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The DAUX Framework: A Need-Centered Development Approach for User Experience in Driving Automation

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Statutory declaration

I hereby declare that the thesis submitted is my own unaided work, that I have not used other than the sources indicated, and that all direct and indirect sources are acknowledged as references. This printed thesis is identical with the electronic version submitted.

Parts of this thesis have been published as international conference papers or journal articles:

- Core Publications: [1, 2, 3, 4, 5, 6, 7, 8, 9]
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Place, Date | Anna-Katharina Frison

Abstract

The individual and societal benefits of driving automation can only unfold if the underlying technology is established on the market. As user acceptance is dependent on users' experience with a technology, i.e. user experience (UX), novel user interfaces (UIs) need to be developed to balance drawbacks of individual automation levels (SAE J3016). Therefore, the predominant innovation- and technology-centered perspective has to be supplemented by a user-centered approach. As a solution, the "DAUX Framework", as part of a need-centered development approach, is proposed. The framework offers guidelines how to a) identify relevant needs for hypothesis/ UI concept development and b) evaluate UX by triangulating behavioral, product-, and experience-oriented methods. To derive recommendations for UI development, the introduced approach is applied in three case studies. Thereby, example UIs for different levels of automation are developed (SAE L2, L3, and L4/5) and then evaluated in a high-fidelity driving simulator. Results about partial driving automation (SAE L2) imply, all properties of an automated vehicle, also usability and aesthetics of an embedded UI, wrongly impact drivers' fulfillment of the need of security. Hence, the current system performance must always be transparent. A safe trip is the basis of positive driving experiences. Further, skipping the launch of conditional driving automation (SAE L3) is not only justifiable from safety, but also from experiential perspective. Results show that due to users' needs for autonomy, competence, and security, the mere possibility of a take-over-request at any time negatively impacts the whole journey experience. At high and full driving automation (SAE L4/5), users worry about their needs of competence, autonomy, and the meaning of driving interactions, e.g., accelerating. Although engaging in non-driving related tasks might balance these problems, there will still be users who appreciate the joy of driving. Hence, optional control should always be offered. The "DAUX Framework", as part of a need-centered development approach, has been applied in different use cases and has proven to be a valid and useful approach for developing UIs to improve UX for driving automation. Consequently, this PhD work supports - by appropriate design and development of UIs - the individual and societal acceptance of the technology of driving automation. This work lays the foundation that promised advantages can be realized.

Kurzfassung

Individuelle und gesellschaftliche Vorteile des automatisierten Fahrens können nur Realität werden, wenn sich die Technologie am Markt etabliert. Da die Benutzerakzeptanz von den Erlebnissen der Nutzer mit einer Technologie, d.h. User Experience (UX) abhängt, müssen geeignete Benutzerschnittstellen (UIs) entwickelt werden, um die Nachteile der einzelnen Automatisierungsstufen auszugleichen (SAE J3016). Die vorherrschende innovations- und technologiezentrierte Perspektive muss daher durch einen nutzerzentrierten Ansatz ergänzt werden. Dafür wird das "DAUX Framework" als Teil eines Bedürfnisorientierten Entwicklungsansatzes vorgeschlagen. Dieses bietet Leitfäden für a) die Identifizierung relevanter Bedürfnisse für Hypothesen/ UI Konzeptentwicklung und b) die Triangulation von verhaltens-, produkt- und erlebnisorientierten Methoden zur Evaluiering von UX. Um Empfehlungen für die UI-Entwicklung ableiten zu können, wird der Ansatz in drei Fallstudien angewendet. Es werden Beispiel-UIs für jede Automatisierungsstufe entwickelt und in einem High-Fidelity Fahrsimulator evaluiert. Die Ergebnisse zum teilautomatisierten Fahren (SAE L2) implizieren, dass alle Eigenschaften eines automatisierten Fahrzeugs, auch die Usability und Ästhetik einer UI, das Sicherheitsbedürfnisses der Fahrer fälschlicherweise beeinflussen. Die gegenwärtige Performanz eines automatisierten Systems muss daher immer transparent dargestellt werden. Eine sichere Fahrt ist die Basis für positive Fahrerlebnisse. Des Weiteren ist der Verzicht auf die Markteinführung des bedingt automatisierten Fahrens (SAE L3) nicht nur aus Sicherheitsgründen, sondern auch aus Erlebnisperspektive gerechtfertigt. Aufgrund der Bedürfnisse nach Autonomie, Kompetenz und Sicherheit kann die bloße Möglichkeit einer jederzeitigen Übernahmeanforderung das Gesamterlebnis negativ beeinflussen. Beim hoch- und vollautomatisierten Fahren (SAE L4/5) sorgen sich Nutzer über die Bedürfnisse nach Autonomie, Kompetenz, und den Verlust der Bedeutsamkeit von Fahrinteraktionen z.B. Beschleunigung. Obwohl die Beschäftigung mit nicht fahrbezogenen Aufgaben dieses Problem ausgleichen könnte, wird es immer noch Nutzer geben, die die Freude am Fahren schätzen. Daher sollte optional kooperative Fahrzeugsteuerung angeboten werden. Das "DAUX Framework" des bedürfnisorientierten Entwicklungsprozesses hat sich als gültiger und nützlicher Ansatz zur Entwicklung von UIs zur Verbesserung der UX beim automatisierten Fahren bewährt. Diese Arbeit legt somit die Grundlage für die Realisierung der versprochenen Vorteile des automatisierten Fahrens.

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List of Abbreviations

AAP	Accident Analysis and Prevention Journal
ACC	Adaptive Cruise Control
ADAS	Advanced Driving Assistance Systems
ADS	Automated Driving System
AmpSum	Sum of SCR-Amplitudes of Significant SCRs wrw
AV	Automated Vehicle
CHI	Conference on Human Factors in Computing Systems
CHRS	Cooper-Harper Rating Scale
CTAM	Car Technology Acceptance Model
DDT	Dynamic Driving Task
DSI	Driver Stress Inventory
DSQ	Driving Style Questionnaire
DSSQ	Dundee Stress State Questionnaire
ECG	Electrocardiography
EEG	Electroencephalogram
EMG	Electromyogram
GSR	Galvanic Skin Response
HCI	Human-Computer Interaction
HEMA	Hedonic and Eudaimonic Motives for Activities Scale
HFES	Journal of Human Factors and Ergonomics Society
HMI	Human Machine Interface
HR (BPM)	Heart Rate (Beats Per Minute)
ISCR	Area (i.e. time integral) of phasic driver wrw
IVIS	In-Vehicle Information System
LKAS	Lane-Keeping Assist System
MABA	Men-Are-Better-At/Machines-Are-Better-At
MMSQ	Multi-Modal Stress Questionnaire
NDRT	Non-Driving-Related Task
nSCR	Number of significant (= above-threshold) SCRs wrw
ODD	Operational Design Domain
OEDR	Object And Event Detection and Response
OEM	Original Equipment Manufacturer
PANAS	Positive Negative Affect Schedule
PBQ	Pedestrian Behavior Questionnaire
RMSSD	Root Mean Square of the Successive Differences
RQ	Research Question

SAE	Society of Automotive Engineers
SAGAT	Situation Awareness Global Assessment Technique
SAM	Self-Assessment Manikin
SART	Situation Awareness Rating Technique
SCR	Average phasic driver wrw window
SOP	Start of Production
SSQ	Simulator Sickness Questionnaire
SSSQ	Short Stress State Questionnaire
TAM	Technology Acceptance Model
TOR	Take-Over Request
TRF	Transportation Research Part F Journal
UCD	User-Centered Design
UEQ	User Experience Questionnaire
UES	User Engagement Scale
UI	User Interface
UTAUT	Unified Theory of Acceptance and Use of Technology
UX	User Experience
wrw	within response window

1 Introduction

Within the next few decades, individual mobility will reach a higher level of innovation. All global players in the automotive industry (e.g., Audi, BMW, Renault, Tesla, Volvo, etc.) as well as technology companies (e.g., Apple, Google, Intel, NVidia, Waymo), are working hard to bring Automated Driving Systems (ADS) [47] with new service and ownership models onto the streets. They aim to create a better way of individual and public transportation [48, 49]. Technology is predicted to involve the societal main benefit of significantly reducing the number of accidents [50] and, at the same time, to allow the users to individually benefit from the fact that *"automation takes on tedious, boring, or error-prone tasks using machines and algorithms [...] that humans will then be free to do more exciting and more cognitively challenging tasks"* [51, p. 41]. Hence, the technology of driving automation ought to improve users' driving experiences by making them safer and more enjoyable (cf. [52]).

Nevertheless, these promises can only come true if users are willed to use such systems. But until now societal acceptance is still unclear. It is also questionable whether driving automation will actually create such positive experiences. The development of driving automation systems seems to be driven by an innovation- and technology-centered perspective [53, 54, 55], [17][1]. Implications on users' experience, which is determined by the changing role from active drivers to passive passengers (see Figure 1.1), are largely ignored. Of course, the technical development has to go on, but to foster user acceptance,

[1] our own publications are highlighted in blue

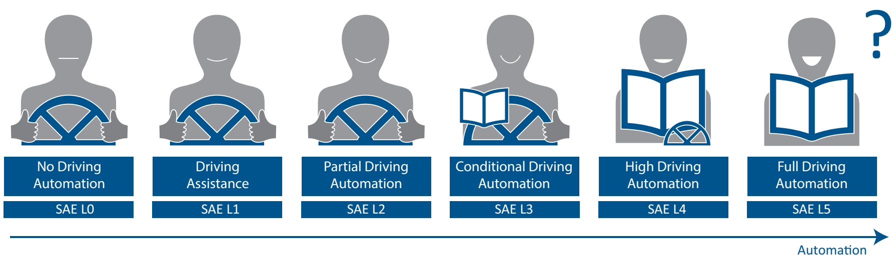

Figure 1.1: Expected changing role and experience of the user within the taxonomy of driving automation (SAE J3016 [47]).

it is necessary to additionally include *user experience* (UX) of driving automation into the development process. Technical restrictions of the different levels of automation (SAE J3016 [47] is introduced in Subsection 1.2.2) and their implications on users' needs have to be carefully regarded in a human-centered development process. Therefore, a holistic method to study UX of driving automation is demanded.
The overall goal of this doctoral thesis is to derive a practical development approach for user interfaces that support users during their drives. Therefore, the following research questions (RQs), that build upon each other, are put forward:

- **RQ1: How is UX in the context of driving automation methodologically addressed in practice?**
- **RQ2: How can UX theory and the insights from UX practice be combined to optimize the development process of driving automation systems?**
- **RQ3: How must user interfaces be designed to positively affect UX *of driving* and *while being driven*?**

The following sections of the introduction are basis and motivation for the research approach of this presented doctoral thesis. They give an overview of the role of the driver as a user in automotive research history from the first automobile in the past to the development of driving automation systems in the present and the future (Section 1.1). Afterwards, the challenges of automation in general and in the driving context, including definition, the taxonomy of driving automation, and current results of studies estimating individual and societal acceptance, are highlighted (Section 1.2). Further, the potential and challenges of UX design approaches are demonstrated (Section 1.3). Implications of these sections lead to the research approach (Section 1.4) and the outline (Section 1.5) of the thesis.

1.1 Historical Overview of the Role of the User in Automotive Research

In history, humans' wish for mobility, to get faster, more safe and more convenient from A to B, always inspired and pushed transport innovations on land, sea, and air. Since at the end of the 19th century the automobile with a combustion engine was developed (Carl Benz 1986) individual motorization started and therewith also automotive research [56].

At those times, the main focus was to set up basic functional requirements for the operational task of driving [57], i.e., longitudinal and lateral control. This was not only done based on experience from other transportation systems, but also based on drivers' requirements.

According to Akamatsu et al. [56], the dawn of human factors design appeared in the years from 1920 to 1939. For example steering equipment and sitting position were optimized, however *"largely [based] on heuristics from engineers' experience"* [56, p. 4]. As after World War I the number of traffic accidents increased in parallel with mass production, combining technology and psychology for vehicle design to increase safety by addressing human capabilities and limitations, received more and more attention.

During World War II, this new branch of research, "human factors" was used to increase efficiency and reliability of military technology, and expanded afterwards to the aviation and automotive industry. The focus, which initially concentrating on drivers' safety (e.g., driver fatigue, mental workload, visual demand), started 1970-1980 to think about occupant comfort. In this decade human factors research was translated into practice by developing design and evaluation standards. Hence, drivers' requirements were actively involved in research and development [56].

In the 1990s, intelligent transportation systems (information and driver assistance systems) with the aid of information and communication technology had their starting point of development. The goal was to enhance mobility and to increase further road safety. In the development process, for the first time insights from human-computer interaction (HCI) about office work were involved. As information technology requires different interaction techniques, HCI evolved as a multi-disciplinary field from computer science, human factors, and cognitive science in the early 1980s [58]. The first wave of HCI research was dominated by the sciences it emerged from, thus, it was model driven, and humans were studied as subjects mainly in laboratory setups [59], [13]. Bannon [60] criticized this in 1995: *"the human is often reduced to being another system component"* (p. 26) – individual values and motivation to use a system in a certain work setting had been so far neglected. In the second wave, majorly influenced by cognitive science, theories about what happens in users' minds (e.g., information-processing [61]) were emphasized [59, 13]. With the entering of HCI research into the automotive research domain, the effects of user interfaces (embedded or mobile systems) on driving safety, were investigated. The main goal was to support *"the driver by reducing the distractions of secondary tasks"* [62, p. 35].

The first steps towards driving automation systems were made in the 2000s with connected vehicle systems and advanced driving assistance systems (ADAS) – adaptive cruise control (ACC) was introduced at the end of the 1990s and

lane-keeping assist systems (LKAS) in 2000 [56]. While safety-related problems still dominate automotive research, the impact of HCI has gained more and more attention. Thus, the AutomotiveUI conference series was founded in 2009. Therewith, automotive research is also shaped by further developments of HCI. Hence, in the third wave, as beginning with this century *"technology spread from the workplace to our homes and everyday lives and culture"* [59, p. 26], HCI researchers and practitioners alike started to postulate a focus on experience-related product characteristics [63] to serve the needs of a post-materialistic experience society [13]. Additional contextual factors, as well as UX, are regarded as part of the design process [64] and UX design became a new profession. Consequently, also in automotive research, UX design of in-vehicle systems received increasing attention [62, 65, 55].
Especially in the context of driving automation, UX is emphasized as important when active drivers become passive passengers. The in-vehicle environment which until now requires high concentration and great responsibility of the driver will be transformed in an area of relaxation and social interaction [66]. Further, new ownership models (e.g., car-sharing) will change users' relationship and emotional attachment to vehicles [10]. By making systems more useful, usable and pleasurable by concentrating on users' needs and requirements within a human-centered approach [67], faster adoption and higher acceptance in the society could be achieved. However, driving automation is still mainly technology-centered [53, 54, 55], [17]. Human-related issues with automation are not solved and questions according to how to allow a *"humane experience"* (p. 99), e.g., addressing humans' wish to contribute to the driving task to stay in control while preserving the benefit of increased road safety, are still unanswered [68]. Hence, applying a *"holistic UX design method"* [55, p. 79] is challenging. Due to the nature of automation and the variety of interfaces users may act in a vehicle equipped with driving automation features, new methods are necessary to explore the future of automotive UX [69].

Implications for this Thesis To conclude, the history of automotive research has shown that the role of the user has received more and more attention. Further, the temporal development shows a shift from pure safety and usability research towards involvement of experiential and emotional aspects. This is of particular importance for successful driving automation development and the establishment of such systems on the market. Nonetheless, methodical approaches to study UX have to be adapted to the requirements of driving automation. To address the recent and upcoming dares and to create positive UX, we have to understand challenges of driving automation and how to design for it. These are described below.

1.2 Challenges of Driving Automation

As shortly touched above, driving automation comes with various challenges, especially concerning unsolved human-related issues. These need to be considered to create positive UX in automated vehicles [55]. Driving automation systems are thereby part of an overarching phenomenon of our time – the automation. Hence, before different levels of driving automation (SAE J3016) and acceptance issues are explained in detail, a general view on how to define automation is given.

1.2.1 Definition of Automation

According to Parasuraman and Riley [70], automation is defined *"as the execution by a machine agent (usually a computer) of a function that was previously carried out by a human"* (p. 231). Reasons to introduce automation in the past, especially in an industrial context, were to manage time-consuming and tedious tasks more efficiently, reliably, and accurately than human operators can do. However, humans cannot be simply surrogated what would be easy from a human factors perspective. Automation rather changes the nature of humans' work by new, often unintended and unanticipated, tasks which occur [70, 71] and affect users' experience with the technology. A reason for this is that automation is not *"all-or-none"* [70, p. 232]. It is defined by different levels of intelligence and autonomy which determine the automation state [72]. It *"can vary across a continuum of levels, from the lowest level of fully manual performance to the highest level of full automation"* [73, p. 287], see Table 1.1.

	Level	**The computer...**
High	10	...decides everything and acts autonomously, ignoring the human.
	9	...informs the human only if it, the computer, decides to.
	8	...informs the human only if asked.
	7	...executes automatically, then necessarily informs the human.
	6	...allows the human a restricted time to veto before automatic execution.
	5	...executes that suggestion if the human approves.
	4	...suggests one alternative.
	3	...narrows the selection down to a few.
	2	...offers a complete set of decision/action alternatives.
Low	1	...offers no assistance, the human must take all decisions and actions.

Table 1.1: Scale of automation levels of decision and control action [74, 73].

Hence, humans cannot be simply replaced, they have to manage the automation [71]. Accordingly, Parasuraman and Riley [70] stated:

> *"One of the considerations preventing the total removal of human operators from such systems has been the common perception that humans are more flexible, adaptable, and creative than automation and thus are better able to respond to changing or unforeseen conditions. [...] Given that no designer of automation can foresee all possibilities in a complex environment, one approach is to rely on the human operator to exercise his or her experience and judgment in using automation"* (p. 232).

Tasks are divided between human and computer, however, especially in intermediate levels of automation it is not only a simple *"who does what"* question, it involves also *"how to work together"* [71, p.53], cf. also [75, 76]. Different approaches to defining types of automation exist, however, they are not mutually exclusive. Each approach has its justification and they should complement each other. Thus, different perspectives enhance the understanding of human-automation interaction and guide automation design [77].

Moss et al. [78] differentiate in the context of aircraft automation between *mission, functional* or *task goals* which can be either done by a *pilot* only (human/operator), a computer only or shared between both. This is similar to Michon's [57] description of driver behavior at manual driving, differentiating between *strategical, tactical* and *operational tasks.* These are also used to describe different types of automation [77] to understand who does what: *strategical* automation (related to *mission goals*) contains the definition of goals and balancing thereby cost and values, e.g., planning a route. *Tactical* automation (*functional goals*) means automated coordination functions, e.g., route guidance and notifications on upcoming turns. *Operational* automation (*task goals*) contains *"perceptual cues and motor"* [77, p. 1624] response like longitudinal and lateral vehicle control. Thereby, different time spans for decision making are necessary – from milliseconds on the operational level to seconds and minutes on the tactical level, and minutes to days on the strategical level. Further, automation on one level may impact users' behavior on another level, e.g., if keeping distance is performed automatically (*operational level*), people decide to do other activities and neglect to monitor system behavior and may fail to override the system if necessary (*tactical level*). According to Moss et al.'s [78] design philosophy, an allocation or substitution of tasks and functions should follow the MABA-MABA principle (Men-Are-Better-At/Machines-Are-Better-At), originally developed by Fitts [79].

Utilizing information processing and its functions is a further way to describe how automation replaces humans by taking over their former tasks of perceiving and responding to the environment [73, 77]. Simplified from Broadbent [80] by

Parasuraman et al. [73], the stages of information processing are *information acquisition, information analysis, action selection,* and *action implementation.* The combination of the stage of information processing and the degree from high to low automation (see Table 1.1) describe different types of automation that pose individual design challenges. Parasuraman et al. [73] propose for automation design a two-stage process evaluating humans' performance consequences like mental workload or situation awareness as primary evaluative criteria and automation reliability and the costs of decision/action consequences, among others, as secondary criteria to decide which tasks to automate and which not.

However, taxonomies, especially the allocation of tasks between system and human according to the MABA-MABA principle [79], is highly debated. Although levels of automation describe the degree of involvement of the user as a supervisor, the allocation as Parasuraman and Riley [73] do with the information processing stages, is criticized as arbitrary. Further, it is deprecated that operators' effort to decide when and how to intervene and to switch between the levels, is neglected [75]. Distinct classification of systems in levels is often not even possible [81]. Moreover, an increasingly autonomous system is not a single element, it is rather a network of multiple interconnected automated elements what may lead, if not considered, to distraction by different independent warning systems, mode confusion, and over-reliance [71].
Contrarily, levels of automation are seen as a useful tool to guide automation design [76, 71]. Kaber [76] contends:

> *"I question how it is actually possible to discuss HAI* [Human-Automation Interaction] *if we do not have some concept of what and how the automation and human will do. Only with such information can engineers begin to talk about interface design and interaction protocols (i.e., 'team play' will always be a strategy for integration of functional capabilities of 'players')"* (p. 22).

He demands an iterative process to develop more fine-grained and descriptive levels of automation. By this, human-automated systems performance can be predicted more precisely.

Implications for this Thesis The discussion about the validity and usefulness of automation levels and different types of automation reveals the complexity of the topic and implications on users, designers have to deal with. Hence, it is imperative to define what is meant by automation when designing for it. Although a classification in distinct levels has its drawbacks, we agree with Kaber [76] and see a taxonomy as an important guideline for automation design. In the following, the taxonomy for driving automation is described in detail.

1.2.2 Taxonomy of Driving Automation (SAE J3016)

In the context of motor vehicles, the SAE International (Society of Automotive Engineers) defined a taxonomy of driving automation, called SAE J3016 [47], and defined all relevant terms and levels of automation (SAE L0-5), see Figure 1.1 and Table 1.2. *Driving automation system* is introduced as the general term for all systems *"collectively capable of performing part or all of the DDT* [Dynamic Driving Task]" [47, p. 5]. This consists of all required operational and tactical functions (cf. Michon [57] above) to operate a vehicle. An Automated Driving System (ADS) specifically addresses SAE L3-5 driving automation systems.

Terminology: Driving Automation

This doctoral thesis was started back in 2016, therefore scientific discussions rely on the SAE J3016 specification of 2014 [82] and 2016 [83]. The term *driving automation* instead of *"automated driving"*, as well as the clear differentiation between *driving automation systems* (all levels) and *Automated Driving System* (ADS, only SAE L3-5) was, however, only introduced in the update of 2018 [47]. To stay consistent with current definitions in the most recent version of the SAE J3016 of 2018, all terms are updated in this thesis. Further, to simplify wording, the term *automated vehicle* (AV) is used to describe a vehicle equipped with any kind of driving automation system feature. In order to be more specific, the respective level is added textually, e.g., *"an automated vehicle in SAE L3"* or *"automated vehicle (SAE L3)"*.

As Kaber [76] demanded, the SAE Recommended Practice was developed in iterations with an initial publication in 2014 and based on the BASt [50] and the NHTSA levels [84]. It claims to be descriptive by including functional definitions and aims to be consistent with current industry practice, across disciplines (engineering, law, media) and public discourse. The taxonomy with six different levels from no (SAE L0) to full driving automation (SAE L5) regards the changing role of user and driving automation system in relation to each other. Thereby, with increasing automation, an active driver becomes a passive passenger, which will radically change road traffic [54] and therewith the general user experience. Former tertiary tasks (not directly related to actual driving, e.g., communication or entertainment [85]) can become to primary tasks receiving largest amont of mental and physical ressources [86, 87]. Further, new activities like working, playing, relaxing and socializing, so-called non-driving-related tasks (NDRTs), can be performed. But this also means that passengers have to trust in a system and relinquish control. However, as users cannot be simply replaced, dependent on the respective level of automation, new unexpected tasks for human operators (drivers) and challenges as well as errors can occur which need to be recognized and supported in the design [9]. The need to be especially user-centered in the context of automation can be somehow interpreted as an irony of automation (cf. [70, 88, 77, 89]). Hence, the SAE levels (J3016) [47] and its discrete and mutually exclusive six levels of automation (SAE L0-5) are an important guideline for design throughout the presented doctoral thesis, see Table 1.2.

No Driving Automation (SAE L0) No driving automation (SAE L0) means the driver performs the entire DDT. Active safety systems, like electronic stability control, are momentary and do not change the role of the driver, hence, are not seen as driving automation feature.

Driver Assistance (SAE L1) With driver assistance, either longitudinal or lateral vehicle motion control is executed automatically, i.e., either ACC or LKAS, in a specified operational design domain (ODD). For the remaining driving task, the user is responsible. The ODD is the operating condition (e.g., environmental or geographical) a driving automation system or feature is designed for and limited to. It can be also seen as the context factor in which a driving automation system is able to operate. Both, SAE L0/L1 can still be seen as manual driving, hence, UX is primarily affected by controlling the system, e.g., the driver performs the driving task on an operational (lateral and/or longitudinal control), tactical (maneuver decisions), and strategical (e.g., navigation) level [57]. In order to support the driver in these tasks, designers must minimize the negative effects of distraction on workload, situation awareness, etc., resulting, e.g., from in-vehicle information system (IVISs) usage [90]. Approaches thereby include (but are not limited to) correct placement of in/output controls [91], or alternative interaction modalities to keep drivers' eyes on the road and hands on the wheel [92, 93] (cf. Section 1.1). However, already the presence of advanced driver assistance systems (ADAS, such as ACC) in lower automation impacts drivers UX. Eckoldt et al. [94] argue that ACC creates a distance between the driver and the vehicle due to the loss of control. They concluded that, if the *"joy of driving"* (p. 165) is important for drivers, ACC is perceived negatively, while for others it can induce a feeling of freedom (*"joy while driving"* (p. 165)). They further stated that the fulfillment of certain psychological needs in a specific context (e.g., feeling competent by successfully managing a difficult situation like parking) is essential to create *"good experiences"* (p. 170). Although this insight is also relevant for higher levels of automation in this presented work, in SAE L0 and L1 user engagement for basic vehicle control is still necessary, thus, both levels are excluded for detailed analysis in this doctoral thesis.

SAE Level		Name	DDT Sustained lateral and longitudinal vehicle motion control	 OEDR	DDT fallback	ODD
Driver performs part or all of the DDT						
0		**No Driving Automation**	Driver	Driver	Driver	n/a
1		**Driver Assistance**	Driver and System	Driver	Driver	Limited
2		**Partial Driving Automation**	System	Driver	Driver	Limited
ADS (“System”) performs the entire DDT (while engaged)						
3		**Conditional Driving Automation**	System	System	Fallback-ready user (becomes the driver during fallback)	Limited
4		**High Driving Automation**	System	System	System	Limited
5		**Full Driving Automation**	System	System	System	Unlimited

Table 1.2: Taxonomy of driving automation (SAE J3016 [47]).

Terminology: UX *of driving* vs. *while being driven*

According to Eckoldt et al. [94] we differentiate between *"UX of driving"* and *"UX while being driving"*. Any experience elicited by activities connected to strategical, tactical or operational driving tasks [57] is referred to as *"UX **of** driving"*. Contrarily, any experience elicited by NDRTs is referred to as *"UX **while being** driving"*.

