) What activities do users engage in during Level 3 automated driving in a real ride?

Since research evolved around tasks that can be described in one or two features, the question arises whether standardized tasks mirror natural activities. Publication 1 addresses this research question and finds that natural non-driving related activities differ from the investigated standardized tasks (Shi & Frey, 2021). In contrast to experimental setups, it seems difficult to identify a single main feature for natural activities that are chosen by users instead of being carefully selected and instructed by researchers. For a differentiation approach of non-driving related activates' effects, it seems not satisfactory to rely on one main feature, especially if the approach shall be applicable to natural automated driving settings.

(2) What are the overall effect sizes for differences in takeover time between non-driving related tasks based on task switching and modality shifting?

This dissertation addresses the identified gap between acknowledging task switching as the underlying paradigm for non-driving related tasks' effects in Level 3 automated driving, and the theories used to explain respective effects. Considering that a single main feature approach seems not suitable for the natural automated driving setting, a task switching based differentiation approach was developed. The aim is to extend limitations in explaining and differentiating effects of non-driving related activities. For a first estimate whether task switching may be a suitable approach, a meta-analysis was conducted (Shi & Bengler, 2022b). The estimated effect sizes represent effects that are expected when applying theory and empirical evidence from research on the task switching paradigm. Specifically, based on task switching theory by Rubinstein et al. (2001) effect sizes for early task processes (stimulus identification, response selection, movement production) were estimated considering the existing body of research that did not build on task switching theory. In addition, one effect size considered empirical findings on reduced switch costs by task similarity. Overall, the effect sizes support a task switching based differentiation approach. Causal inferences cannot be drawn from these effect sizes. For this purpose, an experimental investigation is needed.

(3) Does similarity in cognitive processes that are involved in the non-driving related task and the driving task, influence takeover behavior and subsequent manual driving behavior in a real ride?

This research question was investigated in a real driving setting on a test track. Level 3 driving automation was simulated using a Wizard-of-Oz vehicle. Natural activities served as experimental non-driving related tasks. The three tasks each show a different extent of cognitive similarity to the driving task. Takeover behavior was assessed in terms of takeover time and takeover quality as measured by accelerations. Manual driving behavior was assessed in terms of proximity to an imminent collision with a non-destructive crash target (balloon car). Results indicate significantly faster takeover after the non-driving related task of highest similarity to the driving task, and larger time-to-collision after this task (Shi & Bengler, 2022a). This pattern of results supports task switching theory and contradicts predictions based on multiple task performance.

In conclusion, the proposed task switching based differentiation approach seems suitable to differentiate between non-driving related activities without relying on a single main feature. Because the differentiation approach also considers the context of Level 3 automated driving, it can be used for different purposes. Since this dissertation provides a first step towards applying task switching theory and empirical findings to Level 3 automated driving, future research is needed to corroborate the findings.

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Appendix A: Declarations of Own Contribution

Declaration of Own Contribution

Title: Non-Driving-Related Tasks During Level 3 Automated Driving Phases – Measuring What Users Will Be Likely to Do

Authors: Elisabeth Shi, Alexander T. Frey

Description of Own Contribution

The initial idea for the study was developed by Elisabeth Shi and suggested to Alexander T. Frey. The study was jointly conducted. Elisabeth Shi was in charge of analyzing the data. Alexander T. Frey prepared the methods section of study 2 in German language. Elisabeth Shi wrote the original English manuscript. The manuscript was jointly reviewed before submission to the journal. Elisabeth Shi was in charge of the submission and review process, including correspondence with editor and editing staff members. Revisions were prepared by Elisabeth Shi and jointly reviewed before submission.

Dates and Signatures

[redacted]

Elisabeth Shi (First Author)

[redacted]

Alexander T. Frey (Co-Author)

Declaration of Own Contribution

Title: Non-driving related tasks' effects on takeover and manual driving behavior in a real driving setting: A differentiation approach based on task switching and modality shifting

Authors: Elisabeth Shi, Klaus Bengler

Description of Own Contribution

The initial idea for the study was developed by Elisabeth Shi and suggested to Klaus Bengler. The study was jointly refined and operationalizations were jointly discussed and agreed on. Elisabeth Shi was in charge of executing the study, including funding acquisition, study preparation and study conduction. Elisabeth Shi analyzed the collected data and wrote the original manuscript. The manuscript was jointly reviewed before submission to the journal. Elisabeth Shi was in charge of the submission and review process, including correspondence with editor and editing staff members. Revisions were prepared by Elisabeth Shi and jointly reviewed before submission.