Partial Driving Automation (SAE L2) In this level, both, lateral and longitudinal control are conducted by the automation in a specific ODD. However, there is a probability that events occur in which the system is not able to respond correctly. Hence, it is expected that the driver is monitoring and supervising the system. This includes also the completion of object and event detection and response (OEDR), hence, tactical driving tasks that are only limited available in this level of automation. OEDR is a subtask of the dynamic driving task. Drivers need to detect, recognize, and classify objects and events, be prepared to respond, and intervene appropriately if necessary, i.e., to complete the DDT (e.g., by braking or accelerating, and steering). Thereby, when physical tasks are automated, the type of feedback changes. An example is a feedback of having the feet on the pedals and perceiving immediate reaction on the own behavior which do not longer exist [77]. Consequently, users have to handle more complex cognitive tasks like monitoring, which is challenging over long periods of time [89, 95].
Further, with new possibilities of automation operators tend to adapt their behavior. The way they use and rely on the automation differs based on how designers and managers expected regarding safety maintenance and performance increase. In the worst case, automation failures might not be detected and operators may not able to intervene appropriately when necessary. Thus, they need a proper understanding of how the automation works and where the borders are [77]. Further, designers must aim to keep drivers in the loop, so that they continuously monitor the automation while permanently being prepared for intervention. Recent incidents with L2 technology (such as the fatal accidents with the Uber self-driving Taxi in 2018), but also user studies [95] have highlighted the importance of new interfaces, such as reliability displays, to improve monitoring, interventions, or multitasking [96, 97],[36].
Consequently, in SAE L2 the relevant question for UX design is to balance safety-related aspects like monitoring and interventions, multitasking demand, limited knowledge of system boundaries/capabilities, etc., while preventing automation misuse (i.e., unintentional different usage of systems of automation, as designers expected, e.g., overreliance), abuse (i.e., intentional misuse, e.g., by cheating systems) and total disuse (i.e., not using automation at all) [70].

Conditional Driving Automation (SAE L3) This is, according to SAE J3016, the first level of Automated Driving Systems (ADS). Here, the entire DDT, including the OEDR, is performed by the system when engaged and does not have to be supervised and users are allowed to engage in NDRTs. Though, drivers remain fallback-ready users and must expect to have to intervene upon takeover requests (TOR) which might occur during a ride. TORs are issued by the ADS in sufficient time, however, this also means that after reception users have to respond by resuming manually driving the vehicle or bringing the vehicle in a minimal risk condition if the vehicle is not able to go anymore. Hence, the passive fall-back-ready user becomes again to the active driver. Thus, human-related problems like out-of-the-loop unfamiliarity, surprising mode transitions, and operator skill loss emerge [77]. These issues need to be carefully regarded in design because if the user is not receptive and does not respond appropriately, the system performs a failure mitigation strategy, e.g., stop-in-lane, which might cause fatal consequences. Therefore, the vehicle-driver cooperation design has to be optimized by keeping all facets of human-machine cooperation in mind. For example, Walch et al. [98] suggest a cooperative control interface tailored to specific scenarios, which do not demand the driver to reengage in the full DDT.
In phases of enabled automation, UX will be affected by NDRTs and automation behavior. For example, Kuderer et al [99] claim that the driving style (sportive, ecological, etc.) is highly relevant for the overall UX of driving automation, which is confirmed by Bellem and colleagues [100]. Pfleging et al. [101] analyzed the preferences of NDRTs during driving automation and identified talking to passengers, listening to music, daydreaming, texting, eating and drinking, browsing the Internet, and calling as the most desiered activities. But how to support users in the engagement in these NDRTs, especially in SAE L3 in which they have to expect to intervene at any moment, is still an open question.

High Driving Automation (SAE L4) In SAE L4, also the entire DDT in a specific ODD is performed automatically, however, users are not expected to intervene upon a request. Hence, the SAE L4 driving automation system will achieve a minimal risk condition in the worst case – the DDT-fallback is performed automatically and users do neither have to supervise nor be receptive. The former active driver is now a passive passenger. As SAE L4 is dependent on the ODD, i.e., operational conditions like a specific environment, it can be engaged for whole trips or only for a part of a route, e.g., a dedicated highway (after leaving the highway users have to take-over control). If the ODD ends, the user will be notified to resume operating within a not time-critical period.

Full Driving Automation (SAE L5) This level has simular characteristics as SAE L4 but is not restricted to an ODD – *"the ADS can operate the vehicle under all driver-manageable road conditions within its region of the world"* [47, p. 25]. Of course, there is always a possibility of conditions not manageable by an ADS, but then, achieving a minimal risk condition will be ensured. Regarding UX design, Pettersson and Karlsson [102] revealed a tension between the wish to engage in NDRTs (as the main benefit of ADSs) and a still existent distrust into such systems which hinders users to engage in NDRTs. Future research *"needs to expand from a predominantly 'driver focus' towards a more prominent 'user focus' "* (p. 700), which leads to implications on car interior and HMI design. Distler et al.'s [103] results indicate safety and users' performance expectations as a prerequisite for good UX.

Implications for this Thesis The presented levels of automation are assigned to features to express the design intention *"based on the manufacturer's knowledge of the feature's/system's design, development, and testing"* [47, p. 30] and different levels of driving automation come with different challenges for UX design [104, 69]. According to the requirements and related human issues of the specific levels, manufacturers also need to regard the effects on UX as it finally impacts use, misuse, disuse and abuse of automation [70]. While in other fields (e.g., industry or aviation), operators are professionals and main promises for managers are to increase the feasibility and reduce costs by increased efficiency, lower workload and decreased human errors [70, 77], for driving automation this is different. Users are customers spending their private time in a vehicle which is considered as personal space [69]. Consequently, the demand to solve human-related issues in driving automation is even higher than in e.g., aircraft. Holistic positive UX for users is necessary to achieve individual and societal acceptance. The following section shows a snapshot of the current results of acceptance studies about driving automation.

1.2.3 Individual and Societal Acceptance

While increased safety, optimized traffic flow, less emission, more mobility also for new target groups and better driving experiences [50, 105, 48] are praised and promised, we cannot ignore that users' acceptance of this new technology is still unclear [49]. Below, results from a priori and actual experience on acceptance are summarized.

Especially regarding ADS, it is difficult to capture individual and societal acceptance as users of today are not the users of tomorrow [16]. Surveys and studies lack in their overall significance, as most interviewees have neither experienced yet a drive with ADSs, nor imagined assisting user interfaces which

might increase their acceptance because of meaningful interactions. Statements are based on pure imagination, however, give a picture on priori acceptability [106, 54].
In an international survey Schoettle and Sivak [107] as well as Nordhoff et al. [108] revealed a generally positive attitude towards driving automation with high expectations in the promised benefits. However, the majority still mentioned concerns about safety issues, e.g., by system failures, and expect humans as the better drivers [107]. Only 19% of participants of a survey conducted in Austria [109] believe that automated vehicles will increase road safety. Overall, 25% even think that due to software problems the number of accidents will increase. Roedel et al. [104] investigated technology acceptance and UX of different driving expectations towards different automation levels utilizing the Technology Acceptance Model (TAM) [110] and the Car Technology Acceptance Model (CTAM) [111], an extension for the automotive context adding safety and anxiety as determinants. Further, they used trust and fun as factors to analyze UX. Results show that with increasing levels of automation, perceived UX and acceptance decreases. The authors attribute this to skepticism about the unknown, decreased driving fun, and loss of control in higher levels of automation. Also, a further international study [112] revealed that 80% wish the possibility to intervene and take back control at any time. This is along with Elbanhawi et al. [113] who define the loss of control as comfort criteria for driving automation, a prerequisite for trust which is a key element for acceptance [114, 54]. Besides, also knowledge, risk and benefit perceptions [115], attitude, context like road type and driving environment, sensation seeking and gender [106] are identified as predictors for users' intention to use a driving automation system.

Studies looking at acceptance after actual experiences (not a priori) show an acceptance increase after the first usage, e.g., of ADAS [116] and park assistant systems [117]. Interviews with Tesla drivers about the autopilot system confirm a positive attitude towards partial automated driving on real roads [118]. Further, also studies about highly automated vehicles in driving simulators, test tracks, and on real road with an automated shuttle yield in similar results [54], [37, 42]. However, Distler et al.'s [103] study showed an impairment of acceptance regarding the aspects of participants' performance expectations and perceived usefulness. They analyzed acceptability and acceptance of *"autonomous mobility on-demand"* with a real operating automated shuttle. In their case study, the low speed of the automated shuttle (9-10 km/h) led to a decrease of the perceived usefulness. The performance of the system did not come up to the participants' expectations. Similar problems of operating automated shuttles were also revealed by Nordhoff et al. [119] and by a study we conducted [37, 42].

Van Schaik and Ling [120] revealed that perceived product attributes (pragmatic, i.e., usability, and hedonic aspects which go beyond pure usability by *"cognitive, socio-cognitive and affective influences on users interaction"*(p. 18)) during an interaction experience, are independent determinants for beliefs which again influence users' intention to use a system [121]. This means, appropriate user interfaces can increase user acceptance. Hence, all promises which are given by the concept of driving automation require advanced technology, but in addition, intelligent and well-designed user interface (UI) concepts that support the user during the drive.

Implications for this Thesis While results of a priori studies still question users' intention to use driving automation systems, after really experiencing them in simulators, on test tracks, or even in real traffic, acceptance increased across different levels of automation. These are positive indicators for success, nonetheless, long term effects and individual differences of users are still unclear (Tesla drivers are still early adopters, i.e., generally open to new technology). Further, studies about the automated shuttles which are already driving with low speed on real roads show: if users' expectations are not met, like e.g., appropriate speed, it results in decreased intention to use this system and may end in actual disuse.
Consequently, acceptance in automated mobility concepts depends on appropriate design [103]. The problem is not the automation itself, designing and developing a better cooperation between driver and the driving automation system by meeting users' performance expectations and additional UIs which deliver appropriate information in the right situation [103], using the opportunities of automation while balancing drawbacks, might optimize UX and thus increase individual and societal acceptance [120], [17]. Therefore, the technology-centered perspective needs to be complemented by a user-centered perspective in academia and industry. To elaborate on this, the challenges of UX design are described in the following section.

1.3 Challenges of User Experience Design

Appropriate interface design seems to be the solution to solve human-related issues, creating positive driving experiences and thereby achieve acceptance of the technology in society. However, also UX design comes with various challenges. Similar to automation, part of or even reason for issues academia and industry are facing in practice are due to the definition of UX. Further, special characteristics of driving automation UX and design and development processes need to be carefully regarded.

1.3.1 Definition of User Experience

As an academic discipline, *user experience* (UX) evolved in the multidisciplinary intersection of the fields of computer science, cognitive science, design, and psychology [1]. With UX, in the third wave of HCI research [59], the focus shifted from usability and performance aspects of interactive products towards the emotional and hedonic aspects of product interaction. According to ISO 9241-210:2019(en) [122], it is defined as: *"user's perceptions and responses that result from the use and/or anticipated use of a system, product or service"*. See Chapter 2 for more details.

UX has received increased attention in recent years. For example, Google Scholar hits for the term *"user experience"* increased from 2009 to 2018 from 19,000 to 57,400 hits per year. Also in the daily work of design, marketing, and management departments, UX is a regularly mentioned term [123] and the answer to the question how to create improved customer value. However, while UX considerations have become embedded in research and design processes, they still remain a challenging and strongly discussed area for both researchers in academia and practitioners in industry. It is critisized to be used as a synonym for something "cool", "special", and "visually appealing", or "usability" and "user-centered design" [29, 1], [124]. While UX has become both a buzzword and a holy grail, several initiatives that have their scientific background in HCI, psychology and design, [125, 126, 127, 128], have tried to create a consistent understanding to unfold its full potential. However, it has always been discussed as hard to gain agreement on the scope and nature of UX [129], [1]. Hence, miss-interpretations lead to difficulties in how to study UX as subjective, dynamic and context-dependent construct [130], which rather shifts the focus on usability and functionality than on hedonic/ emotional aspects in product development [123, 131].

Implications for this Thesis As the goal is to achieve high product quality, especially from an experiential perspective, former procedures with a focus on pure usability and safety are not enough anymore. Stakeholders (researchers, designers, developers, and managers) need to understand which aspects UX involves, what it means for driving automation, and how they can address it. Existing best practices have to be analyzed and refined. Although creating a consistent understanding seems to be difficult, tools are needed which facilitate at least communication about UX as a first step.

1.3.2 Special Characteristics of UX in Driving Automation

While UX is getting more and more popular in academia and in industry in a wide range of domains (e.g., mobile apps, gaming, web, professional software, etc. [132], [1]), as already emphasized, also automotive research started study UX (see Section 1.1). The automotive industry has to meet users' expectations which are influenced by experiences with consumer electronics and compete with fast-growing start-ups like Tesla and new business models [133, 134, 135]. Although many aspects of UX in vehicles are similar to other domains, every product type has its own characteristics which need to be carefully regarded in order to create positive UX.

According to Pettersson [133] in-vehicle UX is signified by:

> *"aspects such as the influence of the whole body, multi-sensory interactions, the importance of the temporal stage of use, the social and multi-device context, and the changing relationship between user and car with increased automation"* (p. 109).

Users' experience goes clearly beyond usability and distraction, which dominated automotive human factors research in the past [65], [3]. See also Section 1.1. Instead of interacting with a simple user interface like in mobile apps or websites, the car has multiple interfaces (e.g., steering wheel, instrument cluster, infotainment system, etc.). The embodied experience of noise, smell, and the perception of the seats as well as social interactions affect the overall UX which is formed by long-term interactions. Thereby, the car is a home-like environment, hence it need to be both, effective and comfortable [136, 69]. Thus, it is not surprising that many people have a relationship and feel attached to their cars [137, 138], [10]. Further, with more automation, the role and the relationship between car and driver change [69]. More and more interactions are transferred from the human to the system. As the types of interactions change, thus, of course, the experience differs. UX qualities vary in their importance to which extent they have to be focused [9] and designers have to deal with the transformation from designing for *UX of driving* to *UX while being driven.*

Implications for this Thesis With increasing levels of automation, besides pragmatic aspects like ensuring safety and good usability, especially in lower levels of automation, hedonic aspects get more important in product development. Thus, to bind customers, creating positive embodied experiences and emotional attachment to the car become more important for manufacturers. This highlights the need for UX design.

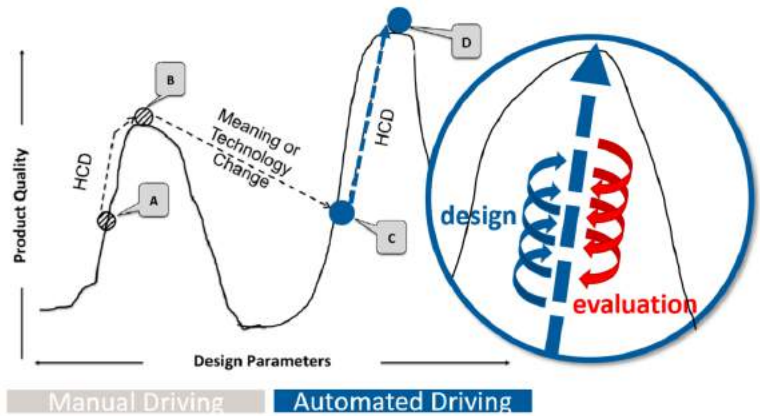

Figure 1.2: Driving automation as radical (by meaning or technology change) vs. incremental innovation (iterative design process). Manual driving systems are evaluated and iteratively improved (A to B) by Human-Centered Design (HCD, equivalent to User-Centered Design). With the development of advanced algorithms, cameras, sensors, etc. ADSs become possible and change the meaning of transportation (C). However, to reach the highest peak of product quality the innovation needs to be improved iteratively (D). Adapted from [139].

1.3.3 Development Processes of Driving Automation Systems

The competition between car manufacturers themselves, who now also have to compete with younger and more agile tech companies and start-ups which joined the market in the recent years (like Tesla), the vanish of traditional quality factors (*"joy of driving"* [94, p. 165]), and decreasing brand attachments [10], demand new strategies and development processes to be able to create such positive driving experiences. Therefore, the introduction of UX departments has been considered by many companies as a solution to create innovations.

Innovations are expected to increase product quality [139], however, therefore, appropriate design and development processes have to be established. According to Norman and Verganti [139], quality can either be improved by iterations (incremental innovation), or technological achievements (radical innovations, e.g., internet) and/or meaning changes of products. Thus, Edisons' improved light bulb changed humans' life and working patterns), see Figure 1.2. We see here parallels to the development of driving automation systems: Driving automation systems in which the entire or part of the DDT are still performed by the driver (SAE L0-2) and the driving automation feature is rather an assistant, thus, might be interpreted as incremental innovation. Contrarily, ADSs

(SAE L3-5) are able to get established only by advances in new technology like advanced algorithms, cameras, sensors. Thereby, the vehicle itself gets a new meaning beyond mere transportation, enabling mobile workplaces or living rooms. Thus, ADSs have the potential to be a technology-, as well as a meaning-driven *"radical"* innovation, possibly achieving an even higher product quality of a vehicle [17, 18]. To further increase the product quality, of lower and higher levels of driving automation system, incremental innovation is necessary. This can be accomplished by applying the User-Centered-Design (UCD) process [67] by utilizing its problem-solving iterative framework: *analysis, design, evaluation* and *implementation*. Users' needs and values have to be observed and analyzed to derive requirements which will be utilized for designing new solutions. By developing prototypes (from low- to high-fidelity), new concepts can be evaluated with real users in an early stage and iteratively improved.

However, automotive UX researchers face several challenges to the application of UCD to driving automation systems, especially ADS. They face the problem that finished products do not yet exist, high cost of fully functional prototypes, and potential risk and ethical concerns (e.g., fatal Uber accident in 2018 with a pedestrian during a test drive) of real-world evaluations. Thus, early stage evaluation using narratives [104], enactments [102], wizard-of-oz setups [140], and driving simulator studies [40] are approaches to analyze future users' experiences [69] already today. A first step towards testing systems in reality are driving simulators (e.g., high-fidelity hexapod moving platform) that can provide controlled settings for testing ADS experiences. But also these simulated study environments lack the required realism to break through existing misconceptions or mental models that users have about future driving [141], [17].

Further, it is challenging to decide which methods to use to study UX in the different phases of the UCD. Researchers in academia and practitioners in industry have developed their own best practices over decades based on experiences, reflection, theoretic background, or intuition, however, a guideline which aspects of UX need to be studied by different available methods and how to combine them is still missing [132, 69].

Implications for this Thesis User research, (instant) feedback and continuous evaluation are imperative to create acceptance of the technology in the society. The correct application of special methods is essential to understand users and the context of automated vehicles [69]. Although we can at the moment only lay the foundations for UX design for driving automation systems of the future by using methods like driving simulators, we are able to develop and establish approaches that support the possibility for updating the knowledge we gain over time.

1.4 Research Approach

Based on the described challenges of driving automation in its different levels of automation and the UX design of vehicles equipped with driving automation systems, following summarizing research claim is postulated:

> **Individual levels of driving automation affect *UX of driving* and *while being driven* differently. In order to create a positive UX, and thus increase individual and social acceptance, the development of user interfaces must take into account the respective human-related opportunities and challenges. This requires a solid, theory-based approach to UX research that addresses the challenges of UX practice in academia and industry.**

1.4.1 Research Questions

This doctoral thesis applies a threefold research approach. Based on UX theory, it starts with an investigation of methodical approaches and challenges of UX practice to set the groundwork for an improved approach, which is applied in the third part. The goal is to support the development of user interfaces which positively affect *UX of driving* and *while being driven*. The following research questions (RQs) are put forward:

- **RQ1: How is UX in the context of driving automation methodologically addressed in practice?**
  - RQ1.1: How is UX in general methodologically addressed in academia?
  - RQ1.2: How is driving automation in general methodologically addressed in academia?
  - RQ1.3: How is driving automation UX methodologically addressed in industry?

To answer these research questions, state-of-the-art UX practice in academia and industry are analyzed by systematic literature reviews, and an interview study with stakeholders of driving automation UI development (researchers in academia and industry, but also involved designers and developers). Insights help to answer the research question of the second part:

- **RQ2: How can UX theory and the insights from UX practice be combined to optimize the development process of driving automation systems?**

As solution, for *driving automation user experience* (DAUX) a need-centered development approach is proposed. The "DAUX Framework" aims at optimizing the development of driving automation systems by addressing predominant challenges in UX practice by unfolding and visualizing the different layers of a driving automation experience based on UX theory. Thereby, it provides a guideline on how to a) identify relevant needs for hypotheses/ concept development and b) evaluate UX by triangulating behavioral, product-, and experience-oriented methods.

Terminology: Framework

A framework is a structure or system supporting the realization of a defined result/goal. While a method is a systematic approach, specifying an *"cohesive and (scientific) consistent"* [142] way how to achieve a goal, a model is schematically simplified representation of a *"selected part of the world"* [143], which can either be a phenomena, data or even theory. A framework is something in between a method and a model. On the one hand, it can include several different models. On the other hand, it gives users of the framework more freedom, how to apply it and models, methods and techniques involved [142]. The "DAUX Framework", introduced in this thesis (see Chapter 4), is setting the frame for all the aspects that need to be regarded when studying driving automation UX. It still depends on the knowledge and expertise of the researchers and practitioners on how to use it, e.g., by triangulating suitable methods dependent on the use case.

In the third part, the "DAUX Framework" is applied to study the impact of user interfaces on the UX of driving automation systems in the different levels of automation. The following research questions are investigated:

- **RQ3: How must user interfaces be designed to positively affect UX *of driving* and *while being driven*?**
  - RQ3.1: How should a user interface be designed to affect UX of driving in SAE L2 with varying system performance?
  - RQ3.2: How should a user interface be designed to affect UX of driving in SAE L3 in which users have to expect to take over control at any time?
  - RQ3.3: How should a user interface be designed to affect UX of driving in SAE L4/5 with limited controllability?

Requirements and user needs in a specific level of automation are analyzed with the help of the framework. Implications derived from related work (and exploratory studies) are used to derive design decisions for user interface examples in the different levels of automation aiming to positively affect driving automation UX. The developed prototypes are then evaluated in a high-fidelity driving simulator (hexapod moving platform), applying the framework as guidance to select appropriate methods for triangulation to address behavioral, product- and experience-oriented aspects. The overall goal is to derive recommendations for driving automation UI development based on the results of all studies.

1.4.2 Research Area and Audience

The scientific contribution is located in the research area of Human-Computer Interaction (HCI), which is, according to the Association for Computing Machinery (ACM) [144, p. 5], *"clearly to be included as a part of computer science"*. Since modern computer applications, like driving automation systems, require components which interact with a user,

> *"it is intrinsically necessary to understand how to decide on the functionality a system will have, how to bring this out to the user, how to build the system, how to test the design"* [144, p. 5].

Thus, the presented experimental research, applying the proposed "DAUX Framework", contributes to computer science by improving the understanding of the role of human individuals' emotions and cognition for successful driving automation system development. It gives a guideline how to study user needs for hypothesis and concept development, and how to evaluate concepts by using an appropriate method mix. This helps to derive concrete recommendations for UI development of driving automation systems.

This thesis is aimed to address academic UX researchers but also UX practitioners from industry from different disciplines (computer science, design, and psychology) to foster a more profound theory-based contemplation of UX in practice. Thereby, the "DAUX Framework" shall facilitate the transfer of research insights into concrete requirements. This aims to enhance interdisciplinary collaboration between practitioners within and between research and industry (computer science, design, and psychology). Further, the derived recommendations of this thesis can be also directly considered for concept development.

1.5 Outline

The application of the research approach is reported in the following chapters (see Figure 1.3):
To set the basis, Chapter 2 analyses existing UX theory to understand which aspects of UX need to be regarded for UI development to create positive experiences. This is set in relation to the related work of driving automation studies. Chapter 3 reports our investigations of the state-of-the-art UX practice in general and in the context of driving automation. For academia, two systematic literature studies, for industry, a qualitative interview study with stakeholders of eight European OEMs and suppliers was conducted. In Chapter 4, the "DAUX Framework" which aims to support need-centered UI development to create positive experiences of driving automation, is presented. The approach is motivated by the UX theory and insights from UX practice. In Chapter 5, three case studies are described applying the "DAUX Framework" for UI development in the different levels of automation (SAE L2, SAE L3, und SAE L4/5) to create a positive UX. Each case study consists of an analysis to reveal which psychological needs are relevant to be fulfilled in a certain level of automation to positively affect UX (related work, exploratory qualitative study), a design phase to derive UI concepts based on the results of the analysis and related work to make design decisions, and an explanatory study evaluating how a user interface affects UX *of driving* and *while being driven* in a certain level of automation. Results of each case study are discussed and core findings summarized. In Chapter 6, results regarding postulated research questions are discussed and recommendations for the individual levels of automation derived. This doctoral thesis will be concluded in Chapter 7 by summarizing the presented work, highlighting contributions, addressing limitations and outlining future work.

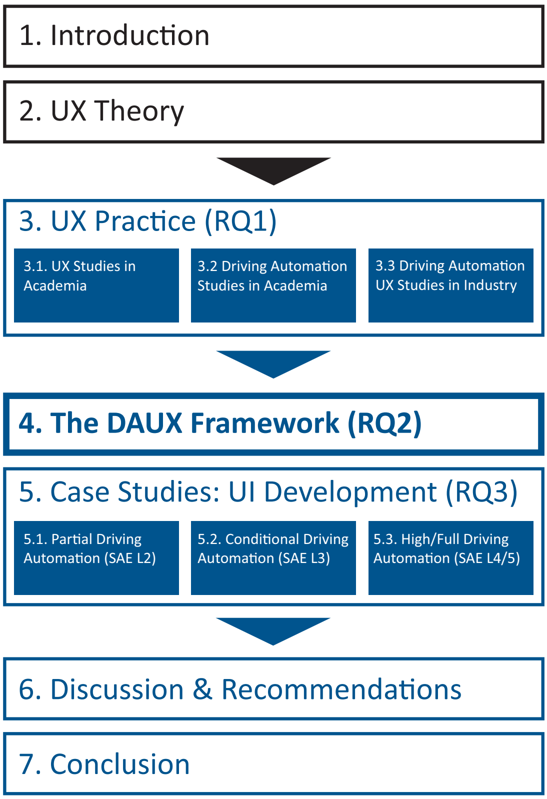

Figure 1.3: Outline of this thesis. *Note: own work to answer and discuss postulated research questions is highlighted in blue.*

2 UX Theory in the Context of Driving Automation

As already elaborated in the introduction, designing for positive driving automation UX faces various challenges. On the one hand, researchers, designers, and developers of driving automation systems, responsible for creating a positive UX, need to understand what driving automation means for the user in the different levels of automation and for which opportunities and drawbacks they should be prepared for. On the other hand, these stakeholders need to have a consistent understanding by which characteristics UX is signified for driving automation and how to design for it. Therefore, it is imperative to understand which aspects UX, based on existing and established theories, involves.

The term UX is described as an umbrella construct, which, as all umbrella constructs, *"tend to be vague and loose, characteristics that challenge our ability to accumulate and communicate knowledge and to capture real-world phenomen"* [145, p. 131]. So, many interpretations, definitions and frameworks of UX exist, and multiple initiatives have tried to establish a unique understanding [146, 129, 147]. Thereby, reductionistic approaches confront holistic ones. While the former try to simplify experiences into concrete constructs, the latter aim to integrate different aspects for developing an overarching framework and are criticizing reductionists' trials to reduce UX to measurable variables [148, 149, 150, 133]. Hence, the ongoing discussions have led to confusion in research and practice, and UX has become a buzzword [147], [1, 13].
Also the International Organization for Standardization (2010) [151] published a definition and updated it in 2019 [122], in collaboration with international experts [152], see also Subsection 1.3.1. Thus, most UX experts from both industry and academia agree on it [129]. According to ISO 9241-210:2019(en) [122], *user experience* is defined as:

> "***user's*** *perceptions and responses that result from the use and/or anticipated use of a* ***system, product or service***
>
> *Note 1 to entry:* ***Users'*** *perceptions and responses include the users' emotions, beliefs, preferences, perceptions, comfort, behaviours, and accomplishments that occur before, during and after use.*

> *Note 2 to entry: User experience is a consequence of brand image, presentation, functionality, system performance, interactive behaviour, and assistive capabilities of a* ***system, product or service****. It also results from the* ***user' s*** *internal and physical state resulting from prior experiences, attitudes, skills, abilities and personality; and from the* ***context of use****.*"

This definition is continuously criticized for not being detailed enough, for lacking depth in explanation [153]. However, until now, it still seems to be the lowest common denomination, with room for interpretation. This is, on the one hand, positive as the broad construct is adaptable and fuels inspiring discussions among UX professionals. On the other hand, the establishment of misconceptions is facilitated. To counteract, as Tracinsky recommends [145] and Roto [147] confirms, we try to unbundle the umbrella term UX by critically examining the UX definition by relating its statements to existing theoretical framework and other definitions. In addition, by a more detailed look, components are put into the context of driving automation. The goal is to be able to replace the umbrella construct by well-defined constructs contained. Thereby, we argue, reductionistic and holistic approaches can and have to be combined. Hence, regarding the ISO 9241-210::2019(en) [122] again, three main determinants for UX stand out: the *user*, the *system, product, or service*, and the *context of use*.

2.1 The User

As the term *"user experience"* already contains, the user is the most critical part of the phenomenon. According to SAE J3016 [47], the term *"user"* refers to the *"human role in driving automation"* (p. 16). The user can have different roles: driver, passenger, DDT fallback-ready user, or driverless operation dispatcher. Thereby, being either a driver or a passenger sitting on the driver's seat depends on the level of automation, i.e., context (see Section 2.3), which entails different requirements for the user. Further, ISO 9241-210:2019(en) states that UX *"results from the user' s internal and physical state resulting from prior experiences, attitudes, skills, abilities and personality"*. Hence, it is subjective per nature [129], and individual differences have to be carefully regarded [150]. But, what does it mean to have a good or bad experience? And what is it that makes users' experience in a specific role a good or a bad one? The following subsections clarify the role of humans' emotions, feelings, affect, and needs in UX. Related studies about driving automation referring to these constructs are presented.

2.1.1 Emotions, Feelings and Affect

Emotions are included in the ISO definition as central elements, just as well as feelings and affect are mentioned in many UX frameworks (see below). This emphasizes the subjective and experiential properties of UX in contrast to usability [133]. Nevertheless, like UX, emotions are controversially debated in psychology and different theories exist [154]. In this field, the term is often interchangeably used with feelings and affect. But there are different semantics behind, which need to be carefully regarded [155]. Thus, before presenting the UX frameworks, terms are shortly clarified.

Psychological Groundwork A feeling is an assessment of the current condition, which is consciously but not-reflective experienced within two dimensions: between pleasure and displeasure (*valence*) and activated and deactivated (*arousal*), cf., circumplex model of affect [156]. By this, simple and non-reflective feeling, the core affect gets accessible [154, 157]. For investigations, this one can be subdivided into the factors positive affect (how active, enthusiastic and alert a person feels) and negative affect (subjective distress and unpleasurable engagement) [158]. Has a person a low positive affect, then this is reflected by sadness and lethargy, contrarily, low negative affect is defined by calmness and serenity. As affect is a neurophysiological state, a person can always access his current core affect, as one is always in a state. The affect

> *"changes in response to many simultaneous influences. Sometimes the influence is a single powerful and obvious external event [...]. More typically, however, there are many simultaneous influences, including some beyond human ability to detect"* [157, p. 1265 ff.].

Thus, affective properties (e.g., the beauty of an object, cf. Subsection 2.2.1) can, but need not have an effect on the core affect. Also imagined and remembered aspects can have an impact. Although it is easy to access a core affect, this makes it so difficult to relate users' captured feelings to a certain aspect of a product (attribution). However, as the goal of UX design is to create pleasure, it is essential to understand why some objects, e.g., products, have an affective quality, i.e., have *"the ability to cause a change in core affect"* [154, p. 147]).
Contrarily to affect, specific emotions (e.g., ecstasy or grief) begin and have an end, thus, it is also referred to them as emotional episodes. But, core affect and emotions are related. Thus,

> *"emotional life consists of the continuous fluctuations in core affect, in pervasive perception of affective qualities, and in the frequent attribution of core affect to a single object, all interacting with perceptual, cognitive, and behavior processes"* [154, p. 152].

This is related to the appraisal theory. Smith and Lazarus [159] define emotions as *"reactions to abstract meanings"* (p. 615). Consequently, not a certain event or stimulus causes an emotion, it depends on the individual evaluation/ interpretation (appraisal as a cognitive process) if an event will either lead to harm or benefit. As a result, emotions motivate to react on a situation (behavioral process).

Relevance for UX Desmet [160] started to build upon Smith and Lazarus' [159] appraisal theory and assumes that the automatic, fast, and non-reflexive cognitive evaluation/interpretation, if a situation or an object has a good (benefit) or bad (harm) effect on one' s well-being, elicits product emotions. Thus, positive emotions motivate towards using a product, and negative emotions push users away, which is due to users' personal interpretation highly individual [161]. Thereby, products are appraised regarding their relation to users' goals, their sensorial appeal, the represented legitimacy of action, and their novelty. Desmet and Hekkert [161] bring all this together in the *framework of product experience*. They differentiate between aesthetics experience, which addresses sensory modalities to delight a user, the experience of meaning, which addresses users' *"personal or symbolic significance of products"* [161, p. 57], and the emotional experience, defined by appraisal connected to the two prior mentioned experience categories which finally elicit emotions. In total, 25 emotions (e.g., kindness, love, respect, etc.), which can be experienced in human-product interactions [162] could be identified.

Further, the emotional aspect is also picked up by McCarthy and Wright [163] who built upon the theories of the pragmatist John Dewey. They defined a list of *threads of experiences*, which aim to facilitate talking, thinking and designing for experience with technology. Thereby, the included *emotional* thread is related to the emotions (frustration/satisfaction) evoked by an experience, by judgment and sense-making if a product fits users' *"values, needs, desires and goals"* [163, p. 85]. Further, they identify the *sensual* (sensory engagement with a situation in which the experience character can be concrete or instinctual), *compositional* (putting all parts of an experience together) and *spatio-temporal* thread (the connection of an experience to the past and future). *Sense-making* is responsible for developing an experience and includes different steps: *anticipating* (expectations based on prior experiences), *connecting* (immediate judgment), *interpreting* (more conscious view on the sensed situation how a user feels about), *reflecting* (evaluation of an interaction and evoked feelings), *appropriating* (evaluation how the experience relates to prior experiences), and *recounting* (reinterpretation by communication/storytelling of the experience to oneself or others). This is related to Forlizzi and Batarbee [164], who define an experience as *"constant stream of 'self-talk' that happens when we interact with products"* (p. 263). Karapanos [165, 166] emphasizes the importance of regarding the temporal dimension of UX, and here, especially the anticipation of how an experience impacts users' expectations. Thereby, we experience and judge a product many times in a single unit, speaking of micro-temporality. Here, our experience changes over time from *orientation* to *incorporation* or *identification*. The sense-making process is also picked up by Kort et al. [167], thereby particular aspects of design elements like *meaning*, *functionality*, and *aesthetics* of a product are perceived, processed, and reflected, what triggers emotions. Mahlke and Thüring [128], as also described in their CUE-model, were able to prove that both, *instrumental* (e.g., usability) and *non-instrumental* qualities (e.g., aesthetics), have an effect on users' emotions (see also Section 2.2).

According to Russel [168], pleasure is the *"fundamental component of human emotion"* (p. 493). Thus, Jordan [169] introduced the four pleasures which can be derived from products: *physio-pleasure* (evoked from senses), *psycho-pleasure* (evoked from rewarding), s*ocio-pleasure* (evoked from social relatedness) and *ideo-pleasure* (evoked from values, believes and ideals). Don Norman [127] defines different levels of how users process experiences for creating pleasure: *visceral* (initial impact, e.g., appearance, which can be perceived consciously or unconsciously), *behavioral* (the experience of using a product) and *reflective* level (the thoughts afterward how it made one feel). And also Hassenzahl [125] argues, product features which are intended to create a certain product character (see Section 2.2) aim to evoke appeal, pleasure, and satisfaction.

Regarding all theories together, following similarities get visible: a certain affect and the evocation of emotions are dependent on users' individual evaluation of a situation regarding a) the product character, b) personal prior and future experiences, and c) needs, values, desires, and goals. Thus Hassenzahl's [124] definition is a good summary. It describes UX as:

> *"[...] a momentary, primarily evaluative feeling (good-bad) while interacting with a product or service. By that, UX shifts attention from the product and materials (i.e., content, function, presentation, interaction) to humans and feelings - the subjective side of product use. In addition, it emphasizes the dynamic. UX becomes a temporal phenomenon, present-oriented and changing over time"* (p. 12).

Thus, positive feelings (pleasure), i.e., positive affect, and related emotional episodes are connected with anticipated or actual product usage and users' individual appraisal. Hence, we know what it means to have a good experience, however, the basis for the aspects on which users appraise is still unclear. What is the *"origin of the positive or negative feeling"* [124, p. 12]? Thereby, regarding user needs, as already emphasized by McCarthy and Wright [163], becomes essential for UX design [124].

2.1.2 Needs

Thinking about *user needs* started when product development changed from solely regarding the user interface to further involving the context of use in order to increase acceptance. Thereby, understanding users' needs helps to inform the design process [170] and ensure a certain level of quality of a product [171]. Mostly this refers to what users require, and not to the original meaning of psychological needs. Thus, before referring to the relevance of needs for UX, underlying psychological theories are presented.

Psychological Groundwork Zentes and Swoboda [172] define *"needs"* as a subjective feeling of deficiency and the urge to eliminate this feeling. Ryan and Deci [173, p. 74] describe it as *"energizing state"* that either leads to *"well-being"*, if needs are fulfilled, or *"ill-being"* if not. As designers want to eliminate any negative feelings (high negative/ low positive affect and related emotional episodes) caused by deficiency while using a product, psychological needs have to be satisfied.

One of the most popular theories about needs is Maslow's *hierarchy of needs* [174], introducing universal human needs, where appetence is dependent on prior fulfilled needs. This means, firstly, physiological needs such as sleep, hunger, thirst, and sexuality have to be satisfied, before the needs for safety and security, followed by love and belonging, esteem and self-actualization become relevant. Human values change according to the acquired needs that have to be fulfilled or satisfied. While Maslow's [174] theory is still present and universal needs in content confirmed, the hierarchical contemplation has been replaced by considering the fulfillment of certain needs such as individual prioritization in specific situations.

Thus, Ryan and Deci [173] postulate in their *self-determination theory* three independent universal basic psychological needs: *competence*, *relatedness*, and *autonomy*. Competence describes the experience of mastery and being in control of your actions and outcomes. Relatedness is defined as the will to be connected, being appreciated for your work and given attention by others. Autonomy implicates the urge to live a self-determined life and to live in harmony with your true self. Humans try to adapt the fulfillment of these needs to their physical and sociocultural environment. Thereby, a motivation for a certain behavior is dependent on the fulfillment of one of these needs. Diefenbach and Hassenzahl [175] agree with these postulated needs by [173]; however, they criticize the selection of three basic needs as too fundamental for covering all possible aspects of an experience. While there are only a few reasons why product usage is perceived as positive, need fulfillment can be experienced in many different ways.

Need	Description
Autonomy-independence*	Feeling like you are the cause of your own actions rather than feeling that external forces or pressures are the cause of your actions.
Competence - Effectance*	Feeling that you are very capable and effective in your actions rather than feeling incompetent or ineffective.
Relatedness - Belongingness*	Feeling that you have regular intimate contact with people who care about you rather than feeling lonely and uncared for.
Self-actualization - Meaning*	Feeling that you are developing your best potentials and making life meaningful rather than feeling stagnant and that life does not have much meaning.
Security - Control*	Feeling safe and in control of your life rather than feeling uncertain and threatened by your circumstances.
Money - Luxury	Feeling that you have plenty of money to buy most of what you want rather than feeling like a poor person who has no nice possessions.
Influence - Popularity*	Feeling that you are liked, respected, and have influence over others rather than feeling like a person whose advice or opinions nobody is interested in
Physical thriving - Bodily	Feeling that your body is healthy and well-taken care of rather than feeling out of shape or unhealthy.
Self esteem - Self-respect	Feeling that you are a worthy person who is as good as anyone else rather than feeling like a “loser” .
Pleasure - Stimulation*	Feeling that you get plenty of enjoyment and pleasure rather than feeling bored and understimulated by life.

Table 2.1: Basic psychological needs [176]. *Note: Needs relevant for UX selected by [63] are indicated by *.*

Diefenbach and Hassenzahl [175] see the diversity of an experience more represented by Sheldon et al. [176], who invested the origin of satisfying events. As many motivation and need theories exist, they analyzed which psychological needs are the most fundamental. To derive a set of need candidates, they used Ryan and Deci’s [173] self-determination theory as a foundation, and further drew from Maslow et al.’s [174] theory of personality. By comparing these two models, which we described before, and adding constructs from other frameworks (e.g., Epstein’s *cognitive-experiential self-theory* [177]), a total of ten psychological needs are presented to summarize the many need theories of the last century: *autonomy, competence, relatedness, physical thriving, security, self-esteem, self-actualization, pleasure-stimulation, money-luxury, and popularity-influence* (see Table 2.1). Thereby a correlation between affect and need fulfillment could be identified. As a component analysis revealed relative independence between all needs, we can assume that a satisfying event is perceived as positive due to the fulfillment of particular needs. Hence, dependent on an activity, different needs have to be prioritized.

Relevance for UX Hassenzahl [124] picked up the correlation of positive affect and needs, and concludes:

> *"Good UX is the consequence of fulfilling the human needs for autonomy, competency, stimulation (self-oriented), relatedness, and popularity (others-oriented) through interacting with the product or service [...]"* (p. 12).

To demonstrate this relationship, he and his collaegues [63] collected 500 experiences with technology and could bring the empiric proof. They showed that an experience can be categorized by the primary need it fulfills. Thereby, particular affective experiences exist, e.g., relatedness led to interest and excitement and competence to strength and activity. Results could be confirmed in later studies by investigating experience and product-oriented evaluation approaches [178], by analyzing users' narratives [179], and by investigating hygienes and motivators for UX [180], see Subsection 2.2.1. Further, the existence of individual need-profiles for activities could be shown [178], e.g., playing led to a high degree of fulfilling relatedness, but low meaning. This proves the assumption of context-dependent prioritization of psychological needs (see also Subsection 2.3) [176, 178]. Moreover, constructs like *hedonia* and *eudaimonia* are added to the concept of UX [181, 182, 183, 184]. Mekler and Hornbaek [183] analyzed the role of eudaimonia for UX, as here:

> *"positive affect is more of a beneficial side effect of (successfully) striving towards one's personal best and need fulfillment"* (p. 4156).

Thus, they identified, besides confirming the correlation of need fulfillment and affect, that the accomplishment of personal goals by the use of technology is directly connected to need fulfillment.

2.1.3 Related Driving Automation UX Studies

Affect, emotions, and needs are focused topics in driving automation (UX) studies, to understand users' performance and experiences, but are also utilized as a source of inspiration for concept development.

Understanding Users' Affect, Emotions, and Needs Jeon [185] detected that emotions like fear and happiness can affect users' driving performance. Braun et al. [186] stated, the optimal affect in an automated vehicle would be medium arousal in combination with high valence. Nevertheless, studies showed, users' expectations on the future technology are rather associated with extremes in both dimensions of affect: curiosity, fear of mode-confusion, delight in novelty [102]. Further, our own study [44], using the PANAS-questionnaire [158] to address affect before and after a drive in a fully automated vehicle in a high-fidelity driving simulator, showed high values for alert, interest, and attentiveness. Participants mentioned the terms insecurity, relaxation, excitement and boredom to describe their experiences [44]. Thus, also Pettersson [133] concluded, based on various studies (e.g., [102, 187]), emotions are highly present in participants' stories about automotive experience, however, these are *"fleeting and interchangeable, depending on context and the mood of the user"* (p.79), see also Subsection 2.3.

In a further study of our own, we [42, 37] investigated technology acceptance (using the technology acceptance model [110]) of an automated shuttle on a real road, comparing elderly with younger users going with a manual or an automated shuttle. Results showed, for elderly users, the automated shuttle was able to increase positive affect and their intention to actually use such a system was higher than for the younger users. Users' need fulfillment was not investigated in this study, which is generally criticized by Hornbaeck and Hertzum [188] on technology acceptance models like TAM [110, 189] or UTAUT [190]. Thus, Distler et al. [103] regarded users' psychological need fulfillment, using UX cards [191], to understand the acceptance and acceptability of autonomous mobility on-demand service, with an autonomous shuttle. Results showed while safety concerns (need of security) before using the system could be settled after experiencing it, due to the lacking effectiveness of the system, fulfilling users' need for competence is crucial for creating technology acceptance.

Further, another study of our own [16], again investigating experiences between different age groups, revealed that the need for security and autonomy has to be fulfilled for every user group. Thus, the possibility to intervene to meet users' performance expectations or to support their subjective feeling safety by giving control, should be provided. However, while elderly users required additional feedback to feel more secure during the drive with an automated vehicle, the younger participants already desired to engage in NDRTs and assumed safety as a prerequisite. This is in accordance with Eckold et al. [94]. They investigated ACC as ADAS from an experiential perspective. The think aloud technique was used to study the experience in a real road study. They identified that ACC creates a gap between driver and car, *"resulting in negative feelings for first-time users and reduced emotionality for the more experienced users"* [94, p. 169]. They highlight the problem of loss of control and competence feeling (lacking need of competence) and demand approaches to rather empower the driver than to assist him to maintain *"joy of driving"* (p. 169). Further, the study showed that ADAS have the potential to allow *"joy while driving"* (p. 169), thus, creating *"the freedom to engage in pleasurable activities beyond driving"* (p.169) which gets especially important for driving automation in higher levels. However, both *"joy of driving"* and *"joy while driving"* driving have to be regarded separately.

Utilizing Affect, Emotions, and Needs for Concept Development Knobel [192], investigated how to design positive experience for drivers and passengers beyond the driving task in manual vehicles. He developed an approach for experience design building upon the work of Hassenzahl and colleagues (e.g., [125, 124, 63]): based on experience reports, patterns are derived to inspire iterative design from a simple headline to an experience prototype which will be evaluated. Knobel et al. [193] used affect and needs to reveal patterns from participants' reports (mixing interviews with the standardized questionnaires PANAS [158] and Need Scale [176]). Thereby, Knobel et al. [193] identified the need of relatedness as most relevant for positive experiences in the car, especially the relatedness between passengers of different cars. To address this need, successively a story headline, experience story, storyboard, mockups and finally an experience prototype were generated. *"ClickTrip"*, as the concept was called, is a navigation system helping two cars to stay together in the traffic, and enables a communication channel if they are close. The system was evaluated by mixing again interviews with the standardized questionnaires as already done in the analysis phase. Hassenzahl et al. [194] presented a well-being-oriented experiential approach for automotive interaction design, to shift from easy and exciting interactions to enjoyable and meaningful activities. In a case study in which they address the daily commute experience, they first try to understand possible enjoying moments of commuting, secondly, design the experience *"that is, how we want people to ideally act, feel and think while a commute"* [194, p. 115] and, finally, translating that in a system. Eckold et al. [195] explore the car design-space by an experience-oriented approach, designing positive experiences by addressing the psychological needs which are already apparent in the car. For example, competence, which is usually connected to the driving task, can also be reduced by park assistants or navigation systems. Therefore, a system called *"MinimalNavigation"* was presented, which only informs drivers where to drive by tactile feedback with vibrating motors to give them the feeling that they know the route. Krome et al. [196] ideated how games can support stresslessness in the automotive domain. Krome [197] presents in his dissertation a simulator study evaluating a concept called *"AutoGym"* by studying need-fulfillment. Significant effects could be revealed for stimulation/pleasure and competence in comparison to a "normal" commute with heavy traffic.

2.2 The Product, System or Service

The question about what it means to have a good UX, and about the origin of positive feelings while product interaction could be answered: users' psychological needs have to be fulfilled to create positive affect, what implies a good UX. However, how can a product fulfill needs? Which qualities have to be assured? How should a product be designed that users evaluate it as good?

According to ISO 9241-210:2019(en) [122]: *"user experience is a consequence of brand image, presentation, functionality, system performance, interactive behaviour, and assistive capabilities of a system, product or service"*. Thus, according to the theories of UX described above, it is expected that affect, whether positive or negative, can be attributed, as above described in the ISO norm, to the characteristics of a product, system or service. This perspective is described as reductionistic and *"engineering-type"*, in contrast to more *"open-ended"* [133, p. 15] holistic approaches. For driving automation UX this means, the automated vehicle can be regarded as a product itself, however, also all integrated in-vehicle systems, e.g., infotainment, and services like car-sharing which are offered by automotive brands.

2.2.1 Product Perception

Hassenzahl [63] describes based on Kaptelinin and Nardi [198] three layers of good UX: (1) a product has to address users' needs (*why* are they using a product?), (2) it has to achieve specific functions (*what* are users actions?), and (3) design decisions have to be made (*how* does a user interact with it?). For a holistic approach, the instrumental *how* and *what*, the achievment of *motor- and do-goals*, need to be extended by also considering the *why* by attaining so called be-goals [199, 124]. In this sense, the terms *pragmatic* and *hedonic quality* were introduced [125]. *"Pragmatic quality refers to the product's perceived ability to support the achievement of 'do-goals' "* [124, p. 12]. Mahlke and Thüring [128] call it *instrumental quality.* According to Hassenzahl [124], it is mainly related to utility and the usability of a product. Usability is defined by ISO 9241-11:2018(en) [200] as:

> *"extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use."*

The *hedonic quality* refers to users' perception that the product they are using fulfills their needs, i.e., achieves be-goals [124], Mahlke and Thüring [128] call it *non-instrumental quality.* It is divided into the *hedonic quality of stimulation* (HQS) and *identification* (HQI). On the one hand, humans want to develop themselves and extend their knowledge and capabilities (HQS), e.g., an automated vehicle of a new chic brand like Tesla conveying innovation can easier achieve a higher hedonic quality of stimulation than an old-established brand like Volvo standing for safety and comfort. On the other hand, it is also important for users that others perceive them as a person in the way they want to see themselves (HQI). A product of a certain brand with a design that represents brand values with which users identify themselves and feel properly represented can achieve a higher hedonic quality of identification [35]. Diefenbach et al. [201] state:

> *"The concept of hedonic quality provides a more concrete idea of product attributes related to positive experience. It created a bridge between the general 'experiential' claim on the one side and product design and especially evaluation on the other side"* (p. 312).

Thus, by designing a product's features (content, presentation, functionality, and interaction) designers intend to convey a certain product character by specific pragmatic and hedonic attributes. Thereby, they hope for creating pleasure, satisfaction, and appeal. From the users' perspective, the product features are perceived and an apparent product character is internally constructed. This one can deviate from the intended one. Users' final situation-dependent (see Subsection 2.3) judgment determines if the product actually created appeal, pleasure and satisfaction [125]. This determines the actual hedonic and pragmatic quality of a product and users' individual UX quality assessment. According to Mahlke and Thüring [128], appraisal of the system leads to the overall judgment, usage behavior, and perhaps choice of alternatives.

Thereby a cognitive bias, called *halo-effects*, may occur, which emerges from the paradox of *"what is beautiful is usable"* [202, p. 127] or *"I like it, it must be good on all attributes"* [203, p. 3], already mentioned by [204, 205, 206]. The interference model [206, 203] proved the existence of evaluative consistency (i.e., *halo-effects*). It assumes that users interfere with unavailable attributes from a general value to keep their overall judgment consistent. Hence, there is an indirect link between beauty which leads to goodness and, with it, pragmatic quality. In contrast, a probabilistic consistency is a conceptually or causally linked judgment (high aesthetics expects a high perceived hedonic quality).
According to this, Tuch et al. [207] identified negative affects, such as frustration from poor usability, as a mediator variable that potentially decreases perceived aesthetics. Further, Minge et al. [208] differentiate between pragmatic *halo-effects*, where usability impacts perceived visual attractiveness, and hedonic *halo-effects*, where visual aesthetics influences perceived usability.

Terminology: UX vs. Usability

Academia and industry still discuss whether UX and usability are the same, or different constructs, or whether usability is a part of UX [124, 132, 209, 210].
However, even the ISO standards give no clear distinction. Regarding the ISO 9241-11:2018 [200], satisfaction can be interpreted as is the intersection with UX. It is defined as:

> *"extent to which the user's physical, cognitive and emotional responses that result from the use of a system, product or service meet the user's needs and expectations.*
> *Note 1 to entry: Satisfaction includes the extent to which the user experience that results from actual use meets the user's needs and expectations.*
> *Note 2 to entry: Anticipated use can influence satisfaction with actual use."*

In this sense, usability might be interpreted as quality assessment of a product, system or service, because emotional results from an experience lead to an extent of satisfaction, which is together with the extent of effectiveness and efficiency a part of usability. Contrarily, the old ISO 9241-210 from 2010 mention the intersection between UX and usability in an additional note:

> *"Note 3 to entry: Usability, when interpreted from the perspective of the users' personal goals, can include the kind of perceptual and emotional aspects typically associated with user experience. Usability criteria can be used to assess aspects of user experience."*

According to the old version, usability, more referring to do-goals, i.e., pragmatic quality is rather a part of UX than the other way around. Consequently, a clear differentiation is not possible, it still underlies individual interpretation. In this presented doctoral thesis, usability is referred to pragmatic attributes, expecting that high pragmatic quality, i.e., good usability, is an essential part of creating positive experiences.

2.2.2 Relationship of UX Qualities, Needs and Affect

Product characteristics and perceived qualities lead to an appraisal of a product, thus, emotional reactions [128, 125]. As positive affect is dependent on the fulfillment of psychological needs [63, 178], there also needs to be a connection between described product qualities, psychological needs, and affect.