Dates and Signatures

[redacted]

Elisabeth Shi (First Author)

[redacted]

Klaus Bengler (Co-Author)

Declaration of Own Contribution

Title: Overall effects of non-driving related activities' characteristics on takeover performance in the context of SAE Level 3: A meta-analysis.

Authors: Elisabeth Shi, Klaus Bengler

Description of Own Contribution

The initial idea of performing the meta-analysis was suggested by Elisabeth Shi to Klaus Bengler. The specifics of the meta-analysis were jointly refined. Elisabeth Shi was in charge of performing the meta-analysis. Elisabeth Shi collected and analyzed the data, and wrote the original manuscript. The manuscript was jointly reviewed before submission to the conference. Elisabeth Shi was in charge of the submission and review process, including correspondence.

Dates and Signatures

[redacted]

Elisabeth Shi (First Author)

[redacted]

Klaus Bengler (Co-Author)

Appendix B: Eidesstattliche Erklärung

Eidesstattliche Erklärung

Ich, Elisabeth Shi, (Vor- und Nachname) erkläre an Eides statt, dass ich die bei der promotionsführenden Einrichtung

TUM School of Management

der TUM zur Promotionsprüfung vorgelegte Arbeit mit dem Titel:

Non-driving related tasks in the context of Level 3 driving automation of passenger cars in traffic jams: A differentiation approach based on non-driving related tasks' characteristics

unter der Anleitung und Betreuung durch: Prof. Dr. Klaus Bengler

ohne sonstige Hilfe erstellt und bei der Abfassung nur die gemäß § 7 Abs. 6 und 7 angegebenen Hilfsmittel benutzt habe.

- [x] Ich habe keine Organisation eingeschaltet, die gegen Entgelt Betreuer*innen für die Anfertigung von Dissertationen sucht, oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt.
- [x] Ich habe die Dissertation in dieser oder ähnlicher Form in keinem anderen Prüfungsverfahren als Prüfungsleistung vorgelegt.
- [x] Teile der Dissertation wurden in vgl. Liste der Vorveröffentlichungen veröffentlicht.
- [x] Ich habe den angestrebten Doktorgrad noch nicht erworben und bin nicht in einem früheren Promotionsverfahren für den angestrebten Doktorgrad endgültig gescheitert.
- [ ] ~~Ich habe bereits am ______ bei der promotionsführenden Einrichtung ______ der Hochschule ______ unter Vorlage einer Dissertation mit dem Thema ______ die Zulassung zur Promotion beantragt mit dem Ergebnis: ______~~
- [x] Ich habe keine Kenntnis über ein strafrechtliches Ermittlungsverfahren in Bezug auf wissenschaftsbezogene Straftaten gegen mich oder eine rechtskräftige strafrechtliche Verurteilung mit Wissenschaftsbezug.

Die öffentlich zugängliche Promotionsordnung sowie die Richtlinien zur Sicherung guter wissenschaftlicher Praxis und für den Umgang mit wissenschaftlichem Fehlverhalten der TUM sind mir bekannt, insbesondere habe ich die Bedeutung von § 27 PromO (Nichtigkeit der Promotion) und § 28 PromO (Entzug des Doktorgrades) zur Kenntnis genommen. Ich bin mir der Konsequenzen einer falschen Eidesstattlichen Erklärung bewusst.

Mit der Aufnahme meiner personenbezogenen Daten in die Alumni-Datei bei der TUM bin ich

- [x] einverstanden,
- [ ] nicht einverstanden.

Bergisch Gladbach, 01.08.2023 [redacted]

Ort, Datum, Unterschrift

Appendix C: Publications included in this thesis

Publication 1

Shi, E., & Frey, A. T. (2021). Non-driving related tasks during Level 3 automated driving phases - Measuring what users will be likely to do. *Technology, Mind, and Behavior, 2*(1). https://doi.org/10.1037/tmb0000006

Publication 2

Shi, E., & Bengler, K. (2022). Non-driving related tasks' effects on takeover and manual driving behavior in a real driving setting: A differentiation approach based on task switching and modality shifting. *Accident Analysis and Prevention*, 178, 1–17. https://doi.org/10.1016/j.aap.2022.106844

The adjunct publication

Shi, E., & Bengler, K. (2022). Overall effects of non-driving related activities' characteristics on takeover performance in the context of SAE Level 3: A meta-analysis. In K. Plant & G. Praetorius (Eds.), *Human Factors in Transportation. AHFE (2022) International Conference* (pp. 69–77). AHFE Open Access. https://doi.org/10.54941/ahfe1002435