Jordan [169] structured the importance of product characteristics according to Maslow's [174] need hierarchy. Firstly, functionality and usability have to be assured, before pleasure can be generated. Although this has never been empirically tested [150], the impact of pragmatic and hedonic qualities on affect and its dependency of psychological needs was investigated in several studies [63, 178, 179, 180, 183]. Thereby, a relationship between hedonic (but not pragmatic) quality and need fulfillment could be proven. However, this correlation is moderated by attribution, which means:

> *"the more people found the product to be responsible for the positive experience, the stronger the relationship between experience and product perception"* [178, p. 532].

Thus, positive affect might not be reflected in the hedonic quality if users' do not acknowledge the role of the product.

Partala and Kallinen [211] identified that the most satisfying experiences are more related to the hedonic quality of stimulation and identification, while the most unsatisfying are *"accompanied by more direct emotional responses, typically to pragmatic problems"* (p. 31). This, in coherence with the discussion of pragmatic (instrumental) qualities as a hygienic factor, which is said to be only able to achieve dissatisfaction but not satisfaction [212, 180]. Thus, these reduce negative affect but are not able to create positive affect. For example, fulfilling the need of security showed only a weak link to positive, however, strong correlation to negative affect [176, 63]. Contrarily, hedonic (non-instrumental) qualities would be motivators to use a product. Although similar effects were proven by [213, 214, 215], Tuch and Hornbaek [180] question a straightforward relation between the concept of hygienes, motivators, and UX qualities. The results of their study were contradictory. They assume expectations on technology, on utility and convenience (pragmatic aspects) are not as high as UX experts think. Pragmatic quality may not yet have become a hygienic factor but may become so in the future.

2.2.3 Related Driving Automation UX Studies

Several studies investigated perceived product qualities of automated vehicles and included in-vehicle systems. Often, questionnaires like AttrakDiff [216] or UEQ [217] are used to additionally evaluate UX of an introduced system (e.g., [218, 219]) [220]. Others investigated the impact of product characteristics and perception in more depth.

Gkouskos et al. [221] studied experiences with modern (but not automated) cars. They could show that qualities like comfort, usability, and aesthetics evoked emotions and directed users' behaviors. Participants expressed to be stimulated by discovering new functionalities. Pettersson and Karlssson [102] revealed that users expect stimulation and ease-of-use also from a highly automated vehicle. The authors demand future research to be more user- instead of driver-focused. In our own study [14], we investigated the impact of the moral behavior on product perception, utilizing the Trolley Problem [20, 41, 39] and a product image of the Mercedes F015. Results showed that if the behavior in a critical situation does not match with users' expectations, not only the individual perception of need fulfillment by the product but also aesthetic and pragmatic aspects were assessed more poorly in contrast to behavior that matched.

Sauer et al. [222] study user requirements for automated vehicle interior in China and Germany. While creating subjective well-being, trust, safety, and usability were identified to be cross-cultural important, Chinese users rated the importance of hedonistic design higher, in contrast to Germans who prefer a focus on pragmatic aspects. Kettles and Van Belle [223], revealed that hedonic motivation (enjoyment) and performance expectancy are significant predictors to use an automated vehicle. This is in accordance with Distler et al. [103], who showed that intention to use a mobility-on-demand service decreased due to low effectiveness although participants felt safe. This is argued with safety to be a hygienic factor, thus, it is not sufficient to create acceptance (cf. [176, 63]).

Ning et al. [224] investigated usability and driving safety in the interaction of activating driving automation. They highlight this interaction as particular important *"since it is the very first step for users to manipulate and understand the system"* (p. 101). They were only focusing on pragmatic aspects, however, highlight the need to regard hedonic aspects to make the interaction with ADS more appealing and interesting. Thus, Schartmüller et al. [218] could show that using a nomadic device, i.e., tablet computer, for take-over control of a SAE L3 vehicle (steering with the vehicle), has a higher hedonic quality than using the normal steering wheel.

Especially, the *"joy of driving"* [94, p. 165] is in the automotive context connected to hedonic qualities, which will be successively omitted with increasing driving automation. Thus, Krome [197], tries to bring these hedonic qualities back in the car by addressing *driveability* (maintaining the feeling of control), *performability* (allowing self-expression) and *explorability* (giving independency) in the integration of non-driving activities.

2.3 Context of Use of Driving Automation

Besides the user and the product, system or service, the context is a big determinant for UX. It is mentioned in the ISO 9241-210 [122] and in UX literature (e.g., [225, 226, 124, 150]). In the following, different definitions of context are discussed and related driving automation UX studies presented.

2.3.1 Definition of Context Factors

Different definitions for the term context exist. Thus, according to Dey [227],

> *"context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and application themselves"* (p. 5).

The ISO 9231-11 [200], defines *context of use* as *"combination of users, goals and tasks, resources, and environment"*, which includes *"technical, physical, social, cultural and organizational environments"*. While for the development of context-aware systems the concentration is on the system itself, for regarding the impact of the context on UX, the user needs to be focused [228]. Thereby, *"context is not only a part of interaction, but is also an essential part of the subjectively experienced outcomes of these actions"* [229, p. 3], as already the above discussed situation-dependency for emotion evocation highlighted [125], see Subsection 2.1.1. Also, Mahlke and Lindgaard [226] revealed that context parameters like usage mode (achieving a goal with vs. exploring a system), influences the product's quality assessment and emotional reactions. Thus, according to Forlizzi and Ford [225], *"user-product interactions take place in a context of use, shaped by social, cultural and organizational behavior patterns"* (p. 420). There is an infinite, unpredictable number of possible mutually dependent context characteristics that possibly affect an experience [228], especially for mobile systems like automated vehicles, where the context continuously changes. Jumisko-Pyykkö and Teija [229] identified five context categories that need to be regarded for mobile systems in general: *physical, social, task, temporal, technical* and *informational context*, see Table 2.2.

Hence, as the prioritization of pschological needs, responsible for positive experiences, is context-dependent [176, 178], see Subsection 2.1.2. UX varies based on all mentioned context categories [229]. Thus, there is the need *"to understand the users, products, contexts, and nature of interactions that may happen"* [225, p. 420]. Thereby, stakeholders for the development of driving automation systems can become active decision-makers for building a relationship between the *"components of a user-product interaction"* [225, p. 421].

2.3.2 Related Driving Automation UX Studies

Regarding related work about in-vehicle UX (manual or automated), which involved the context, already gives first insights about the impact of specific context factors in the context of driving automation. Thereby, driving automation itself can also already regarded as a context factor.

Type of Context	Description
Physical	Apparent features of situation in which the human-mobile computer interaction takes place, including spatial location, functional place and space, sensed environmental attributes, movements and mobility, and artefacts present.
Temporal	User's interaction with the mobile computer in relation to time in multiple ways such as duration, from time of day to years, the situation before and after use, actions in relation to time, and synchronism
Task	Surrounding tasks in relation to user's task of interacting with mobile computer containing the subcomponents of multitasking, interruptions and task domain. Task context is related to the demands of the entire situation upon one's attention.
Social	Other persons present, their characteristics and roles, the interpersonal interactions and the surrounding culture that influence the user's interaction with a mobile computer.
Technical and Information	Relation of other relevant systems and services including devices, applications and networks, their interoperability, informational artefacts or access, and mixed reality to the user's interaction with the mobile computer.

Table 2.2: Context categories for mobile systems [229].

Identifying Relevant Context Factors for Driving Automation UX Lilis et al. [230] defined an ontology for describing the process of car driving in general, consisting of dozens of static and dynamic parameters in the dimensions driver, vehicle, and environment, e.g., the road segment, purpose of driving, regulations, road type (cf. operational design domain for driving automation) and driving session. Gkouskos et al. [221] investigated in-vehicle UX of modern cars. A qualitative approach, combing contextual inquiry [231], reflexive photography [232], and the UX Curve method [233] to address also temporality, was applied. Results highlight the importance to address the context and results reflect the categories of Jumisko-Pyykkö and Vainio [229], see Table 2.2. On the one hand, users were physically placed in the car, on the other hand, time of day, driving purpose and social context impacted UX. Jeon [185] revealed that affective experiences can be elicited by driving-irrelevant, e.g., good or bad music, and by driving-relevant factors, e.g., heavy traffic, in-vehicle context. But also by out-of-vehicle context, e.g., being early or late for an appointment. Rahman et al. [234] also investigated in an online-survey the impact of internal context parameters of drivers' fatigue, time pressure and the external factor time of the day (cf. [221]) on users' acceptance of ADAS. They revealed a higher intention to use an ADAS when users are fatigued or do not have time pressure. Bjørner [235] used the method of in-depth interviews to study a priori diving pleasure with video examples. He revealed that e.g., different speeds, road conditions, purposes, driving distances, and numbers of people in the car affect automated driving pleasure. The pleasure was highest in traffic jams and for parking, but participants were concerned about trust, loss of control and sense for freedom. Regarding the impact of the level of automation as a context factor, Rödel et al. [104] revealed that with increasing automation users' fun and perceived control (trust) decrease. Thus, specifically for driving automation, circumstances of the different levels of automation (see Subsection 1.2.2) and implications on the user need to be carefully regarded. Thus, Krome et al. [236], proposes a context-based design approach, to address the requirements of driving automation. They built upon the methodology research through design including exploration by conducting a contextual inquiry, ideation by using a method called *"Car-Storming"* (brainstorming in the car in the commuting context they designed for), prototyping building *"AutoGym"*, and evaluation.

Studying Context of Driving Automation Including the context in current user studies is not easy, as future automated vehicles, especially in higher levels, do not yet exist. Thus, workarounds have to be developed. Pettersson and Karlsson [102] analyzed expectations in future vehicles by letting participants collage and draw how they imagine future ADSs. Further, expected interaction and interior design were investigated by participants' drawings on a parking slot (*setting the stage method*). Users acted engagement in an imagined context aimed to elicit UX. By analyzing users' narratives they revealed a tension between the wish to engage in NDRTs (as one main benefit of ADSs) and existent distrust into the system, which again hinders users to engage in NDRTs. The interactive method, giving participants a context, facilitated to access emotions like curiosity, fear of mode confusion, or delight towards the novelty of automated vehicles. However, also storyboards, as used also by Rödel et al. [104] were shown as a useful approach to make the context of future experiences explicit [237]. Pettersson [187] compared the UX data gathered from an in-vehicle system in the field (real context) with the experience of the same system using VR-glasses. It could be identified that narratives in VR were more general, contrarily, investigations in the real context more data on emotions, reflection on aesthetics, and design proposals could be elicited. Also driving simulators, using a virtual environment, can simulate the context only to some degree (i.e., predict the real world). Participants behave differently due to the absence of real danger. Further, difficulties like simulator sickness and the need for simulator training have to be taken into account. Nevertheless, context factors like weather, traffic, and lightning can be controlled and experiments and driving situations as important context factors reproduced [238]. As real vehicle studies are expensive and often even not possible, wizard-of-oz setups enable researchers to realistically investigate human expectations and experiences towards the integration of automated vehicles in their everyday life contexts [239, 240, 69]. Krome et al. [241] built on participants' pure imagination during their daily commute. While the investigator took over participants' driving tasks, participants were interviewed to identify possible context factors relevant to regard in design for pleasurable and entertaining experiences. Results revealed that identified context-factors were generally applicable to commuting, but not with automated vehicles.

2.4 Implications for This Thesis

All definitions, theories, and approaches, reductive or holistic, differ slightly but also complement each other. Nevertheless, there is an agreement that UX is *subjective*, *dynamic* and *context-dependent* [146]. Especially the complexity of driving automation in the different levels of automation and the intangible topic of UX makes it challenging for investigation. Thus, summarizing UX theory, we provide our own definition for driving automation:

> *Driving automation UX is a multi-layer construct involving interdependencies between the* ***user****, whose role is in between an active driver and a passive passenger, the* ***automated vehicle*** *in a specific level of automation* ***as product*** *with* ***included systems*** *and* ***services****, and the* ***context of use*** *defined by an infinite number of internal and external factors.*

Driving automation UX studies have already investigated implications on emotions and the relationship between positive experiences and need-fulfillment. Thus, using relevant psychological needs as a source of inspiration for concept development seems to be a promising approach to optimize driving automation UX to increase individual and societal acceptance. Further, also the perception of product attributes regarding UX quality is predominant in driving automation UX studies, as well as the importance to examine the impact of influencing context factors, and thus, to include the context in UX studies. However, a systematic approach to study all interdependent aspects, i.e., which psychological needs are relevant concerning technical restriction and requirements of the different levels of automation and other context factors important for the driving automation context, is still missing. Existing work mainly focused on fragments of UX. Further, proved user interface examples addressing context-dependent requirements of driving automation do not yet exist. Thus, this doctoral thesis builds upon related work and existing theses in the field. We argue, to be able to establish and facilitate a user-centered approach, users' experiences with a driving automation system have to be analyzed in a systematic way. Thereby manifested and valid knowledge that can be used as a common ground for discussions in design and development processes can be generated. To be able to create such a systematic approach, existing challenges of UX practice have to be analyzed. This differentiates the presented doctoral thesis from existing work.
Thus, the following chapter looks at the state-of-the-art practice in academia and industry. Existing methodological approaches in driving automation UX practice are studied to reveal how the different aspects as well as layers of an experience have been and can be better addressed.

3 UX Practice in the Context of Driving Automation

As the previous chapter highlighted, UX is a construct, determined by many aspects and layers. Hence, it is debated and criticized as "fuzzy" [130, p. 1]. However, aren't there ways to deal with the subjective nature of UX? Sanders [242] calls an experience a *"constructive activity"* (p. 2), which we cannot really design. She reasons:

> *"If we can learn to access people's experiences (past, current and potential), then we can make user experience the source of inspiration and ideation for design"* (p. 19).

Thus, it is important to reveal what users feel in order to be able to emphasize and to recover what people dream (latent needs). Thereby, researchers, designers, and developers get a tacit knowledge, that cannot be expressed in words [242]. Only with an iterative approach with evaluating users' experiences we are able to achieve step by step the best possible product, which leads in the end to the best possible UX [139]. By this, we are able to shift from a technology-centered to a real user-centered approach, in which the user remains the most critical and important factor.

Hence, general UX practice is mainly discussed in the context of evaluation. The approaches used for empirical UX evaluation have been debated for many years (e.g., by [149, 130, 243, 244]). Nevertheless, an ambition of sound empirical evaluations applicable to UX still exists [130]. Thereby, epistemological directions of different disciplines involved in UX practice collide (engineering - measuring vs. humanistic - understanding). This refers to academic as well as industrial approaches, which differ concerning purpose (creating new knowledge vs. product development [245]) and demands on evaluation. While validity, reliability, and repeatability have to be ensured obligatorily in academia, industrial UX practice is in addition determined by the hectic pace of development processes, principles and practices of agile or lean approaches, limited resources and the discrepancy between designing for the *"user"* or a *"customer"* [245, 244, 243, 246, 247, 248, 249], [34]. This leads to a gap between academia and industry UX practice which needs to be considered in the development of driving automation systems. In addition, individual characteristics of driving automation research have to be regarded. Hence, this chapter aims to elaborate on the following research questions:

- **RQ1: How is UX in the context of driving automation methodologically addressed in practice?**

  - RQ1.1: How is UX in general methodologically addressed in academia?

  - RQ1.2: How is driving automation in general methodologically addressed in academia?

  - RQ1.3: How is driving automation UX methodologically addressed in industry?

Hence, the following sections analyze academic approaches to study UX and driving automation and industrial approaches to study driving automation UX, aiming to identify individual and joint challenges.
Therefore, academic practice is studied by conducting two systematic literature reviews. In the first review, to understand the development of UX evaluation in general (not only for driving automation UX), we [29] conducted a state-of-the-art review of UX evaluation techniques from 2010 to 2016[1]. Our analysis, therefore, includes trends regarding the number of UX publications, UX dimensions studied, study contexts, method application, and triangulation patterns derived from the analysis of method application. In the second review from 2010-2018[2], we [3, 2] focused on Human Factors/HCI driving automation studies in general (not only for driving automation UX). The aim was to present an overview of the investigated constructs of driving automation and the state-of-the-art of existing methodological approaches. Thereby, besides the construct of UX, other constructs are analyzed in detail regarding collection methods and used parameters. Industrial UX practice is investigated in the context of driving automation only, by conducting interviews with eight UX practitioners from four different European OEMs and four suppliers/agencies working for OEMs. The analysis includes trends regarding the role of UX in the automotive industry and methodological approaches of driving automation UX studies. Results aim to create an approach, addressing these challenges by using in addition insights from UX theory and methodological approaches from academic UX practice. All three studies are presented in the following sections after elaborating respectively on related work about academic and industrial UX practice.

[1]As the paper about was written in 2017, the years 2017, 2018 and 2019 are not analyzed
[2]As the paper about was written in 2019, the year 2019 is not analyzed

3.1 UX Studies in Academia

Previous meta-analyses about UX practice which were conducted around 2010, had identified several challenges [132, 250, 244, 243, 251]: dimensions of UX are too unclear and easily interchangeable with the concept of usability and UX evaluation often lacks regarding the application of UX theory. Further, satisfactorily validated UX methods are missing, thus, researchers create their own questionnaires. According to method application, especially a lack of solid mixed-method/ triangulation approaches, i.e., rational UX method triangulation that addresses the multidimensionality of experience triangulation, is repeatedly stressed. Thus, Law et al. [252] state:

> *"employing quantitative measures to the exclusion of qualitative accounts of user experiences, or vice versa, is too restrictive and may even lead to wrong implications"* (p. 540)

Also, Visser et al. [253] suggest that experience data should be made accessible in layers, e.g., moving between the expressible by interviews, and tacit behaviors by observation techniques, and latent experience data of knowing, dreaming, and feeling by, e.g., generative sessions [253, 242]. Applying several methods in practice can help researchers to learn about users and their ways to express experiences [254]. However, guidelines and recommendations how to combine methods in UX, are still missing.

Triangulation

Triangulation, also referred to as mixed methods, is a research strategy applying two or more methods, to obtain valid and well-founded evaluation results from different perspectives. The aim is to balance the weaknesses of every single applied method. The roots of method triangulation approaches trace back to the *paradigm wars* [255] and grew in popularity during the 1980s in social, behavioral and human sciences [256] to bridge different epistemological standpoints in research; applying triangulation approaches served as a way to overcome differences in approaches to knowledge production, enabling both the abilities of qualitative research in understanding the subjective as well as the quantitative to determine statistical trends and connections. Denzin [257] outlined four types of triangulation in order to study a phenomenon: (a) *data triangulation* (i.e., the use of a mix of data sources in a study), (b) *investigator triangulation* (i.e., a number of researchers researching the same phenomenon), (c) *theory triangulation* (i.e., the use of a number of theories used for interpreting results of a study), and (d) *methodological triangulation* (i.e., the use of more than one method to study a phenomenon). Creswell [258] describes the overarching two different types of employing two or more methods; either *sequential* (firstly either a quantitative or qualitative method is used, and secondly the other type is used in the following study to explain, explore or validate the results) or *concurrent* (where two or more methods are employed within the same study to cross-validate findings). Employing triangulation to study a subject has been claimed to contribute to a more reliable, holistic and well-motivated understanding of phenomena [256], and to counteract inherent biases from data sources, investigators and especially methods.

Consequently, our goal was to update the knowledge from previous work and provide an analysis of the current characteristics of empirical studies in UX from 2010 to 2016. In particular, we were interested in how the multi-dimensionality of UX is approached by using (or not using) method triangulation.

▶ RQ1.1: How is UX in general methodologically addressed in academia?

In order to answer RQ1.1, we reviewed papers stating to evaluate UX as a part of their description of the study. By evaluation, we mean a focus on assessing specific designs, from early concept ideas, prototypes to finished products, in order to inform a design process.

This section is based on the following publication: [1].

3.1.1 Study Setup

We decided to pursue a systematic analysis approach, based on a representative sample of publications in the field of HCI and UX, to derive suitable insights regarding triangulation approaches in academic UX studies. Our approach (see Figure 3.1) is based on a procedure similar to Bargas-Avila and Hornbæk [132] and Lachner et al. [248]. Hence, similarly adapted from the QUOROM statement [259], which specifies guiding principles on how to conduct meta-analyses including a quantitative data synthesis and a clarifying flow diagram, see Figure 3.1.

Step 1: Identification of possibly relevant publications Academic work related to UX evaluation is spread across multiple scientific journals and conferences and continues to gain interest. To limit the scope of our analysis we decided to only use the ACM Digital Library (DL) as a research database,

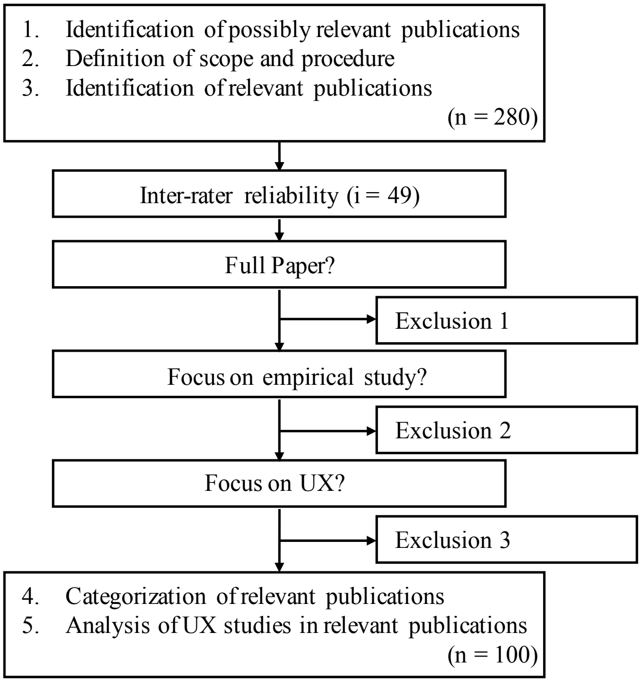

Figure 3.1: Procedure of the literature review.

including 476,316 records (207,571 from 2010 to 2016) in total at the time we conducted our review. Furthermore, besides being a rich source of UX research, it contains influential conferences and highly ranked journals such as CHI, DIS and TOCHI. We further narrowed down the scope through our selection of suitable target conferences and journals. We based the selection of suitable venues on the h5-index indicated by Google Scholar as well as the relevance for our study aim hence omitted proceedings that target a specific domain (e.g., automotive, robotics, mobile, etc.). As a consequence, eight ACM conferences were selected (see Table 3.1).

We used the search query *"user experience" AND "evaluation OR method OR measure OR assessment OR study"* in any field and limited the search results to the period 2010 to 2016. We excluded the current year (2017), since the publication year was not yet finished and thus not yet all possible relevant papers available. Next, we selected the conference proceedings (respectively the journal) of all selected venues and excluded all extended abstract, adjunct, and companion proceedings if they were listed individually (based on [132]). False positives were excluded at later stages. Our procedure led to 280 papers in total, as shown in Table 3.1.

Conference / Journal	Database (ACM DL)	Search Results (total)	Relevant Publications
CHI	7,482	137	50
UbiComp	2,265	34	10
DIS	1,092	40	14
CSCW	1,701	17	8
UIST	839	13	3
ICMI	843	1	0
IUI	837	20	7
TOCHI	278	18	8
Total	*15,337*	*280*	*100*

Table 3.1: Number of search results (excluding results from extended abstract, companion, and adjunct proceedings) and relevant publications for our analysis (per venue, from 2010 to 2016).

Step 2: Definition of scope and procedure As a next step, we defined criteria to exclude publications that were out of scope of our study aim. A publication was excluded if (1) it was not a full paper, or (2) if there was no trace of an empirical study, i.e., not including an empirical study of any kind, not including a clear description of the evaluation process or the study results, or (3) if the authors of the paper did not clearly state that evaluating UX (in any form) of a product or service was the aim of the empirical study. For the third exclusion criteria, it is important to note that we only included publications where the authors directly linked their study to UX while we excluded publications where the term "user experience" was only mentioned in the abstract, key words, related work, and/or introduction and not as a part of describing the specific study. We did not judge the authors' views on UX; if authors claimed to study UX, they were included in our detailed categorization.

Next, we selected the categories (based on [132]) that we used to analyze all relevant publications. Name and type of method were categorized (e.g., self-developed questionnaire, standardized questionnaire, free interview, semi-structured interview, activity tracking, live observation) and information if the method was referenced or not was noted. The (data) type of the methods in each publication (qualitative, quantitative, or both), task orientation (exploratory use where the user was free to explore without guidance, or task-oriented), and if a motivation for the use of triangulation was stated (if two or more methods/types of data were applied). We also noted place of study (lab/field) and period of use (single-session/shortterm/longterm). For each study, we noted if there were references to UX literature and theory, as well as which dimension of UX that was studied. Thereby we differentiated between the consideration of following aspects: generic UX (experience is studied as an own construct without mentioning directly what is to be collected or measured), pragmatic quality (usability, functionality), hedonic quality ("psychological well-being through non-instrumental, self-oriented product qualities"

[201, 204]), aesthetics/appeal, satisfaction, affect/emotions, enjoyment/fun engagement/flow, frustration, motivation and other constructs. Further categories will be elaborated in the results section.

A common understanding and acceptable inter-rater reliability of the definition and interpretation of the exclusion criteria and the screening categories was ensured by four cross-checks before the final screening, containing of in total 60 papers mutually reviewed in full. Each of the the four cross-check rounds consisted of an independent analysis as well as a joint telephone conference of the first three authors to discuss 15 papers from each of the venues CHI '16, CHI '15, DIS '16, and DIS '14. These cross-check helped to decide how to interpret the inclusion or exclusion of papers and how to assign the defined categories. Most prominently, we sharpened selection criteria 3 and decided to exclude evaluations that mainly target the analysis of experiences with technology in general, e.g., with the aim to derive UX theory, as compared to the evaluation of a specific product or product type. Whereas Hayashi and Hong [260], for example, state that *"the overall goal of the studies was to investigate the user experience in using an authenticator [...]"* (p. 384, included in our review), Tuch et al. [179] start their survey study with the question *"Bring to mind a single outstanding positive experience you have had recently"*(p. 2081, omitted). Similarly to the latter, Mekler and Hornbaek [183] aim *"to identify hedonic and eudaimonic components of [...] experiences"* (p. 4511). Both latter examples were excluded from our review for stringency to our meta-study by a clear focus on the directed evaluation/exploration of a product/service type or case.

Step 3: Identification of relevant publications We considered the exclusion of publications as crucial for the subsequent analysis. To ensure the reliability of the selection process, the first three authors conducted a final screening test round. In the test round, each author individually screened the same set of 49 papers (17,5% of all possibly relevant publications). The set consisted of randomly selected papers of each conference/journal and year. The inter-rater reliability for the exclusion was found to be $\alpha = .8307$, 95% in a CI of (0.7161, 0.9345). According to Krippendorff [261], values for α higher than .8 can be seen as a satisfactory. For the final screening procedure, we split all publications of papers between the first three authors with weekly meetings to discuss borderline papers. Firstly, 30 publications were excluded because they were not full papers. Second, 46 papers were excluded because they were not empirical studies of a specific product or product type. Third, 102 papers were excluded for not relating the concept of UX to the empirical study (see Figure 3.1).

Step 4: Categorization of relevant publications After identifying all relevant publications, the three authors categorized the same set of publications according to the defined screening categories. Once again, weekly meetings where held to handle unsure cases of categorizations.

Step 5: Analysis of UX studies in relevant publications After about half of the time needed for the categorization in step 4, we organized a workshop at DIS 2017 [29] to discuss initial insights with researchers in the UX field. At the workshop, we presented first insights of our review, including, for example, types of products studied, UX dimensions addressed, referenced UX theory, employed methods, and triangulation approaches. Together with all workshop participants, we interpreted our initial findings at that time. These interpretations provided an initial basis for our final screening and analysis process. Finally, we finished screening and categorizing all relevant publications. The final screening also included one more cross-check for borderline papers. For the analysis, we first looked at general developments in the field of UX evaluation. Second, we specifically examined mixed method approaches/triangulation patterns.

3.1.2 Results

Below we report our results in following structure: We begin by describing general insights about the development of the amount of UX publications over time (1), the studied dimensions (2), and context (3). Then, we present our analysis of the applied methodology (4), which ends up in detailed insights about common triangulation patterns (5) in UX studies.

The Development of User Experience In general, we see a temporal development of the papers we rated as relevant (empirical studies with a focus on UX) with a percentage increase of 283% from 2010 to 2016. This means that in total 40% (N=100) (of all identified full papers (N=250)) were identified as relevant for a detailed categorization. However, the percentage of all full papers that have been excluded because they did not focus on UX (in total 41%) converges over the years with the percentage of papers we rated as relevant. Looking at the linear trend lines, there is only a slight decrease (-2.5%) of papers rated as relevant, and a slight increase of *no UX papers* (5.1%). Thus, neither a positive nor a negative development was observed over time (in terms of amount of relevant papers, i.e., the numbers of publications containing the search words increased continuously) but the percentage of papers found relevant in relation to the total numbers of papers containing the search words, remained fairly stable. This means that there is a continuous growth of UX studies. Below, we will discuss some insights regarding the UX dimensions we studied, the context and the methodology we used.

UX Dimensions In the detailed analysis and categorization of relevant papers (N=100), we found that the category that we summarized as *Generic UX* was the most frequently evaluated UX dimension (56%, see Table 3.2 for a full list of all UX constructs we used). In the *Generic UX* category, UX authors

UX dimensions	%*	Examples**
Generic UX	56	[262],[263],[264]
Pragmatic Quality	22	[265], [266],
Aesthetics/Appeal	7	[267]
Hedonic Quality	6	[268]
Satisfaction	4	[269]
Affect/Emotion	4	[214]
Enjoyment/Fun	4	[270]
Engagement/Flow	3	[271]
Frustration	2	[272]
Motivation	1	[273]
Other Constructs	16	e.g, trust [274]

Table 3.2: Dimensions of UX research. *Note: *multiple dimensions in one study possible, based on all relevant papers (N=100), **examples are randomly selected, and number of examples is dependent on the percentages: <20:1, <30:2, >30:3.*

understood UX as a general construct and did not specify which aspects they studied in detail. For example, Woo et al. [262] describes: "we conducted a qualitative user study to understand people's experiences with DIY smart home products". In Bargas-Avila and Hornbæk's study of papers from 2005-2009 [132], *Generic UX* was also the main experiential dimension, yet slightly less prominent (in 41% of all papers). Consequently, there has been an increase from 2010 to 2016 of papers that evaluate UX as a broader construct. In 2010, only 1 out of 6 papers studied UX as a general construct [275]. In 2016, 52% of the papers did not define any additional concrete dimensions. In addition, 22% of all relevant papers measured the pragmatic quality, by constructs of usability, ease of use, and/or efficiency. The reasoning behind focusing on the pragmatic quality differed, e.g.,

> *"to better understand the impact on the User Experience, we conducted a lab-based user study to evaluate the effectiveness of different time series visualizations that use varied interaction techniques, visual encodings and coordinate systems for four tasks [...]"* [265, p. 5447].

Other constructs which were understood as a dimension of UX included aesthetics/appeal (7%), hedonic quality (6%) and satisfaction (5%). Enjoyment/fun and affect/emotion, both considered as core dimensions in [132], are only investigated in 4% of all papers. Engagement/flow, frustration and motivation were also rarely studied.

The high percentage of papers using a vague description of UX is also reflected in the theoretical frameworks of the papers. Overall, only 17% of all papers use a definition of UX, 83% do not. Furthermore, established UX theory papers, e.g., [151, 164, 129, 252, 125, 124] are only referenced extensively in 8% of all papers, to some extent in 17% and in 75% not at all. Häkkilä et al. [276] wrote:

> *"[...] Although there is hardly a unified definition for UX [146, 129], it is widely agreed that UX goes beyond usability and instrumental aspects [129]. A definition presented in [124] describes UX as 'a momentary, primarily evaluative feeling (good-bad) while interacting with a product or service'[...]"* (p. 1012).

This is an example of a paper containing extensive references to UX theory. Such extensive descriptions were rarely found in all relevant papers.

Context In total, 56% of all studied products are presented and discussed as prototypes (of which 96% are high-fidelity prototypes), 39% are finished products or beta versions. Earlier stages of concepts were rarely evaluated. Only two papers used a wizard-of-oz setting and only one paper analyzed stories in a narratated form.

In contrast to [132], where only 21% regarded the context of the product in their study, from 2010 to 2016, almost the half (45%) of the publications described a field study and thus involved the context in their investigations. Ghellal et al. [277], for example, studied the experience of an augmented reality game within a horror and vampire genre. At the same time, 41% were lab studies. Remote studies were conducted by only 8% and a mixed setup (lab and field) by 4% (all percentages rounded). We found that professional software tools (77.8%; n=7), mobile phone/apps (53.3%; n=8) and connected services (75%; n=3) were mainly investigated in a field study, while interactive games (61%, n=8) are more frequently evaluated in a controlled lab setting.

Furthermore we can report that 63% of all selected UX studies are evaluating the UX within a single session. These sessions were mostly conducted in the lab (61.9%; n=39), or within a field study (25.4% n=16). However, at least 34% of all UX studies used a long term setup (several weeks). Of these, 76.4% are conducted at the field, 14.7% assess UX remotely and 5.9% are performed in a lab. Only 3% are analyzed in a short term setting (i.e, several days, thus longer than a single session but not for weeks or longer). In total we can speak of a positive development since 2010, where the studies stretching over several weeks were only available in *"some papers"* [132, p. 6]. However, "truly" longitudinal studies which *"cover typical product life cycles over several months and years"* [132, p. 6] are still missing at large, with important exceptions such as [278].

Method Application In order to evaluate UX, a variety of methods from related fields, as well as newly developed methods have been employed over the years. With regards to method deployment in our data set (see Table 3.3), we

Method Type	%*	Examples**
Self-Developed Questionnaire	53	[279], [276], [263]
Semi-Structured Interviews	46	[280] , [276],[262]
Activity Logging	31	[281], [268],[275]
Standardized Questionnaires	26	[282], [283]
Live User Observation	19	[267], [284]
Videorecording	16	[268], [285]
Free Interview	9	[286]
Think Aloud Feedback	6	[274]
Diaries	6	[284]
Focus Groups	5	[284]
Online Feedback	3	[287]
Probes	3	[288]
Physio-psychological	2	[289]
Others	5	e.g., sticky labels to capture context [290]

Table 3.3: Methods used in UX research. *Note: *multiple methods in one study possible, based on all relevant papers (N=100) **examples are randomly selected, and number of examples is dependent on the percentages: <10:1, <30:2, >30:3.*

observed that self-developed questionnaires were used in more than half of all papers (53%), 46% conducted semi-structured interviews, 31% employed activity logging, 26% used a standardized questionnaire, and 19% observed their users. Probes (i.e., additional material given to the users to elicit experiences, such as the possibility to express experiences through video, photo or drawings) and objective measures such as physio-psychological methods were rarely used. Self-developed questionnaires are also the method which is most commonly used stand-alone (11%), followed by semi-structured interviews (9%) and standardized questionnaires (6%).

When looking at established methods that focus on a specific evaluation scenario, an analysis shows that there is a broad range; 40% use a unique method, which no other study employs in our dataset (see Table 3.4). The NASA-TLX questionnaire, developed to assess workload [291], was (perhaps surprisingly) the most frequently used method in all UX studies (7%). Next, the AttrakDiff questionnaire [216] (5%) and a second version of it (2%) were employed. The System Usability Scale was used in 3% of the papers. As a consequence, we cannot report a high consensus in methods in general.

Our systematical categorization shows that 32% of the data collected in UX studies is solely quantitative (e.g., activity logging, questionnaires, psycho-physiological data) and 22% solely qualitative (e.g., interviews, observations). However, combinations of different methods based on the same data type, meaning either two or more qualitative (respectively quantitative) methods, are part of these numbers. The bigger part of the papers (46%) applied both quantitative and qualitative measurements, meaning that the studies used two or more methods, i.e., a triangulation approach.

Specific Method	%*	Examples**
NASA-TLX	7	[283]
AttrakDiff	5	[214]
System Usability Scale	3	[280]
AttrakDiff 2	2	[275]
User Engagement Scale	2	[271]
Aesthetics scale	2	[292]
PANAS	2	[193]
Others	40	e.g., SAM [293]

Table 3.4: Specific methods used in UX research. **multiple specific methods in one study possible, based on all relevant papers (N=100), **examples are randomly selected and number of examples is dependent on the percentages: <10:1, <30:2, >30:3.*

Triangulation Patterns Analyzing the methodology of the 100 selected papers, we can observe that the majority (72%) uses a triangulation approach. While 21% mix only the method (e.g., Campbell et al. [294] use activity logging during the interaction with weblog posts and a post-use self-developed questionnaire focusing on ease of use, enjoyment, and intention to return), in 46% also the data type (quantitative and qualitative methods) was triangulated. Only two papers mix theory [295] or user groups [296]. We were able to cluster and identify 8 insights about triangulation patterns based on our analysis of general method combinations (see Figure 3.1) and data type per temporal stage of assessment, i.e., before, during, or after the evaluated interaction as described below.

Our analysis shows that many authors justify the use of multiple methods. In 32 (44%) of all papers that use any kind of triangulation (N=72) the authors state a motivation for the use of multiple methods. Besides, e.g., Ardito et al. [284] who justify their approach based on related work in the field of triangulation, most authors briefly mention that their aim of applying more methods or data types was to get deeper insights (e.g., [297] or [298]). Additionally, a second main reasoning behind method triangulation was to better understand the results of other applied methods, e.g., using post-use interviews to make sense of observations (see [299]) or post-use interviews to make sense of video recordings (see [300]).

Our analysis also shows that the majority of method combinations is only based on a small set of different methods. More precisely, we saw that self-developed questionnaires are most frequently used together with activity logging (23%) or semi-structured interviews (20%). Furthermore, semi-structured interviews are often combined with activity logging (15%) or with standardized questionnaires (11%). A typical triangle of methods (not necessarily applied in isolation) is the combination of self-developed questionnaires, semi-structured interviews, and activity logging (10%). The most frequent triangulation pattern, which is used standalone (without any additional methods) is self-developed questionnaire and activity logging (9%), whereas 6% additionally use semi-structured interviews. Thus, compared to previous research [132], we see a substantial increase of the use of activity logging as a complement to more traditional self-reporting. However, when qualitatively reviewing the content of the method descriptions, results, analysis and discussions, we often found weak links between the conclusions drawn from both sources.

Table 3.5 shows an emphasized interest in evaluations during and after the interaction. In particular, 96% of all studies assess UX after the product usage, whereas 65% of all studies assess the UX during the interaction. Although 22% of the relevant papers investigate UX before the actual use, only three publications from recent years pursue an expectation-focused approach focusing on the analysis of pre-use and post-use evaluation. Furthermore, 19% assess UX in all temporal stages. Uriu et al. [286], for example, conducted interviews before and after the assessed interaction plus video recording during and after the interaction. Their goal was to study the UX of a whole cooking support system. Current research emphasizes the focus on pre-use and post-use evaluation (e.g., [301]). Expectation is a key aspect of an experience, yet still rarely analyzed in academic studies.

Interviews and questionnaires are not only two of the most common method types that were used in all relevant publications, but also the preferred triangulated methods, as previously stated. In our analysis, we see a tendency towards post-use triangulation of interviews and questionnaires, either as a stand-alone data type triangulation, e.g., [302] or [303]) or in combination with the additional evaluation before and/or during the interaction. In total, one quarter of all analyzed publications triangulate only questionnaires and interviews to evaluate the experience afterwards. Vermeeren et al. [250] also observed that scale-based questionnaires, often have a follow-up interview to better understand research findings. In contrast, Alves et al. [304] more recently outlined that in practice, companies prefer observation and think-aloud over questionnaires and interviews.

It would seem plausible that the more data we collect, the more insights we can derive. Vermeeren et al. [250] question why researchers always want more data and suggest to rather focus on suitable combinations of methods. Our analysis confirmed the tendency towards applying more methods in UX studies, as only 28% of all relevant papers base their user study on only one method. Furthermore, the studies that pursued an explorative approach (i.e., with the main goal to explore a product or prototype freely rather than evaluating a specific task) tend to be based on more methods than task-oriented studies. From all 16 publications that use 4 or more methods in their empirical study, 12 (75%) pursue an exploratory user study (e.g., [297] or [305]). When we had a closer look at the papers that only applied 1 method in their study, we saw that 11 (39%) out of 28 publications focus on Generic UX (e.g., [306] or [279]).

Before	During	After	%*	Examples**
	♦	♦	42	[271], [284], [292]
		♦	32	[307], [308], [309]
♦	♦	♦	19	[290], [273]
	♦		4	[310]
♦		♦	3	[287]
22%	65%	96%		

Table 3.5: Temporal aspect of UX evaluation: paper which evaluated before, during and/or after interaction visualized by diamonds. *Note: *combinations are sorted by frequency of occurrence, based on all relevant papers (N=100), **examples are randomly selected and number of examples is dependent on the percentages: <10:1, <30:2, >30:3.*

We agree with Vermeeren et al. [250] that it is not a cause in itself to add more methods, but careful consideration of combining the right method is key. We, however, consider the tendency towards more methods to be a generally positive trend in the exploratory studies to better understand the results.

The joint evaluation of expectations, UX during the interaction, and post-use UX is usually time-consuming and costly, but pointed out as an important key understanding of user experiences [165, 163]. Based on our analysis, we can see that such holistic evaluations of UX before, during, and after the interaction are often conducted for long term studies. From all relevant publications in our analysis, 19 analyze all temporal stages whereof 13 (68%) focus on a long term evaluation. We had assumed to find more holistic studies addressing all temporal stages of UX evaluation, since their importance and value have been highlighted before [311]. However, similar to our findings, the review of Bargas-Avila and Hornbæk [132] in 2010 highlighted 17% of papers which analyzed all temporal stages and 3% that focused their evaluation on pre-use and post-use experience.

Almost one fifth (19%) of all relevant papers analyze all temporal stages, including the experience before the interaction (i.e., expectations), during the actual use, and post-use UX. Although about half of the publications that analyze all temporal stages focus either only on quantitative methods or only on qualitative methods , we identified a variety of different data type triangulation approaches. While Shin et al. [312], for example, base their study on mixed data pre-use, quantitative during use and mixed data post-use, Park et al. [274] use quantitative methods before and after the interaction and qualitative methods during the interaction.

3.1.3 Discussion

After analyzing the data, we presented our results at a workshop [29] and discussed them with UX experts of academia and industry (N=8). This helped us to critically analyze and assess existing approaches of academic UX practice application from a practical and non-biased perspective.

How is the UX Research Field Evolving? While the overall number of UX studies is increasing, only a quarter of the papers make any kind of reference to UX-specific literature. This raises the question: *"Is the theory of UX already taken for granted or is it too vague or unknown?"* We had to exclude 104 papers which used the term "user experience" as a buzzword but did not address the topic at all (based on our understanding). Often the term was even used within the title or the author keywords but nowhere else in the paper. One of the workshop participants stated: *"UX is gaining attention, everybody wants to say they do UX – even though they don't do it".* The fact that theory was often only vaguely addressed likely had consequences on the quality of evaluation. Furthermore, the lack of reuse of UX-specific methods was apparent in our data. The reasons behind this could not be revealed in our empirical data, but perhaps the nature of specific experiences (e.g., of a mobile health service [313] or a navigation system [314]) may not appear to be translatable to more generic methods for approaching the evaluation topic, and the researchers turn to, for example, self-developed questionnaires rather than reusing existing, validated ones.
UX evaluation still appears to struggle with the same issues as in previous meta-reviews (e.g., lack of theory, lack of validated methods, overlap with usability), and one could question whether the field is maturing or disintegrating. UX is a diverse topic and hence it may be misleading to look for a *"one solves it all"* method. One should rather choose more specific methods for the specific type of experience and/or triangulation to accomplish a useful UX evaluation.

How Can we Exploit Data-Driven Methods for UX? Surprisingly, the data-driven and objective method "activity logging" belongs to the 4 most frequently used methods in UX studies. But is it really a valid measurement to assess users' experiences? This was also discussed at the workshop [29], and one participant stated: *"Activity logging is only used to report data, but relationships are rarely investigated".* Similarly, we found a large number of papers employing user observations, but often it was not clear how observations were analyzed and how they actually contributed to the results. Exceptions were, of course, found, which contributed to a better understanding of the experience (see, for example, [315]). We believe that there is much more work to be done in this area to guide technological efforts that can be of value when studying UX. Dove et al. [316] write: *"It is no longer enough for UX designers to only improve user experience by paying attention to usability, utility, and interaction aesthetics."* and suggest that much more can be done to improve UX by employing machine learning for offering new value, such as personalization of systems by learning from user interactions. We found very little efforts in this area in relation to evaluation, and look forward to further progress of data-driven methods to help us understand UX, finding patterns and relationships instead of isolated data. **For data-driven methods, we believe that triangulation of qualitative insights and quantifiable measures is important, either by sequential triangulation (i.e., using qualitative data to understand identified patterns in quantitative data or the other way around [258]) or concurrent triangulation, to better grasp and validate the UX data as it is gathered.**

Why are Early UX Evaluations still rare? Michalco et al. [301] and Kujala et al. [278] suggest to study the relation between expectations and UX as expectation disconfirmations, which has a significant effect on the overall UX. However, our study revealed that still, only few publications investigate the relation between expectations and the post-use experience (assessment before and after the experience). The infrequent comparison between expectations and after-use evaluation is also related to the persisting lack of UX evaluation at early design process stages, although this is often claimed to be important in a design process [244, 243, 250, 132]. We had assumed to find more of these studies, but we did not, even if the examples of methodological approaches of wizard-of-oz (i.e., a human controlling the interface to respond to a user in a test setting) used in the field [297, 299] were very informative. In addition to this, we were interested to see if there were approaches uncovering not only the expressible and readily available responses to an experience, but also the tacit and the latent aspects of experiences (c.f. [242]). Of all papers, 4% used extra stimuli/probes during the evaluation, such as the possibility to express the experience in video and audio material (see [290]). We think that these are interesting approaches deserving further exploration.
We conclude that most studies are focused on tangible and complete or almost complete designs; early stage evaluation relies heavily on the imagination of the study participant and is a step researchers may be unwilling to take. However, for studying future technology like driving automation, early stage evaluation is necessary and valid approaches have to be provided.

How to Apply Triangulation? Our analysis of sequential and concurrent triangulation patterns (cf. [258]) demonstrated the complexity and variety of UX evaluation. In this area we could see most progress in the research field, but also identified several methodological gaps. In the papers we reviewed, there were examples of well executed sequential triangulation. Sequential triangulation holds the possibility of ensuring a systematically user experience-driven process, where initial findings can be followed up by additional data for further explanation, validation or exploration [258]. As examples of studies where data was explored sequentially, Leong et al. [290] used an initial diary study as later basis for further explanation during interviews with the participants. Hart el al [302] challenged their results from questionnaires based on unexpected findings in qualitative interview data. Hayashi and Hong [260] validated their primary data source by deriving from the quantitative data that the participants had a reasonable amount of exposure of the system to evaluate it qualitatively. Results like these serve an important role in building confidence for the data validity. Triangulation of sequential exploration of themes found in initial user studies were common, such as Lederman et al. [287] who employed sequential exploration by first understanding a product space qualitatively, triangulated with the evaluation of a designed prototype. This was a more commonly applied type of triangulation than for example validation of data points across data sources.

We found very few examples of concurrent triangulation that carefully match quantitative with qualitative data to derive a truly joint analysis, where results can be questioned or strengthened based on correlations or the lack thereof in the data. In many papers reviewed that applied triangulation, different types of data are gathered, but rarely cross-analyzed. Many studies left us with questions whether there was not more to be learned from the data with regards to correlation or differences between different types of data. There appears to be a growing understanding in UX research that using more than one method is beneficial, but a well-grounded knowledge about how to systematically cross-analyze data appears less widespread. Actively analyzing overlaps and differences in, for example, qualitative and quantitative data, that can add to richer and better validated knowledge of the evaluated topic, is still rare. Valuable exceptions are however for example Woo et al. [262] who make connections between data points over time as well as from different formats, to strengthen the outcomes.

Many studies provide a very short and general motivation of triangulation, if any, but there are exceptions, such as Kim et al. [317] who describe the process of applying grounded theory for the understanding the nature of the experiences and numeric data of questionnaires and log data of system usage for providing descriptive statistics linked to the themes. Ardito et al. [284] use a thorough motivation of their triangulation of data sources such as observations, questionnaires and focus groups, later cross-analyzing and making connections between the sources. Perhaps the “sad lack of reference” [10] between the quantitative and qualitative is beginning to lessen, but a widespread understanding how both approaches can contribute to each other apparently has not been accomplished yet. There could have been many more good examples of better integration of data during the analysis of results, as triangulation approaches have been claimed to lead to deeper understandings and sometimes unexpected results.

We conclude, there is a need to elaborate on methodological approaches concerning sequential and concurrent triangulation. These need to underlie to sound motivations for such approaches. A framework, guiding sound triangulation may help to improve UX practice.

3.1.4 Limitations

In our review, sources outside ACM were excluded, which may have resulted in a bias towards approaches founded in engineering and human factors perspectives rather than, for example, a design, psychology or a marketing perspective on UX. Directing the search to, for example, more design-oriented conferences and journals will most likely provide further insights into the state of UX evaluation. Further work could also encompass additional sources inside ACM that were now excluded, such as the NordiCHI conference series, which were excluded due to our selection basd on the h5-index. Especially, there is a need to constantly keep the analysis up-to-date with each finished publication year, starting with 2017. UX is still a developing research field which needs to be observed continuously.

3.1.5 Core Findings

In the following, the core findings of this study answering **RQ1.1**, are highlighted:

- **UX is often studied as a general construct without operationalizing which aspects are collected.**
- **There is still a weak link between UX theory and evaluation approaches. UX evaluation is currently still depending on personal perceptions of UX rather than on aggregated theory.**
- **There is a tendency towards traditional methods. Rather are semi-structured interviews and self-developed questionnaires used than methods specifically developed to study UX.**
- **Most studies use multiple methods, however, rather analyze data in parallel than perform sound sequential and/or concurrent triangulation.**
- **There is a need to provide guidelines and practical examples for effective combinations of different methods, i.e., triangulation strategies in UX evaluation.**

3.2 Driving Automation Studies in Academia

The huge potential of technological progress of driving automation has sparked enthusiasm among human factors and HCI researchers to develop user interfaces for this novel technology. Investigations of such interfaces through user studies are conducted to first determine feasibility, and in the next step, to fine-tune conceptual approaches. Here, basic research findings from HCI, human factors, and engineering psychology have been applied by academia and the automotive industry. Furthermore, some lessons learned from prior automation development in, e.g., the aviation sector [318, 319, 320] could be transferred. However, driving automation systems imply different preconditions which makes the situation much more complex. First, the driving environment is highly time-critical, and thus interventions must happen in seconds or even fractions of a second, while in airplanes, pilots usually have more time to respond to critical events. Second, there exists a greater variety among the targeted user groups spending their time in the car (see also Section 1.3.2). Similar to UX in general, also driving automation HCI/human-factors research has still no common agreed-upon methodological framework for evaluating driving automation systems and in-vehicle UIs.

There have been first efforts to give an overview of the evaluation of in-vehicle information systems [321], on the evolution from manual to automated driving [55], and also with a focus on driving automation [220]. In automotive studies in general, a trend towards performance measures, interviews and questionnaires could be revealed. Similar to the results of general UX studies (see Section 3.1), early-stage evaluation and the usage of collaborative, creative methods, were identified as rare [321]. An increasing amount of automated driving-related research in the history of the AutomotiveUI conference is visible [62, 55], [3]. Ayoub et al. [55] highlighted various upcoming challenges: there is a need to establish approaches different than for studying manual driving, e.g., reducing distraction vs. creating holistic driving experiences). They further showed that most studies were conducted in driving simulators, only a few in a realistic environment which questions transferability, reliability, and validity of results. Motion sickness and low fidelity, costs and risk can affect results. The usefulness of wizard-of-oz cars on the real road is highlighted. Forster et al. [220] revealed this also for driving automation research. Studies lack in the usage of both, observational and self-report data. Only by a multi-method approach, a comprehensive image can be derived. This is similar to our insights on general UX studies, see Subsection 1.3.2. They highlight the issue of preference-performance dissociation, i.e., self-reported and observational data lead to contradictory results. Therefore, valid and reliable methods according to psychometrics with a sound theoretical foundation need to be used.

The heterogeneity of constructs, use cases and driving automation operationalization results in a wide range of challenges that need to be overcome, and a multitude of papers addressing these timely issues have been published over the last years. To give an overview of past and current methodological approaches, we developed and followed a structured approach for reviewing related literature, presented in the following. The goal was to answer the following research question:

- RQ1.2: How is driving automation in general methodologically addressed in academia?

This section is based on the following publications: [2, 3].

3.2.1 Study Setup

With the considerations about the current research status, topics of interest in AD HCI research, study possibilities and the authors' experience in driving automation research in mind, we defined the reviewing process for this literature review.

Step 1: Identification of relevant venues To first identify relevant journals and conferences in the Human Factors community, we conducted a pilot study. An online survey was distributed via social media (e.g., Twitter, LinkedIn etc.) and to peers of the authors. In the survey, participants could indicate (1) both the top 3 journals and conferences where they have already published as well as (2) both the top 3 journals and conferences where they consider submitting an article (favored). Moreover, the survey included questions on whether the authors had already published original research on automated driving (yes vs. no) and the year of the author's first publication. Eventually, demographic data (i.e., age, gender, academic degree and academic background) was collected.

Demographics showed that mean age of the N=21 participants (n=5 female) was 32.81 years (SD=5.65).Most participants (n=10) held a Master's degree, n=9 a PhD and n=2 were professors. The Academic Background showed that the majority were psychologists (n=8), followed by engineers (n=5), computer scientists (n=5). N=2 participants had a Human Factors or Media Informatics background (multiple choice was allowed). Out of the 21 participants, n=19 had already published whereas n=2 had not yet published their research. The earliest publication had dated back to 1999 and the latest to 2016.

For the identification of relevant venues, we counted the overall number of instances independently from its position (i.e., 1st vs. 2nd vs. 3rd rank). The results regarding journals showed that Transportation Research Part F (TRF, n=7 publications, n=11 favored), the Journal of Human Factors and Ergonomics Society (HFES, n=7 publications, n=11 favored) and Accident

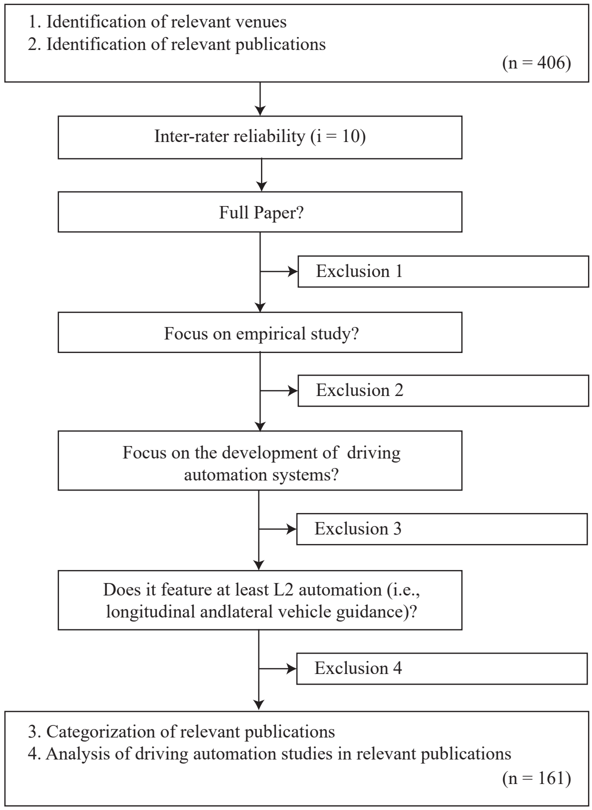

Figure 3.2: Procedure of the literature review.

Analysis & Prevention (AAP, n=7 publications, n=6 favored) were the most frequently indicated venues. Regarding conferences, the AutomotiveUI (n=6 publications, n=13 favored), the Human Factors and Ergonomics Society Annual Meeting (HFES AM, n=2 publications, n=11 favored) and the Conference on Human Factors in Computing Systems (CHI, n=2 publications, n=6 favored) were mentioned most frequently. Based on this expert survey we selected these three journals and three conferences to be included in our structured literature review.

Step 2: Identification of relevant publications The basis for the selection of papers for the present literature analysis were all research papers that were published in the respective venues between 2010 and up to 2018 (inclusive). We developed a decision tree to decide in a standardized and step-wise manner, whether or not to include each paper. This decision tree is depicted in Figure 3.2. It features four steps represented through binary decisions, where each has to be answered with "yes" for a paper to be included into our analysis. To pass the first step of the decision tree, the paper had to contain at least one of a set of keywords related to driving automation in the full text (see below). These keywords were selected to initially reduce the amount of papers in a reasonable way, while at the same time ensuring that no potentially relevant paper would be excluded. The first step of the decision tree was carried out by querying the respective online data bases using the following search terms:

"automated driving" OR "autonomous driving" OR "self-driving" OR "self driving" OR "autonomous vehicle" OR "automated vehicle"

Papers that did not feature driving automation represented by at least one of the keywords, as well as short papers, posters, and adjunct proceedings [322] were excluded in this step. For the remaining papers, the next step in the selection process consisted in examining if the papers' objective was an empirical study to discard other literature reviews, as well as juridical, theoretical, or ethical papers [220, 323, 324]. The subsequent step of the decision tree aimed at the actual primary focus of the empirical papers. If this was not research and development of driving automation, the respective paper was excluded from further analysis. This step was incorporated to rule out works on a concept that, in principle, could be used for the development of driving automation, but was not originally investigated with that purpose [325]. In the last step of the selection process, we took a closer look at the levels of automation [47] that were investigated. The level of mere driver assistance (Level 1) as well as concepts which do not count as driving automation according to SAE definition [326, 327] were out of scope for this literature analysis. Thus, only papers examining L2 and/or higher levels of automation (i.e., simultaneous lateral and longitudinal vehicle control) were included.

Overall, n=161 research papers passed all steps of the decision tree and were included in the present work. To ensure inter-rater reliability, a random selection of 10 papers was compared by means of intra-class correlations (ICC). ICC estimates were calculated based on a single-rating regarding the inclusion criteria (outcome of the decision tree to find out whether a paper should be included for further analysis), using a 2-way random-effects model. Results revealed a high inter-rater reliability with a correlation of r=.809 (F(9,36)=22.170, p<.001).

Step 3: Categorization of relevant publications After selecting the papers, we developed a reviewing strategy for literature analysis in two expert workshops. The first workshop lasted six hours and aimed at developing a standardized reviewing procedure. After the workshop, the resulting categories/dimensions as well as their emerging relations were translated into a database. Subsequently, five reviewers classified the selected 161 research papers by sorting them into the categories of the database. In case a new category occurred in the papers that had not been considered before, it was added to the database. After reviewing a subset of the 161 papers, we conducted another expert workshop which lasted approximately four hours. During this workshop, lessons learned from a first subset of publications (n=42) were derived and each reviewer could put unclear classification up for discussion. This ensures potentially high reviewer agreement in classification of the remaining papers (ambiguities in the subset have been resolved during the workshop).

Step 4: Analysis of driving automation studies in relevant publications We set up an MS Access Database to capture the relevant information needed for our investigations. The schema consists of the five main tables *Paper, Construct, CollectionMethod*, *Parameter*, and *Relationships*:
For each *paper*, we collected descriptive information (title, abstract, year, authors, conference), as well as the levels of automation addressed in the study. The following additional information was collected: The type of user (driver, passenger, external), road type (urban, highway, rural, not relevant), study type (lab, test track, real road, survey), the representation of the AV (static text description, sketch, driving simulator, wizard-of-oz, real vehicle), study period (single session, short-term, long-term), type of research (basic research, concept evaluation, method development, model development), as well as participant information, such as the number of subjects, their mean age, as well as if they were internally (students, employees, etc.) or externally recruited. *Constructs* represent the topics of investigation. To avoid subjective interpretation by the reviewers, we only collected constructs which were explicitly mentioned by authors in the papers, (such as *safety, trust, acceptance, etc.*). All constructs which were only investigated by one single paper were summarized within an *other* construct. Generic investigations on participants' opinion and general perception without directly mentioning specific constructs were summarized with a *General Attitude* construct. Relevant data *collection methods* are, e.g., driving performance, TOR performance, ECG, standardized questionnaire, interview. Again, we came up with initial suggestions that were expanded in case a new item emerged during the reviewing process. *Parameters* that were used in the different data collection methods are, e.g., reaction time (could be used to measure driving performance), gaze behavior, gaze number (eye-tracking), TAM [328], NASA-TLX [329] (examples for standardized questionnaires). To structure our data, we created a *relationship* table to represent (n:m) relations of papers, collection methods, parameters and constructs. Thus, each paper can investigate different constructs, where each construct can be assessed by one (or multiple) data collection methods, and each data collection method by one (or multiple) parameters. For each relation, we categorized whether the combination represented behavioral, self-reported, or physiological data. Furthermore we assessed if the parameter had been measured before/during/after a trial in the experiment. This data model allowed us to store all information without duplicates (each combination of paper/construct/collection method-/parameter was stored only once using database key constraints), while the relations allowed to perform powerful queries on the data (in comparison to pure list/sheet based representations).

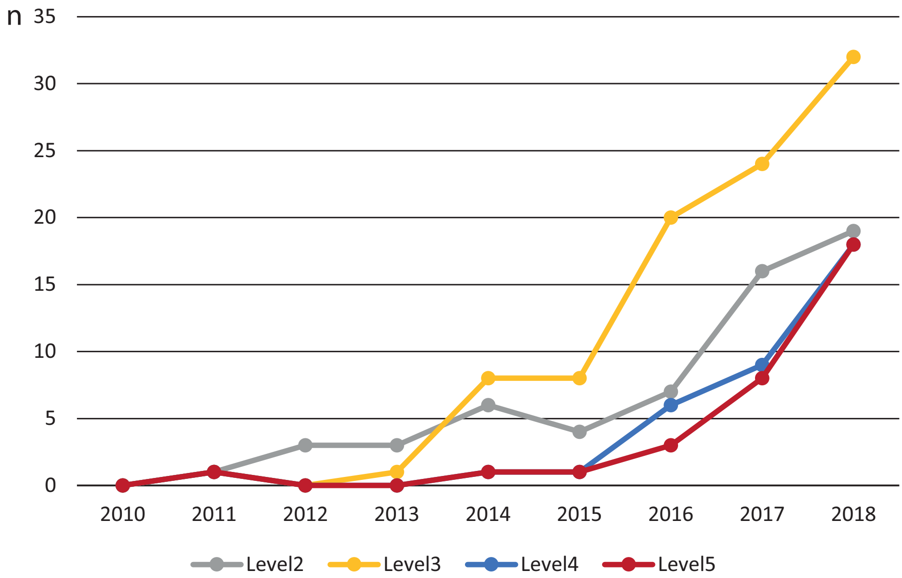

Figure 3.3: Development of driving automation papers concerning the investigated SAE level over time. *Note: *SAE L0 and L1, and 2019 are excluded.*

3.2.2 Results

In the following the obtained results are reported from of the final selection of 161 papers. All selected conferences and journals (see above) are represented in the final analysis: HFES AM (n=34), AutomotiveUI (n=42), CHI (n=10), AAP (n=18), HFES (n=20) and TRF (n=37). All results were obtained using the built-in structured query language (SQL) of MS-Access.

General Study Details Regarding driving automation research, we found that SAE L3 is the most frequently studied level of automation with 58.39% (n=94) followed by SAE L2 (36.65%, n=59) and SAE L4 (22.36%, n=36). SAE L5 was investigated in 19.88% (n=32) of the studies. Thereby, the number of publications gradually increased up to 2018 regardless of a specific level of automation. Outstanding is SAE L3, which attracted earlier attention than the other levels (see Figure 3.3), however, the steepest increase in driving automation research was observed between 2015 and 2016.

Overall, 73.29% (n=118) of all studies were conducted in a lab environment, 13.66% (n=22) as a survey, and 11.80% (n=19) on real road, while only 2.48% (n=4) reported results obtained on a test track. This is in accordance with the utilized AV representation. 71.43% (n=115) of the papers reported to have used a driving simulator, 12.42% (n=20) a real vehicle, 11.18% (n=18) a textual description, 7.45% (n=12) a wizard-of-oz setup and 3.11% (n=5) a visualization. We observed thereby a clear tendency towards single session evaluation (94.41%, n=152), only 9 papers called in participants multiple times, where 3.11% (n=5) investigated automated driving use over a short time period (e.g., up to one week) [330] and three studies (1.86%) long-term effects in longitudinal studies (e.g., by following a survey approach [331]).

While 60.25% (n=97) of the papers conducted basic research such as observing pedestrians' interaction behavior with AVs on real roads [332], 34.78% (n=56) papers evaluated a specific concept in their study (e.g., a haptic seat to prepare driver for TORs) [333]. Smaller percentages of studies conducted empirical research about driving automation with the aim to create a method (8.07%, n=13) or a model (1.86%, n=3). The center of empirical research on driving automation is clearly the driver, who was investigated in 78.26% (n=126) of all studies. Passengers (9.32%, n=15) and other road users (6.83%, n=11, e.g., pedestrians) are still a side topic in driving automation HCI research. The environmental driving context is varying, while 47.83% (n=77) investigated a highway setting, 19.88% (n=32) addressed urban and 19.25% (n=31) rural road conditions. For the remaining studies (13.04%, n=21), the road type was either not relevant or not described.

Methodological Approaches Regarding methodological approaches, we observed that 74.91% (n=119) of all papers involve self-reported data collection, 64.60% (n=104) behavioral, and 10.56% (n=17) psycho-physiological data. Over half of the papers triangulated different types of data (55.28%, n=89). Thereby, 44.72% (n=72) of the papers triangulated behavioral and self-reported data. Less common is the triangulation of self-reported, behavioral and psycho-physiological data (6.21%, n=10). The combination of behavioral and psycho-physiological data (n=5), or self-reported and psycho-physiological data (n=2) is even more rarely applied. A large portion of the papers (44.72%, n=72) is working with only one type of data. These papers use mainly self-report measures (27.95%, n=45), while 16.77% (n=27) of the papers report exclusively behavioral data. Overall, we identified n=22 different collection methods. The self-defined questionnaire is the most frequently used method (51.85%, n=84) in driving automation research papers. This is in accordance with the large number of self-reported data collection. Standardized questionnaires (44.44%, n=72) and TOR performance (37.65%, n= 61) are frequently used as well. Eye tracking/gaze behaviour (24.07%, n=39), driving performance measures (22.22%, n=36), interviews (16.05%, n=26) and secondary task/NDRT performance (8.64%, n=14) are used more seldom. Furthermore, rarely applied collection methods are special techniques such as heart rate variability (3.70%, n=6), think aloud (2.47%, n=4), probing, electroencephalography (EEG) and detec-

	n	%*	Examples**	see Table in Appendix
Safety	82	50.93	[334],[335],[45]	B.1
Trust	37	22.98	[336],[337]	B.2
Acceptance	34	21.12	[119], [338]	B.3
Workload	32	19.88	[339]	B.4
General Attitude	20	12.42	[219]	B.5
Situation Awareness	18	11.18	[340]	B.6
Stress	15	9.32	[45]	B.7
Interaction Behavior	11	6.83	[332]	B.8
Drowsiness/ Fatigue	11	6.83	[341]	B.9
User Experience	10	6.21	[342]	B.10
Productivity	9	5.59	[343]	B.11
Comfort	9	5.59	[344]	B.12
Emotions	8	4.97	[345]	B.13
Usability	7	4.35	[346]	B.14
Cognitive Processes	7	4.35	[347]	B.15
Motion Sickness	5	3.11	[348]	B.16
Cooperation	3	1.86	[349]	-
Wellbeing	3	1.86	[333]	-
Mental Model	3	1.86	[116]	-
Ethics	2	1.24	[350]	-
Other	36	22.36	e.g., Habituation [351]	-

Table 3.6: Constructs investigated by papers. *Note: *multiple dimensions in one study possible, based on all relevant papers (N=161), **examples are randomly selected and number of examples is dependent on the percentages: <10:1, <30:2, >30:3.*

tion tasks (each 1.85%, n=3), UX curve, sorting, electromyography (EMG) and galvanic skin response (GSR; each 1.23%, n=2). Methods only used once are near infrared spectroscopy (NIRS), focus group, facial expression detection, and matching tasks. Details of the applied methods are described in the following section.

Investigated Constructs To specify empirical research on driving automation in more detail, we took a closer look at the constructs, which were investigated in the individual studies. The most frequently investigated construct is *safety*, followed by *trust*, *acceptance*, and *workload*. UX as construct was only investigated by 10 papers (6.21%). However, together with related constructs, i.e., aspects of UX according to UX theory and UX dimensions revealed by the literature review of UX studies in general (see Chapter 2 and Section 3.1), including comfort, emotions, usability and wellbeing (although they did not relate these aspects to the concept UX), 22.9% (n=37) the growing impact of this perspective gets visible, see Table 3.6 for all constructs, respective number of papers and exemplary references. We observed that there was a broad range of 36 distinct constructs that were addressed only once. We summarized it here as *other*. In the following paragraphs, individual constructs, summarized in paragraphs according to their occurrence of investigation (thus UX is described later), are described by elaborating on the applied collection methods (n $\triangleq$ number of distinct papers) and collected parameters (n_p $\triangleq$ number of parameters). One distinct paper can investigate more than one parameter.

Parameters (p) selected for the driving automation studies on *safety* mainly include behavioral data (n_p=273, only n_p=22 collected self-reported data). Hence, the most applied collection method for *safety* is the measurement of participants' TOR performance, which is applied by n=58 distinct papers. Thereby, the most collected parameter is participants' reaction time, which includes the time to first driving action like braking or accelerating, to system deactivation, button press or hands on the steering wheel. Further, the lateral position is another frequently utilized parameter, including maximal lateral position, standard deviation of lateral position, or Daimler Lane Change Performance [352]. Furthermore, Time to Collision (TTC), speed, TOR timings and acceleration and braking parameters were also repeatedly collected. Driving performance (which is, in contrast to TOR performance that assesses the immediate response, calculated based on longer phases of manual driving) is also often used (n=24) by e.g., collecting data on participants' lateral position, speed and reaction times. Eye-tracking (n=12) by regarding gaze percentage, duration and number on areas of interests like mirrors or road, etc., observation (n=12) of participants' crossing behavior, NDRT engagement parameters, etc., and a self-defined questionnaire (n=11) are further important collection methods for safety. Standardized questionnaires like the scale for criticality assessment of driving and traffic scenarios [353], secondary task performance and interviews are more seldom used (n<=3), see Table B.1 for more details.

Trust in driving automation is investigated as second most used construct, see Table 3.6. Here, in contrast to safety, more self-reported (n_p=42) data is reported. Most common is the usage of a self-defined questionnaire (n=19), or a standardized questionnaire, especially the Automation Trust Scale (ATS) [354] (n=12) is popular. The interpersonal trust scale (ITS) [355], trust in technology scale [356], Van-der-Laan scale [357], the Trust Perception Scale-HRI [358] and the Propensity to Trust Scale [359] are each used only once. Interviews, structured and semi-structured, are more rarely used than questionnaires (n=4). However, also behavioral parameters (n_p=19) are collected, by observing (n=5), e.g., body pose and movements, acceleration and braking behavior, or gaze duration on an area of interest. Also eye-tracking (n=4) is conducted. Only one paper [360] used driving performance (braking and steering behavior) and TOR (reaction time) performance measures. This paper additionally collected participants hands on wheel and eyes on road time using observation, see Table B.2.

Acceptance is investigated by self-reported parameters as intensively as *trust* (n_p=41). Researchers mostly apply standardized questionnaires (n=18). Thereby, the Van-der-Laan acceptance scale [357] is the most frequently used questionnaire. Furthermore, the technology acceptance model (TAM) [328], the

Unified Theory of Acceptance and Use of Technology (UTAUT) [189] or the Car Technology Acceptance Model (CTAM) [111] are frequently used approaches. The self-defined questionnaire is also here a popular collection method (n=13). Behavioral data (n_p=3) on acceptance is collected by observing (n=3) the time to system activation, and the number/share of times the automation was enabled/disabled by study participants. Driving performance, or qualitative methods like interviews or focus groups are applied less frequently (n<=2), see Table B.3.

Workload is also investigated mainly by using self-reported measures (n_p=26), usually by implementing standardized questionnaires. The NASA Task Load Index (NASA-TLX, n=17) [329] is the most popular, other questionnaires like Driver Activity Load Index (DALI) [361], Rating Scale Mental Effort (RSME) [362], scale for subjectively experienced effort (SEA) [363] or the global mental workload measurement by [364] are more rarely applied, as well as self-defined questionnaires (n=4) and semi-structured interviews (n=1). As behavioral data (n_p=7), the secondary task performance collecting data on NDRT performance (i.e., number solved tasks), using the Surrogate Reference Task, or Twenty Question Task, observation, eye-tracking and driving performance measures were conducted, see Table B.4.

Participants' *general attitude* towards driving automation is investigated by the majority of the papers by self-reported data (n_p=22), by a self-developed questionnaire (n=15) or interviews (n=5). One paper derived insight based on observation.

Situation Awareness in contrast is examined more by behavioral (n_p=26) than byself-reported data (n_p=14). However, almost the same share of papers apply a self-developed questionnaire (n=6) as eye-tracking is used (n=7). Thereby, gaze duration, number and percentage is collected, as well as glancing and blinking behavior. Also TOR performance (n=2) measures were collected like lateral position, reaction time, acceleration and time to collision parameters. A popular standardized questionnaire is the situational awareness rating technique (SART), or the situation awareness global assessment technique (SAGAT) [365]. See Table B.6.

Stress is investigated by psycho-physiological (n_p=11) and self-rated data (n_p=8). Hence, standardized questionnaires like the Short Stress State Questionnaire (SSSQ) [366], Dundee Stress State Questionnaire (DSSQ) [367], or the Driver Stress Inventory (DSI) [368] are used, but also heart rate variability, GSR and EMG. Observation, interviews and driving performance measures were only used by single papers. See Table B.7.

Participants' *interaction behavior* with AV/ADS was mainly investigated by behavioral data n_p=11) observing (n=6) e.g., pedestrians' walking behavior, number/share of times the automation was activated/deactivated, or utilizing eye-tracking analysis (percentage of the gaze on different AOIs). However, also standardized questionnaires (n=3) like the Pedestrian Behavior Questionnaire (PBQ) [369], Brief Sensation Seeking Scale (BSSS-8) [370] or the theory of planned behavior (TPB) [371] were used. Two papers developed their own questionnaire, and single paper applied eye-tracking, conducted an interview or collected data on secondary task performance, see Table B.8.

Drowsiness/ Fatigue was investigated by self-reported (n_p=11) and behavioral data (n_p=7). Hence, standardized questionnaires (n=7) like Karolinska Sleepiness Scale (KSS) [372], Driver Stress Inventory (DSI) [373], Multidimensional Fatigue Inventory (MFI) [374] are mainly used as well as self-developed questionnaires (n=2). However, researcher also observed (n=2) blinking behavior or yawing, as well as conducted eye-tracking, collected data on driving performance or adapted the method of UX Curve [233]. See Table B.9.

User Experience is mainly investigated by self-reported measurements n_p=16, n_p=5 collect behavioral data, only once psycho-physiological measures by capturing Heart Rate Variability is utilized. Various standardized questionnaires (n=4) like AttrakDiff [216], UEQ [375] etc. are applied, or interviews (n=4), and other qualitative methods like UX curve [233], think aloud and sorting have been conducted. Behavioral data is collected by one paper regarding participants' driving performance, e.g., acceleration, braking, speed and lane changes. See Table B.10.

Identified Driving Automation UX Studies in Detail

Although UX is still a side topic, the number of investigations has increased, especially from 2017 to 2018 (in the selected venues). UX was investigated for the first time in 2013 by Terken et al. [345]. They evaluated a system to support relaxation after work in a semi-automated vehicle. In 2014 Rödel et al. [104], already referenced as related study (see Subsection 2.3.2), investigated the impact of different levels of automation on UX. Then, only again in 2017, driving automation UX was studied by van der Heiden et al. [376] by investigating UX of auditory pre-alerts before hand-overs in *"semi-autonomous cars"*. The second study looking at UX in 2017 is my own study [8] and is also part of this doctoral thesis. We investigated UX of highly/fully automated highway driving (see Subsection 5.3.3). In 2018, already six papers investigated UX: Distler et al. [103], referenced as related study (see Subsection 2.1.3), looked at UX of autonomous on-demand shuttles; Goedicke et al. [377] built an VR driving simulator for real road and conducted a first pilot study; Karjanto et al. [348] investiagted a peripheral visual feedforward system. Maurer et al. [219] evaluated a system called "guardian angle" which overrides the driver in critical situations. Oliveira et al. [342] investigated the impact of user interfaces displaying operational-related information to the driver. Moreover, an additional study of mine also investigated UX of conditional driving automation by comparing expectations of different age groups (referenced in Subsection 2.1.3, however, but not part of this doctoral thesis). In total, four UX studies utilized a driving simulator, four used a wizard-of-oz setup, one was conducted in a real vehicle, and another used static text. Thus, six studies were conducted in a lab environment, two on real road, one on a test track and another conducted a survey. All papers reported a single session experiment.

Researchers interested in *productivity* collect behavioral data $n_p=20$, primarily about participants' secondary task performance (n=6), including performance (e.g., characters per second, number of answered questions, etc.) but also engagement and accuracy (e.g., error rate) parameters (NDRT duration, frequency or percentage). Single papers also observed participants, used eye-tracking or collected driving performance measures. Also only one semi-structured interview was conducted, see Table B.11.

Contrarily, *comfort* was rather investigated by self-reported data ($n_p=11$), mainly by self-defined (n=7) or standardized questionnaires (n=2), Driving Style Questionnaire (MDSI), UEQ, TAM, and UTAUT. One paper reported behavioral data about participants' acceleration, see Table B.12.

Also *emotions* are investigated by self-reported data ($n_p=12$) using self-defined (n=4) and standardized questionnaires (n=4) like PANAS, Affect Grid, Multi-Modal Stress Questionnaire (MMSQ), Affect Scale [378] etc. Further, emotions are investigated by observing facial expressions, think aloud technique or an interview (each n=1). See Table B.13.

Moreover, *usability* is investigated as well mainly by self-developed (n=4) and standardized questionnaires (n=3), e.g., SUS is a popular method. Further also semi-structured interviews (n=2) and the think aloud technique are applied. Hence, solely self-reported data is collected ($n_p=11$), see Table B.14.

Cognitive processes, in contrast, are analyzed by self-reported ($n_p=4$), behavioral ($n_p=4$) and psycho-physiological data ($n_p=2$). Thereby, most developed their own questionnaires (n=3) and one paper used an standardized questionnaire, the Driver Stress Inventory (DSI). EEG is utilized twice, while respectively one paper applied driving performance measures (e.g., lateral position) or a detection task method collecting reaction time and accuracy. See Table B.15.

Motion Sickness is mainly investigated by the standardized questionnaires (n=4), the Simulator Sickness Questionnaire (SSQ) [379] and the Motion Sickness Assessment Questionnaire (MSAQ) [380]. One paper developed its own questionnaire. However, also Heart Rate Variability as well as the measure of Motion Sickness Dose Value was collected, see Table B.16.

A wide range of further more special constructs were investigated, including *cooperation, well-being, mental models* and *ethics*, only a few papers were interested in (n<=3), and we identified many special constructs, only single papers were interested in (n=1), e.g., personalizing, intuitiveness, immersion, helpfulness, annoyance, motivation, etc. While *cooperation* was investigated mainly by driving performance measures like reaction time, duration of vehicle interaction etc., and self-defined questionnaires and *well-being* by self-defined and standardized questionnaires and observation, researchers interested in *mental models* and *ethics* solely applied self-defined questionnaires. The more special constructs, here summarized as *other* were investigated in the most cases by self-defined questionnaires (n=15) or specific standardized questionnaires (n=12).

3.2.3 Discussion

The present literature review shows that safety aspects received most attention to date, followed by trust, and acceptance. In the following, we discuss what to study in the context of driving automation, how study setups can be improved, and how to apply triangulation in driving automation studies.

What to study in the context of driving automation? First, it turned out that some studies included parameters whose focus of research was not clearly defined. Despite setting up a large number of constructs during the expert workshop and adding further options during the review process, there still remained a considerable number of of parameters that could not be assigned free of doubt. This resulted in the two constructs *general attitude* and *interaction behavior* (see Table 3.6). In these instances, information was rather scarce and only high level indications about interface evaluation were provided by the authors. We therefore encourage researchers to first clearly state objectives and classify these within a specific body of research. This should allow both authors and readers to eventually compare the obtained results with existing findings, and derive implications of the reported work.
The majority of parameters were well classifiable within our database. The safety construct constituted the largest part of all measures (see Table 3.6).This shows the importance of safety concerns when it comes to investigate driving automation technology. Investigations on TOR performance during system

failures have been the first scenarios in human-automation interaction research [334, 335, 381, 382]. Here, many issues such as trust [360, 383], [45], controllability [381], fatigue [384] or mode awareness [385] have been discovered. Right now, it seems like a re-orientation of recent research is taking place which is also reflected in the remaining constructs of the database. Trust [386] and intention to use [328] constitute precursors of actual system use, and therefore research has more closely investigated these constructs. Beside the outlined well-investigated constructs, there remain other constructs that have rather been neglected until now. The reason why research has paid less attention on usability, UX, or productivity until now might be that these are rather precursors of the higher priority constructs (i.e., safety, acceptance). Another reason might be that the scenario where automation fails and humans need to step into action was an important issue to determine feasibility of driving automation in general. We argue, that more emphasis should be paid to other types of interaction such as ongoing automation, user-initiated or planned transfers of control, as most likely, these use cases will occur more frequently than automation failures [387, 388]. From that, the need to investigate efficient and effective interaction arises [389]. Also it might not be sufficient to develop interfaces which users are satisfied with [390], but which they have fun and enjoy interacting with. Here, UX and research on users' emotions and need fulfillment can path the way to developing not only proper but great UIs for AVs, which increase individual but also societal acceptance of this emerging technology.
Similar to the methodological approaches of general UX studies in which generic UX is the most studied UX dimension (see Section 3.1), driving automation studies also often lack in specifying what they are really investigating. Thus, the constructs general attitude or interaction behavior occur often. This leads into ambiguity and difficulties regarding methods/parameters selection for evaluation. While safety is predominant, the emotional side of driving automation is still a research gap, however, receiving more and more attention.

How could study setups get improved? Concerning representation and study type we found that most studies were conducted using driving simulators. Hence, present research supports high internal validity making interpretations of effects of differing conditions on dependent measures possible. On the downside, the obtained results might lack external validity, and there is no guarantee that they generalize to real world settings, since driving simulators may lack realism due to insufficient field of view, or motion feedback. Thus, by lacking a feeling of presence [391], transfer of behavior found in the laboratory to real world settings might be limited [392]. Conditions in realistic driving studies are not as controlled as in a laboratory but might differ in terms of surrounding traffic, weather conditions or vehicle speeds. Despite the restric-

tion of high internal but limited external validity, we can assume that strong and consistent effects such as the dependency of TOR response time on driver state ([384, 393, 334, 394], [45]) will also show through in real world driving. Especially when it comes to safety and trust issues in real driving, research should determine validity of the findings. While participants in driving simulator studies might behave more liberal due to the absence of realistic severe consequences, it remains to be seen how these effects pertain on the real road. Relative validity of effects in driving simulator studies can well be assumed [395], but there are still research efforts necessary for validating safety relevant human-automation interaction scenarios. Despite this criticism, we acknowledge that driving simulators are still immersive research tools providing a certain, and, in many cases sufficient, degree of external validity [396, 238]. Nevertheless, the present results point towards the need of conducting studies in real vehicles equipped with driving automation technology [353, 397], [37], or wizard-of-oz settings [398, 399, 69].
Review results also revealed that most studies targeted single sessions of interaction, and thus provide only snapshots of first time use. While usability can already make reliable estimates about user behavior within a single session experiment [389], UX, trust, and acceptance might take a longer period of time until behavior and attitudes have reached a stable level [400, 401], [1]. Long-term studies tackling exactly these issues are rather scarce since they require high efforts. One example of such a study comes from [116] who observed users of L1 automation (i.e., Adaptive Cruise Control) over ten repeated one-hour sessions (however, due to the restriction to SAE L1, this paper would not satisfy the inclusion criteria for this review). Such studies can provide valuable insights into acceptance, trust and system understanding. The present database only includes a small number of publications that investigated long term use such as described in [331]. This study example, however, did not follow a longitudinal approach, but rather a cross-sectional approach by surveying Tesla drivers. We expect important insights into behavioral adaptation over longer time periods, such as the amount of actual use or NDRTs that users engage in. Similarly to field operational tests [402] or naturalistic driving studies [403], there is still a blind spot in research on driving automation that could open up with commercial availability. First efforts in this direction with L2 automation are reported in [404], or planned in the L3-Pilot project [405]. Thus, there are open research directions towards ongoing and long-lasting effects of driving automation on use and interaction between the human operator and the ADS.
We conclude, to increase validity, existing findings should and still need to be be validated on real road and in longitudinal studies.

How to Apply Triangulation? Concerning collection methods, the review results show that a vast majority of studies collected self-report data. In comparison to that, behavioral data was only reported in every second publication. From there, the question arises, what the reasons for this observation are.

One obvious reason is that survey approaches [104, 406] might focus more on technology readiness and deliberately collect attitudinal measures only. For these approaches, to date, there is no available behavioral criterion, such as buy/usage rates. Studies operationalizing acceptance via the TAM [328] do not provide the possibility to provide insights into behavioral measures. As soon as the functions are available, however, research needs to investigate whether predictions made by these studies hold true. With commercial availability of L2 automation, such a study could have already been conducted, but to our knowledge this is still missing. One positive aspect of self-report measures is that psychometrically validated scales have been applied frequently. This shows the professionalism of research of the reviewed venues and deliberate preparation of study design.
Another factor for the imbalance might be that these are much easier to collect. It does not take comparably much effort to hand out a questionnaire or interviewing participants. In contrast, the collection of behavioral data is much more complex. For example, dynamic vehicle data requires extensive pre-processing before descriptive and inferential analyses can be run. The collection of eye-tracking data requires even more resources due to the need for manual calibration to ensure data quality, although such data provides the possibility to make direct inferences about cognitive processes [407]. For example, prior research has suggested that the number of gaze switches (i.e., monitoring behavior) can serve as an indicator for trust/reliance [383], or interface understanding [389]. One solution to the difficulty and extensive effort of collecting behavioral data might be experimenters' single-item ratings of interaction performance [408, 409, 410]. However, this approach requires well-trained raters and, ideally, ratings are given single-blind, so that the rater is not aware of assigned experimental conditions for the participant. Also, there should be more than one rater to ensure inter-rater reliability. Despite requiring additional time and cost efforts, the analysis of behavioral data should be an inherent part of a user study, since it can provide additional valuable insights about the tested interface or feature. It is not for nothing that the usability ISO-9241 [390] includes effectiveness and efficiency as behavioral components and satisfaction as an attitudinal component. These sources of data do not always align well [220, 411], which is not necessarily a bad study outcome. It rather supports the assumption that both sources of data are necessary to derive a holistic impression of an interface.
We conclude, that this result is in line with the previous literature review about UX in general (see Section 3.1). Researchers in the field of human-automation interaction should always triangulate and consider additional to self-ratings also behavioral aspects. Further, quantitative and qualitative data should be mixed.
Therefore, approaches are necessary which guide sophisticated triangulation of behavioral, psychophysiological, and self-reported measures.

3.2.4 Limitations

The here presented literature review comes with some limitations. First, the restriction to the most relevant six sources (three journals and and three conferences) limits the reach of included works. However, comparing the obtained results with a prior review concentrating only at one of the six included sources [3] shows, that the results did not drastically change after extension. Second, we (subjectively) felt a trend to experiments that are published multiple times with slightly adapted focus. As our review focused on publications rather than single experiments, we cannot guarantee that some studies in our database are duplicates, which may have slightly impacted the results. Third, the inter-rater reliability is calculated based on the inclusion/exclusion criteria of papers, while the subsequent classification process is not completely free from subjective assessment, although we tried to keep the level of subjective interpretation to a minimum (by defining a standardized reviewing procedure).

3.2.5 Core Findings

In the following, the core findings of this study answering **RQ1.2** are highlighted:

- **Many studies lack in a clear operationalizing which constructs are actually collected.**
- **There is a tendency towards self-reported data. Self-developed and standardized questionnaires are the most frequently used methods, interviews are conducted more seldom.**
- **Half of the paper triangulate data, mostly self-reported and behavioral data, however, triangulation strategies and consistent parameter collection are still missing.**
- **HCI/ human factors research for driving automation is still focused on safety, trust and acceptance, however, UX and related experiential/emotional constructs are emerging.**
- **Methodological approaches from other constructs, e.g., safety, trust, interaction behavior, etc., should be considered in driving automation UX studies.**
- **Due to the specific nature of in-vehicle UX, especially driving automation UX, which is created by a stream of many experiences, triangulation (data, method, researcher, and theory) is imperative.**

3.3 Driving Automation UX Studies in Industry

The concept and practice of UX are discussed in academia as well as in industry, however, rather isolated and with different perspectives. Hence, in an industrial environment, similar but also further and other challenges emerge. Earlier this decade - around 2014 - it was revealed that most companies neglected UX and usability evaluation in software development [412, 246, 413]. Aleves et al. [304] showed that only 50% of evaluation studies involved real end-users, software engineers performed the evaluation studies themselves or sometimes only assumed user perceptions. Although HCI reseachers, as well as software engineers, expressed the wish to change the situation, they still complained about not suitable methods and high demand for resources for usability evaluation [246]. Also Gray [414] criticizes the lack of literature that describes concrete UX competencies for successful UX practice.

UX has become more and more popular over the years, but the situation does not seem to have improved. Kashfi et al. [415, p. 11] revealed four fundamental and four tactical themes of UX challenges: There is a (1) *"lack of consensus on definition and construct of UX"*, which has its roots in that neither in research nor in practice a consensus exists. Thus, the term is often used as a synonym of usability or interaction design. Thereby views on it are sometimes inconsistent and contradictory. Moreover, they bemoan (2) *"the lack of consensus on the value of UX"*. UX is often down prioritized to functionality. Further, business stakeholders, customers and management do not value UX. Incurred costs are not justified for them. (3) *"Low industrial impact of UX models, tools and methods"* originates in UX practitioners' lack of UX theory knowledge. Competencies are rather gained individually, however, not by existing theories. This is supported by companies, which resist introducing tools and methods. Hence, traditional methods are still applied. Kashfi et al. [415, p. 11] further mention (4), the *"focus on objectively measurable aspects of software"*, what is related to over-prioritizing the functionality while ignoring the relation to UX. Stakeholders focus on actual quality, hence, objectively measurable characteristics and down-prioritize perceived characteristics. These fundamental challenges explain why there are: (5)*"difficulties in engineering UX related requirements"*, (6) *"focus on evaluating functionality & usability not UX"*, (7)*"lack of consensus on UX related competencies & responsibilities"* and the (8)*"communication & collaboration gap between UX & and non-UX practitioners"*. UX integration in companies is dependent on external decisions outside the authority of UX practitioners. Thereby, a succesful UX integration can be understood as a mindset change of a company. Further, *"characteristics of UX"* need to be considered and addressed to prevent a focus on *"pragmatic aspects of UX, consequently leave the hedonic aspect unaddressed"* [131, p. 37]. As the development process of vehicles slightly differs from software development, we conducted a separate analysis by interviewing (semi-structured) eight UX practitioners from four different European OEMs and four suppliers/agencies working for OEMs. The goal was to answer the following research question:

- RQ1.3: How is driving automation UX methodologically addressed in industry?

This section is based on the following publication: [4].

3.3.1 Study Setup

To get insights into the practice of driving automation UX design, we conducted a qualitative interview study with UX practitioners (N=8, UX researcher, manager, designer) from the European automotive industry. Involved were 4 different OEMs from Sweden, UK, and Germany, and 4 suppliers/ agencies working for various OEMs. Interviewees were recruited at the CarHMI Europe conference 2018 in Berlin and via personal contacts. Names and affiliations of interviewees must remain anonymous. For a content analysis. participants' narratives were transcribed (three translated from German to English) and sorted and categorized using affinity diagrams. Thereby, trends regarding the role of UX in the automotive industry and methodological approaches of driving automation UX studies were identified.

3.3.2 Results

Results of the interviews are presented in the following subsections.

The Role of UX in the Automotive Industry Interviews showed that it has been recognized by the automotive industry that there is a need to involve user-centered strategies and processes. Only one participant from an agency reported to have never been involved in a project with an evaluation phase. The agency is only commissioned for concept development and visual design, thus, they do almost no user testing. However, interviewees reported that more and more UX and innovation departments are created to focus on positive in-vehicle experiences: *"UX is such an important topic, if I write it at my organization in the headline I get money for it, thus, I do this"* (P3). However, all professionals of the OEMs and also suppliers and agencies report about the difficulties to establish this new mindset in this traditional industry.

> *"There is a lot of talk about the voice of the user, meeting customers' needs and expectations what we need to do. But in the end I feel that it does not drive our design decision, our budget decisions, also what does come in the car in the end. A lot of it is innovation*

> *that drives this company, and innovation is not always user driven. A lot of is technology driven, there is a lot to do something different, to show what is the newness factor, what you have improved, what you have changed. And often, improving experience, you cannot show it, you cannot sell it in a show room so easily."* (P4)

Trying to get a new way of thinking established, i.e., to start thinking about a product from users' needs and not from the technology is praised as a *"revolutionary step"* for the automotive industry, however, also UX departments *"fall always back into old technology-centered patterns"*. Possible reasons are an existing lack of knowledge why iterations and evaluations are necessary and how to perform them, however, also the still existing *"arrogance to know it better than the user"* (P3). This goes hand in hand with the statement from P7:

> *"The major challenge is not UX evaluation, it is the company itself. Sometimes you struggle to get things done. A major part of the job is to make people understand how important it is to evaluate your design [...]".*

Also professionals from suppliers and agencies confirm the internal view of OEMs, they see themselves as kind UCD and UX ambassadors:

> *"We don't want to do projects which are not user-centered, however, sometimes it is difficult. Everything is downsized to numbers and money and clients don't pay for it. We have to create more awareness with our clients but also here in our agency with many visual designers"* (P1).

Working with automotive industry as a client in a user-centered way was mentioned to be especially difficult, as time lines were too hard to make iterations.

> *"We have following problems: Either we are testing something, but we are too nearto SOP* [(start of production)], *that our results do not have an impact anymore. Or we are testing and besides there are further developments at the OEM and our evaluation is not based on the final version. All this is owed to the development process, there is almost no wiggle room for delays, if there are delays, evaluation is the fist thing to remove. The date for the SOP cannot be postponed."* (P2)

This was also confirmed by an OEM UX professional (P3) who bemoaned that evaluations were either very small, like asking the colleague if a design worked or not, or huge studies which lasted a year or longer, and results were already outdated when studies had finally been conducted.

Professionals reported to be familiar with standard UX norms and definitions, i.e., ISO 9241-210 [151, 122] and ISO 9241-11 [416], and to have heard, e.g., during their studies (at university or special usability certificates from UXPA/ German UPA) about the work of, e.g., Don Norman, Jacob Nielson, Tim Brown and Marc Hassenzahl. However, UX departments themselves are still in the *"finding process"* to define what UX means for them. *"It does not matter with whom you are talking, everybody understands something different"* (P3). Still, it is used as *"buzzword"*, what makes it difficult to address UX in evaluation studies and also leads to conflicts between new UX and former human factors, usability and ergonomics professionals about the question which aspects UX involves. Hence, especially experienced professionals with a non-UX background face identification problems.

> *"I have a colleague, he stands for the topic UX, and he thinks he is the god of UX, he makes everything and also holistic etc.. Thereby, my topic ergonomics is only a disappearing small part in the figures he shows to us about UX, so it's hard for me to say it [ergonomics] is a part of UX. I think it always depends on the perspective."* (P6)

Thereby, to achieve this holistic contemplation of UX, described by P4 as an *"overloaded thing"*, in all aspects of an in-vehicle experience, is mentioned as especially difficult by an OEM UX professional:

> *"In the larger scope of this company there are so many levels of UX, all those hedonic and pragmatic aspects that come together. And then, quite often, it is not just using one little component, it is the whole journey that comes into play, and how you link experiences together that make the whole UX better. When we are looking at all the hedonics and pragmatics, we have the problem that we have different departments that are looking at different aspects. You have a design department that is really focusing on the hedonic, and another department that is really focusing on the pragmatics. And they are fighting [...]. And when you are looking at the whole journey, we are looking at the different departments that all work on their little particular function or feature, they are not grouping it together for the UX. And then you look at that, how you can bring it in the car, and we are developing in different time lines. The seat is developed at a different time than the body of the car."* (P4)

Hence, there is still a gap between professionals' desired ideal process (direct user involvement and many iterations *"in the way it is described in the books"* - P7) and the current procedures. They request that UX evaluation must becomes a daily business in the organization of a car manufacturer in the future.

> *"If I present a concept to my boss, my boss has to ask 'What did the user say?' I need to have an answer for him. It has to be defined in the development process when we are testing. The development process needs to spin around which experience we want to create with the user"* (P3)

Methodical Approaches Addressed challenges regarding the role of UX in the automotive industry also show up in the methodical approaches of driving automation UX studies.

Interviewees report a focus on pragmatic aspects of UX, like usability, controllability, safety dimensions, but also likeability (would users like to have such a feature in their car) to be the most studied dimensions in their UX evaluation studies. Emotions and needs are highly debated among the interviewees: *"I am critical of needs and emotions. As psychologist I see them as no good criteria, emotions are not stable and hard to measure"* (P2). Others, while also agreeing that needs and emotions are very difficult to capture, see here the highest potential to really evaluate UX.

> *"For me, the most important thing is the user need to understand. I think not every product you have is based on all these different aspects, different emotions and aesthetics, but understanding the basic user need, if [...] we do not design for this need it is always going to be a problem. Users have different needs, and we have to capture these"* (P4).

Also P5 said:

> *"The focus of people are needs, that is the main thing. If you understood what people need, you could design around them, elaborate on that. A need contains people's expectations, aspirations, the more fluffy part [...]"*

Thus, also P3 reports:

> *"We would like to add an evaluation loop where we have specific use cases with the needs which we revealed as relevant and evaluate in the end the use cases to see if users really feel what we thought they would feel."*

Regarding the product development stage, it is reported that, although low-fidelity prototypes exist, mainly further developed products are tested (see above, testing rather shortly before SOP).

> *"Many features are tried to be shown only as mature product. This is based on organizational issues. If you want to show it to your management, that has no abstraction capability, high effort is conducted to make it really good. Only if it is really finished it is given to the test. Fast and short tests are performed rather seldom."* (P3)

This procedure is also confirmed by P6, a UX professional of another OEM.

Further, interviewees report to do studies in the lab with simulators but also directly in the field on real road. However, until now, most studies are conducted as single sessions:

> *"It is very hard, especially with the research department, you are not allowed, you cannot give things to people. Either it is not developed that it can be used right away, a lot of things are ideas, you cannot build prototypes that can be used for two weeks. Or the confidentiality aspect."* (P4)

However, more and more longterm studies are conducted directly at the OEM (e.g., Drive Me study at Volvo [417]).

Regarding data type, interviewees report that there is a slight tendency towards quantitative measures. On the one hand, for mature products shortly before SOP, large samples are needed to achieve a high validity (P2). On the other hand, quantitative data is favored by management: *"We do statistical analysis in different qualities, this is also what my bosses want to see. They want to get a red and a green graph."* (P3). Especially when working with clients from Asia, qualitative data is not *"good enough"*: *"the significance of a result is estimated higher when you can show a value"* (P6). Thus, another UX professional explained that they developed approaches to deal with the *"fluffiness"* of UX, to be able to present valuable results to the management and not only numbers:

> *"The challenge is the management thing, they tend to like numbers, the challenge to be able to present stuff, to make this credible that they rely on the data, because it is fluffy, in an engineering firm it is hard to get acceptance. We learned to deal with this, we show videos to make user behavior experienceable."* (P5)

Further, P4 and P5 report that they try to mix quantitative and qualitative methods:

> *"We use mixed methods, before and after interviews, we also measure quantitative data with sensors, psycho-physiological and car*

> *sensors. I am pushing forward mixed methods approaches, because you learn from different methods. In [fully] driving automation car data does not give much, but if you have a study where people interact it gives insight about behavior"* (P5)

Regarding applied method, we see a tendency towards traditional methods, like semi-structured interviews and self-developed questionnaires. Also observations, either live or by video-recordings are often used methods. Standardized questionnaires are also frequently applied. This is in coherence with the statements above according to collecting rather quantitative than qualitative data. Thus, exploratory methods like probes and diaries are done only sometimes or even never (see Figure 3.4).

Triangulation approaches are highly individual, and hard to capture as a statement in an interview, nevertheless, we can derive some insights from letting interviewees draw lines between two lists of methods (used from the academia study, see Section 3.1). The most combined methods are a semi-structured interviews together with a standardized questionnaire (n=6), followed by a self-developed questionnaire with a semi-structured interview (n=4). This confirms results from academia (see Sections 3.1 and 3.2) – established approaches and an agreement to how to mix methods for studying UX, is also in industry still missing.

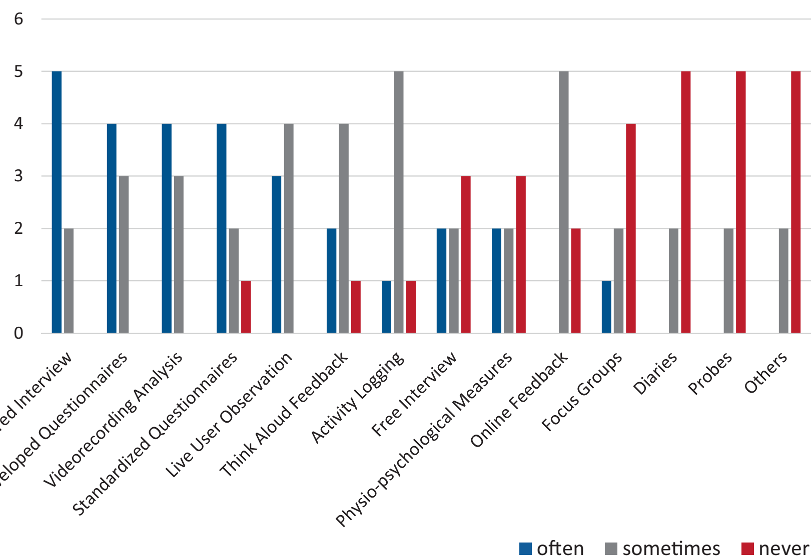

Figure 3.4: Methods applied in industry for UX research. *Note: *based on prioritization from UX professionals (N=7/8).*

3.3.3 Discussion

The presented interview study shows that most challenges identified by Kashfi et al. [415] can be confirmed. In the following, we discuss identified challenges regarding the definition of UX and implications on UX practice.

Like Kashfi et al. [415], we agree, the lack of consensus on the definition but also the value of UX, seem to be the core problems. The vagueness of UX fuels up discussions about the importance of specific aspects which lead to a good UX. We cannot agree that the low impact of UX models, tools and methods originates in UX practitioners' lack of UX theory knowledge. At least our interviewees were aware of existing UX theories, and their approaches do not differ much from academic UX research. We argue major challenges are mainly owed to the development process and lack of theoretical knowledge of decision-makers and non-UX collaborators in UX projects. Therefore, tools are needed which support communication about UX and clearly show which aspects have to be regarded in the development process. Further, although new ways of thinking are starting to pervade organizations in the automotive industry, old structures and processes are still too entrenched. To improve development processes, Ardito et al. [246] recommended closer collaboration between academic UX research and industry practice in carrying out empirical research. As our studies showed (see Sections 3.1 and 3.2), academia also lacks in optimal established processes. Nevertheless, closer collaboration could inspire and improve the work of both academia and industry.
To satisfy all parties involved in the development process, UX professionals with interdisciplinary backgrounds have to combine their knowledge instead of *"fighting"*. Involving all different perspectives of UX automatically leads to a mix of theories, methods, and data, thus, triangulation. To use the value of interdisciplinary work, guidelines for sequential and concurrent triangulation are demanded. This way, the overall UX, created by a stream of many different experiences in a vehicle, can be optimized.

3.3.4 Limitations

The presented qualitative interview study gives insights behind the doors of the automotive industry. To get a realistic and non-glossed over picture is hard. Recruiting and interviewing is difficult, as responsible practitioners are not willing to participate or neglect to answer questions even on methodological approaches, and are trained to present the company in the best possible light. Only a small sample, open to answer questions honestly, could be interviewed with the premise to stay anonymous, as well as the company. Besides European OEMs, companies from the USA and Asia would also have been relevant.

3.3.5 Core Findings

In the following, the core findings of this study answering **RQ1.3** are highlighted:

- **UX is an emerging topic for the European automotive industry, however, entrenched development processes with multiple disciplines and mindsets involved prevent an ideal application of the user-centered design process.**

- **There is still no agreement which aspects UX involves and how these have to be prioritized in design and evaluation.**

- **UX practitioners demand a focus on user needs during design and evaluation.**

- **Quantitative results are important to *"sell"* insights to management. Thus, standardized questionnaires for UX are often used besides traditional methods like semi-structured interviews and self-developed questionnaires.**

- **The usefulness of sequential and concurrent triangulation is known, but established strategies or best-practices do not yet exist in the industry.**

3.4 Implications for this Thesis

Based on the core findings of the studies conducted in academia and industry, major challenges for UX research could be identified, which were refined during two workshops (in Gothenburg, Sweden and at CarHMI Europe, Berlin, Germany[3] in 2019) with researchers from academia and practitioners from different OEMs and suppliers. At the beginning of each workshop, brainwriting was used to collect participants' major challenges in UX research practice. After presenting the results from the literature reviews and interviews, using affinity diagrams, participants allocated their own challenges to existing categories or created new one. After the two workshops, challenges stayed stable and categories could be identified.

[3]https://www.car-hmi.com/sessions/pre-event-method-design-workshop-designing-for-automated-vehicles-ux-design-methods-put-to-test/

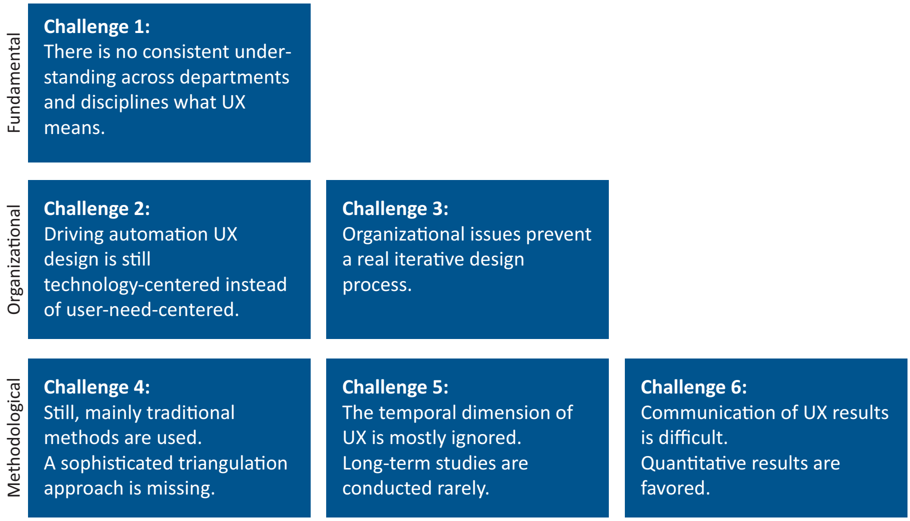

Figure 3.5: Identified challenges of (driving automation) UX research.

We differentiate between *fundamental*, *organizational* and *methodological challenges* which interact: Contrarily to [415], we argue UX research challenges are mainly based on one *fundamental challenge*. There is still no consistent understanding across departments of companies and different disciplines what UX is and what aspects it involves. Of course, this has been already criticized for many years in the HCI community (e.g., [418, 153]), however, nothing has changed and UX still remains a buzzword which leads to a unilateral focus on pragmatic aspects in research and product development. Though, there is a lot UX theory which is based on fundamental research in psychology and HCI (see Chapter 2). An orientation on it, as suggested by [131] can support a unique understanding by including all involved and related disciplines. Hence, UX knowledge from different theories and definitions needs to be bundled in one framework involving all aspects of UX, unbundling the umbrella term by referring to concrete constructs [145, 147]. We argue, only if we achieve agreement, so-called *"fights"* (see Section 3.3) and discussions within the organization can be stopped and methodological problems be solved. Traditional entrenched procedures cannot be changed overnight and by biddings from the top (e.g., management). The change needs to come from the members of an organization themselves by finding a joint mindset. If this joint mindset is generated, then *organizational challenges* like focusing on users' needs instead of solely technology and feature generation (challenge 2), and applying a user-centered design process which involves sequential triangulation (challenge 3) are facilitated. Further, within academic and industrial organizations, a consistent understanding of UX can also support solving *methodological challenges*. If researchers know about involved aspects of UX and theory behind, they will be able to derive a right method mix, i.e., triangulation approach (challenge

4) which should involve traditional behavioral data from automotive safety studies (especially for lower levels of automation), however also experience and product-oriented aspects. This naturally results in a mix of observational (mainly quantitative) and self-rating (quantitative and qualitative data) [220]. Thus collaboration of different disciplines automatically supports concurrent triangulation. Moreover, a better understanding of the nature of UX should foster awareness of the temporality aspect of UX (challenge 5). Thus, reviewers of conference and journal papers, and managers in industry can be satisfied by results of the collected quantitative and qualitative data from different aspects of UX (challenge 6).

To address the identified challenges, the following chapter aims to combine UX theory and UX practice for an optimized approach. The "DAUX framework" lays down the foundation for the methodology of a need-centered development approach, which is applied afterward in Chapter 5 to create user interfaces for positive driving automation experiences in the different levels of automation.

4 The “DAUX Framework”: A Need-Centered Development Approach

Driving Automation UX is complex due to the various contextual influences of the different levels of automation, which need to be carefully regarded. Further, UX practice in academia and industry is still struggling with conceptualizing UX. Thus, the following chapter aims to answer the subsequent research question:

- **RQ2: How can UX theory and the insights from UX practice be combined to optimize the development process of driving automation systems?**

Based on the revealed insights from the state-of-the-art UX practice, we developed the “DAUX Framework”, inspired by the work of [178, 94, 195], embedded within a need-centered development approach (see Figure 4.1). A framework is a structure or system supporting the realization of a defined result or goal (see blue box in Section 1.4, [142]). Visser at al. [253] suggested that experience data is accessible in layers. Thus, the framework unfolds the different layers of UX based on theory, as [131, 145, 147] recommend and provides guidelines on how to study UX for need-centered hypothesis/ concept development and evaluation of driving automation UIs within an iterative design process. Further, it suggests an approach for *sequential* (combining inductive and deductive research) and *concurrent* triangulation (mixing methods to address different aspects which all imply a certain experience). By application of the framework, it is aimed to create a consistent understanding to facilitate communication within interdisciplinary teams. The goal is to support moving the term UX away from being only a buzzword towards a real concept for AD UI development. Thereby, the identified fundamental challenge and, with it, also related organizational and methodological challenges in UX research practice shall be addressed (see Section 3.4). In the following section the “DAUX Framework” (see Figure 4.1) summarizing and visualizing UX theory in the context of driving automation (see Chapter 2), is presented. Further, an introduction for use for driving automation UI development is given, as well as feedback on the framework from UX practitioners.

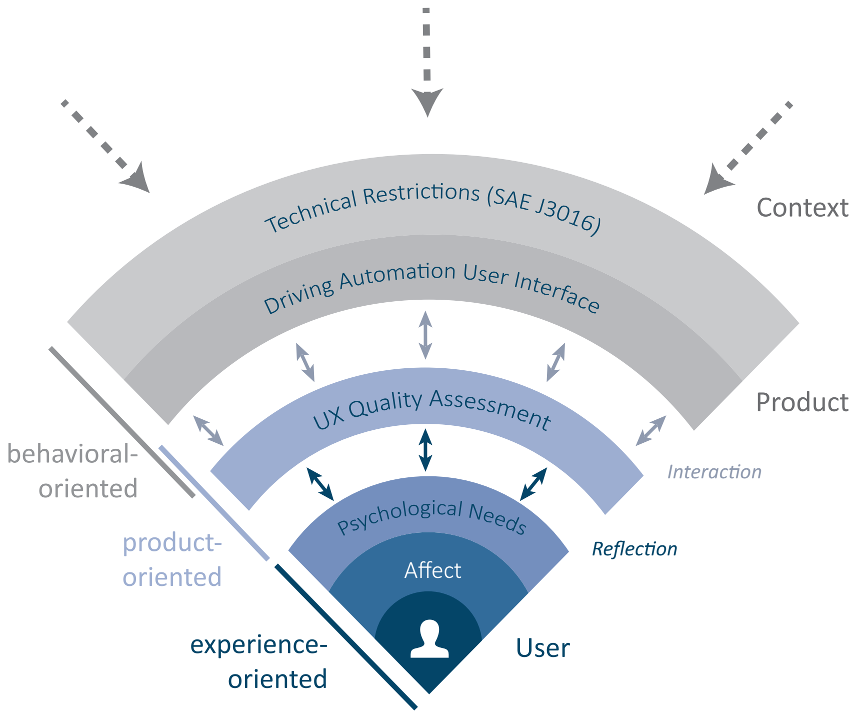

Figure 4.1: The DAUX Framework: Context and restrictions of the different levels of automation act as constraints potentially impeding UX quality. Need profiles emerging from these restrictions lead to positive or negative affect, thus, positive or negative UX quality assessment. A structured investigation of the need profiles may help to design properly, and visualized layers of UX help to evaluate driving automation user interfaces triangulating experience-, product-, and behavioral-oriented methods.

4.1 The “DAUX Framework”

The foundation of the “DAUX Framework” is the UX theory (see Chapter 2). It evolved over time by reviewing UX literature and understanding the challenges of UX practice (see Section 3.4).

As UX is *“a momentary, primarily evaluative feeling while interacting with a product or service”* [124, p. 12], experiences lead to appraisal of emotions [161]. Thereby, affect/emotions are correlated with the satisfaction of basic psychological needs (seven as most relevant for experiences with technology [63, 178]: *autonomy, competence, meaning, stimulation, security, relatedness* and *popularity*). According to Sheldon et al. [176], need fulfillment is not regarded as hierarchy (cf. Maslow need theory [174]), but rather as situation-dependent prioritization of specific needs. Hassenzahl et al. [178] confirmed the existence of individual need profiles for specific activities. Thus, specific needs, identified as relevant for an activity have to be fulfilled to create positive affect which is the core of positive UX.

For example, when *interacting* with a *user interface of an AV* in a specific *level of automation* (e.g., of a highly automated ADS) in a certain *context* (e.g., driving on a highway with low traffic volume), users *reflect* whether relevant *psychological needs* are fulfilled or not. Fulfillment of these needs leads to *positive affect*, thus, a positive experience, and consequently to a positive evaluation of a product. Thereby, actual experiences contribute to a user’s assessment of the *UX quality*, consisting of pragmatic and hedonic qualities [125, 124].
Hence, the big term *user experience* involves different interacting perspectives: *behavioral-oriented* (users’ interactions – what does the user?), *product-oriented* (users’ reflections on a product, system or service before, during and after interactions – how does the user like the product?) and *experience-oriented* (users’ need fulfillment and resulting emotions/affect before, during and after interaction – how does the user feel?). See Figure 4.1.

Based on this theoretical groundwork, this framework allows for a systematic and potentially holistic contemplation of the problem domain. It fosters a need-centered development approach and provides guidelines for *sequential* triangulation consisting of (a), identification of relevant needs for concept development and (b), evaluation of UX by *concurrent* triangulation of *behavioral, product-*, and *experience-oriented aspects*. Thereby, as UX is based on human-factors issues, other frequently studied constructs in the context of driving automation are somehow related (see Table 3.6). Hence, methodological approaches can be utilized and adapted (see Table 4.1), and correlation with UX aspects should be carefully regarded. The following section gives an instruction on how to use the presented approach for UI development.

4.2 Instruction for Use

The application of the “DAUX Framework” follows the principles of design thinking and user-centered design, and can be applied within these existing processes.

Pettersson [133] recommends the CARE approach for ideation and formative evaluation. It includes: *contextualization* to bring users into the right context and to expand imagination by e.g., low-fidelity representations; *action/interaction* to elicit personal experiences by e.g., enactment; *reflection* by e.g., using multiple methods to approach the experience from different perspectives; and by supporting multiple ways of *expressions* by e.g., drawings or observing users' behavior. We agree on this, however, further suggest, based on the approach from [94, 195], to study which psychological needs are relevant for users in a specific context and level of automation according to the technical restrictions users have to deal with. The contemplation of users' basic psychological needs (*security/safety, meaning, relatedness, stimulation, competence, autonomy, popularity*) is thereby essential for UX definition and evaluation since their satisfaction leads to positive affect, thus, positive UX. Psychological needs are broad concepts, however, the simplified view on UX facilitates to understand underlying problems of interactions and user interfaces. Based on the needs, researchers and designers can dive deeper to understand why users have certain feelings, why certain needs are satisfied or not, and why a product is rated as god or bad. This need-centered approach helps to iteratively explore the design space and can be applied for hypothesis and concept development, as well as for evaluation, as described in the following.

4.2.1 Application for Hypothesis/ Concept Development

HCI research and product development processes do not differ much in their original procedure. A concept or design is created based on hypotheses that ideally are revealed by initial research or related work. Also, academic HCI research develops prototypes to test hypotheses. Hypothesis development based on individual assumptions or solely based on technological circumstances should be prevented. The “DAUX Framework” fosters a need-centered approach with the necessity to create hypotheses for concept development based on exploratory research about users' needs. However, the framework also caters to the technological perspective. We cannot ignore that technological challenges of AD development will influence users' experience in the next decades and also in fully automated vehicles there will be restrictions due to the technology (e.g., being able to intervene). A joint goal between disciplines to optimize in-vehicle experiences can use benefits and balance drawbacks of automation (for a certain level of automation) in a meaningful way. We recommend to regard the "DAUX Framework" alternating from inside to outside and from outside to inside beginning in the center with the user by asking the following questions (see Figure 4.2):

1. What are the special requirements of the *user* we are designing for?
2. What are the special requirements of the *context* we are designing for?
3. What are the technical restrictions of the *level of automation* we are designing for?
4. **Which *psychological needs* have to be satisfied in the *context* and *level of automation* we are designing for to create *positive affect*?**
5. How can these needs be satisfied by creating a *high pragmatic* but also *hedonic quality*?

To understand which psychological needs are relevant, different methods and approaches exist (e.g., in-depth interviews using the laddering technique [419], the valence method [420] or focus groups using UX cards [191, 103], etc.) and others (e.g., contextual inquiry [231] and literature review of academic studies) can be adapted. As this kind of research is exploratory, suitable methods are rather qualitative than quantitative, however, if needed for management or to increase validity for publications, results can be quantified by, e.g., conducting a structured content analysis.

Based on this, concepts can be created by using ideation techniques and design methods. These should be iteratively developed using insights from formative evaluation for design. This fosters sequential triangulation combining inductive and deductive research. How to apply the framework for evaluation is described in the following section.

4.2.2 Application for Evaluation

The framework can be used as a guideline for formative but also summative evaluation to test a hypothesis or UI concept represented from low to high-fidelity prototype.

Different methods exist to study relevant perspectives on UX (*behavioral-*, *product-*, and *experience-oriented*), but due to their strong relationship we argue that they cannot be evaluated in isolation (see Figure 4.1). Only by trian-

UX Perspective	Example Collection Methods	Example Parameters	See Tables of Related Constructs in Appendix B
Behavioral-Oriented	Tor Performance	Reaction Time, Lateral Position, Time to Collision, Speed Parameters	Safety, Trust, Situation Awareness, Stress
	Driving Performance	Lateral Position, Speed Parameters, Reaction Time	Safety, Trust, Acceptance, Workload, Drowsiness/ Fatigue, Productivity, Comfort, Cognitive Processes, Motion Sickness, UX
	Secondary Task Performance	NDRT Engagement, NDRT Performance, Reaction Time	Safety, Acceptance, Workload, Situation Awareness, Interaction Behavior, Productivity,
	Eye Tracking/ Gaze Behavior	Gaze Percentage, Gaze Duration, Gaze Number	Safety, Trust, Situation Awareness, Stress, Interaction Behavior, Drowsiness/ Fatigue, Productivity
	Observations	NDRT Engagement, Reaction Time, Body Pose/Movements, Acceleration, Braking	Safety, Trust, Acceptance, Workload, General Attitude, Situation Awareness, Stress, Interaction Behavior, Drowsiness/ Fatigue, Productivity, Emotions, UX
	Think Aloud	*N/D*	UX, Usability
	Standardized Questionnaires	CHRS, SART, PBQ	Safety, Workload, Interaction Behavior
	Probes	SAGAT	Situation Awareness
Product-Oriented	Standardized Questionnaires	AttrakDiff, UEQ, SUS, Van-Der-Lan Acceptance Scale, CTAM, TAM, UTAUT, DSQ, UES, Aesthetic Scale	UX, Usability, Acceptance, Usability, Comfort
	Self-Defined Questionnaires	*N/D*	UX, Usability, Acceptance, Usability, Comfort, General Attitude
	Interviews	Semi-Structured/ Unstructured Interview	–”–
Experience-Oriented	Standardized Questionnaires	Sheldon Need Scale, HEMA Scale, Affect Grid, PANAS, PANAS-X, SAM, Affect Scale, MMSQ, SSSQ, DSI, DSSQ, SSQ,	Stress, UX, Emotions, Motion Sickness, Drowsiness/ Fatigue
	Interviews	Semi-Structured Interviews	Stress, UX, Emotions, Trust
	Heart Rate Variability	HR (BPM), RMSSD, Physical Position	Stress, Motion Sickness, UX
	GSR	AmpSum, ISCR, nSCR, SCR, Phasic Max	Stress
	Observation	Facial Expressions	Emotions
	Think Aloud	*N/D*	UX Emotions
	UX Curve	*N/D*	UX, Drowsiness/Fatigue
	Diaries	*N/D*	-

Table 4.1: Overview of collection methods and parameters possibly applicable for UX studies addressing the different UX perspectives. *Note: further example methods and parameters identified by the presented literature review (see Section 3.2), can be derived by the Tables in Appendix B.*

gulating quantitative and qualitative/ observational and self-rating methods to study these three aspects and correlations between, we are able to understand why users behave and interact in a certain way (e.g., driving performance, TOR performance measures, eye-tracking), rate a product and its aspects as good or bad (e.g., standardized questionnaires like AttrakDiff or UEQ, interviews, etc.) and have particular feelings while usage (e.g., standardized questionnaires like PANAS, psychophysiological measures, interviews etc.). This information is essential to iteratively improve driving automation UX. Thereby, besides specific (e.g., AttrakDiff [216]) or commonly used collection methods (e.g., interviews) to study UX, UX researchers can also utilize approaches known from other constructs frequently investigated in driving automation studies (e.g., safety, situation awareness, workload). Exsiting methods can be classified into the categories of UX perspectives, see Table 4.1. For example, users' TOR performance while interacting with an AV might affect the overall experience. Hence, driving or TOR performance measures, usually used to investigate safety, can be utilized to retrace the implications of behavioral aspects on the product and experience-oriented aspects. See Table 4.1 for further example methods and parameters inspired also by other constructs frequently studied in driving automation studies (see Section 3.2).

Consequently, we aim at holistically evaluating UX of automated driving by combining multiple evaluation methods and measurements (triangulation) that address all relevant aspects of UX.

4.3 Practical Application of the Framework

The approach was presented at a half-day workshop at CarHMI 2019 with 30 international participants from the automotive industry (OEMs and suppliers). The goal of the workshop was to receive first feedback from UX practitioners on the usefulness and clarity of the framework.

The UX knowledge of the group was heterogeneous, from beginners to experts. Different aspects of UX based on UX theory were even unknown to some of them. Hence, in the beginning, basic UX concepts were shortly introduced using the framework. Afterward, participants were expected to utilize the templates (see Figure 4.2) to firstly create a UI concept, and secondly to think about an evaluation strategy in groups of five people. After the session, concepts were presented and the usefulness of the framework was discussed.

Although the application was only in a short time period without a real analysis phase of relevant psychological needs, all participants (beginner and experts) understood the procedure quite fast. They hypothesized which needs might be relevant to be fulfilled in a certain context and level of automation, which they could choose on their own, and created UI concepts based on it. The only

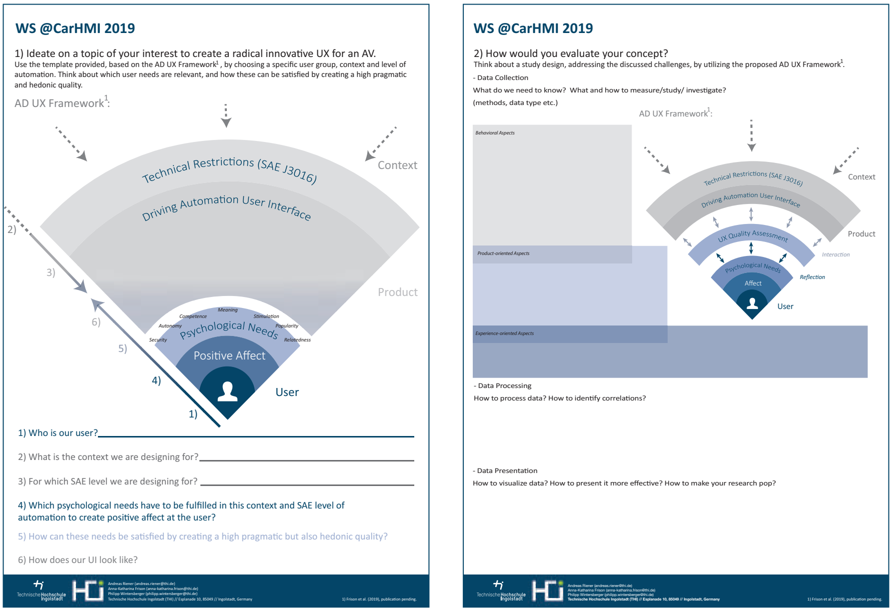

Figure 4.2: Templates to Use the “DAUX Framework” used at Car HMI 2019.

group that had problems focused on motion sickness. As this issue of driving automation is related to physiological needs (of physical thriving [176]), participants had difficulties to create UX concepts. The solution would be to prevent motion sickness. They concluded solving this problem might be a prerequisite as well as security, thus, it can only impede negative affect but will not create positive experiences (cf., pragmatic quality and Herzberg’s notion of hygiene and motivators [176, 180]). In the discussion afterward, one UX practitioner indicated the danger to neglect a double diamond approach, as the team might be too focused on creating one concept instead of different variants. This feedback needs to be taken into consideration carefully. Thus, an introduction for use needs to emphasize that the frameworks is to be applied within established design processes. For example, design thinking implies the principle of the double diamond approach. Overall, the framework was rated positively. Especially its usefulness for interdisciplinary teams with different perspectives was appreciated: *“The framework supports collaboration between different backgrounds so that user needs can be addressed with combined knowledge”*. Another participant stated: *“It is a good tool to support communication in the team and with clients”*.

This first feedback confirms our assumptions: A framework, unfolding the different layers of UX, helps to understand which aspects need to be regarded for successful UI concept development and evaluation. However, the feedback is only based on the experience of applying it in a short exercise. To gain more experience in applying the framework for UI development, the framework was applied in three different case studies, each in a different level of automation. On the one hand results of these case studies aim to support the derivation of general recommendations how to design positive driving automation experiences with UIs. On the other hand using the framework within the research and design processes should give further insights on its usefulness. These case studies will be described in the following chapter.

5 Case Studies: User Interface Development for Driving Automation

The following chapter uses the theoretical background and the groundwork for developing user interfaces for the different levels of automation (SAE L2,L3, and L4/5), aiming to create positive experiences. Therefore the introduced need-centered development approach is applied utilizing the “DAUX Framework”. The goal is to derive recommendations for UI development in the different levels of automation. Hence, the following research question will be investigated.

- **RQ3: How must user interfaces be designed to positively affect UX *of driving* and *while being driven*?**
  - RQ3.1: How should a user interface be designed to affect UX of driving in SAE L2 with varying system performance?
  - RQ3.2: How should a user interface be designed to affect UX of driving in SAE L3 in which users have to expect to take over control at any time?
  - RQ3.3: How should a user interface be designed to affect UX of driving in SAE L4/5 with limited controllability?

Therefore, each case study firstly analyses the impact of the respective level of automation on the user, secondly derives hypotheses and develops in a design phase example user interface aiming to satisfy identified relevant psychological needs responsible to create positive user experiences. Thirdly, the example user interface is evaluated applying the triangulation strategy proposed by the “DAUX Framework”. This doctoral thesis concentrates on the context of individual (not public) traffic and highway driving.

5.1 Partial Driving Automation (SAE L2)

In partial automation (SAE L2), the primary task of driving is transferred to the system, and designers must aim to keep the driver in the loop, so that they continuously monitor the automation while permanently being prepared for intervention (see Table 5.1). Recent incidents with L2 technology (such as the fatal accident with the Uber self-driving Taxi in 2018), but also user studies [95] have highlighted the importance of new interfaces, such as reliability displays, to improve monitoring, interventions, or multitasking [96, 421], [36]. Here, the relevant question for UX design will be to balance safety-related aspects (monitoring and interventions, multitasking demand, limited knowledge of system boundaries/capabilities, etc.), while preventing automation disuse and misuse [70]. The following research question will be investigated:

- RQ3.1: How should a user interface be designed to affect UX of driving in SAE L2 with varying system performance?

Role of User	**Role of Driving Automation System**
Driver **(at all times)**:	***Driving Automation System*** **(while engaged)**:
Performs the remainder of the *DDT* not performed by the *driving automation system*	Performs part of the *DDT* by executing both the lateral and the longitudinal vehicle motion control subtasks
Supervises the *driving automation system* and intervenes as necessary to maintain safe operation of the vehicle	Disengages immediately upon driver request
Determines whether/when engagement and disengagement of the *driving automation system* is appropriate	
Immediately performs the entire *DDT* whenever required or desired	

Table 5.1: Roles of human driver and driving automation system in SAE L2.

This section is based on following publication: [5].

5.1.1 Analysis

To identify which psychological needs are relevant to satisfy in SAE L2, related work in the area of human factors about partial automation is analyzed. Based on this, a user interface is developed to study the impact of a UI on the UX.

5.1.1.1 Related Work

Monitoring over longer periods is challenging, especially for drivers who are not necessarily well-trained domain experts like, e.g., pilots [422]. Further, especially on highways, where monitoring is monotone, younger participants experience automated driving as safe and trustworthy [16]. Thereby the wrongly fulfilled need of security may lead to issues of overtrust which can have fatal consequences in SAE L2 as recent accidents already confirmed [423]. Actually, trust and the fulfillment of the need of security should be in line with an objective measure of trustworthiness, i.e., the current system performance of the driving automation system [424, 401] which is in SAE L2 varying. However, trust in automation is influenced by a variety of aspects, including aesthetics, design, usability and other factors of user experience (UX) [425]. This needs to be carefully considered in the design process. On the one hand, UX qualities of vehicles must be maximized to maintain competitiveness. On the other hand, a vehicle should be designed to prevent overtrust to ensure road safety.

In the HCI community, UX and trust research are two areas which are often considered in isolation or treated as the same. However, similarities between both constructs cannot be denied and, thus, we aim to consider them in a holistic way and to investigate correlations.
Trust in automation can be defined as *"attitude that an agent will achieve an individual's goals in a situation characterized by uncertainty and vulnerability"* (p. 51), and is built upon analytic, analogical, and affective processes [401]. Trust is sensitive to individual traits (such as age, personality, etc.) and states (self-confidence, emotional state, etc.), properties of the automation (complexity, task difficulty, etc.), as well as design features (appearance, ease of use, communication style, etc.) [425], and is the result of processes happening before (*"dispositional trust"*), during *("situational trust")*, and after *("learned trust")* system interaction [425]. In contrast, UX can (according to ISO 9241/210 [122] be defined as a *"users's perceptions and responses resulting from the use and/or anticipated use of a product, system or service"*. Thereby, experience can *"occur before, during and after use"*, and *"[...] is a consequence of brand image, presentation, functionality, system performance, interactive behaviour and assistive capabilities of the interactive system, the user's internal and physical state resulting from prior experiences, attitudes, skills and personality, and the context of use"*, see Chapter 2.

Although trust and UX have separate definitions, they seem to be influenced by similar factors and processes. Hence, it is not surprising that trust is a mentioned (however, not yet focused) construct in UX theory literature. The term trust is regarded as a component of UX [418], users' personal quality of experience [126] or as (context-dependent [426]) perceived value [427]. Desmet et al. [162] mention trust within their general set of 25 emotions relevant in human-product interaction. Although trust is not an emotion itself, a product can help users to feel confident and courageous if it is perceived as trustworthy. Thus, designers need to decide which psychological needs they want to fulfill. Distler et al. [103] revealed the need of security as one of the most important needs for AVs which defined as: *"feeling safe and in control of your life rather than feeling uncertain and threatened by your circumstances"* [176, p. 339]. In order to fulfill this need, a specific form of interaction has to be selected which aims at expressing trustworthiness and thereby triggers trust [428, 429, 430, 431]. In this sense, trust can be regarded as subjective sentiment and evaluative feeling dependent on the fulfillment of users' higher goals, such as the psychological need of security [125, 63]. To provide examples, Väätäjä et al. [432] include trust as item in the AttrakWork questionnaire to measure a product's hedonic quality and Rödel et al. [104] chose trust as relevant UX factor when evaluating user acceptance and experience of driving automation at different levels. Thus, trust can be seen as additional experience-oriented aspect to be relevant to capture for a holistic contemplation for driving automation UX.

The main difference between both concepts becomes visible when looking at the goals both constructs aim to achieve. UX research tries to maximize the quality of interaction by satisfying psychological needs and thereby providing pragmatic and hedonic quality [125, 124]. For designers, there is no upper limit – the more these qualities are supported, the better. Thus, previous research focused on the impact of visual aesthetics, usability, and branding on users' perceived trustworthiness, predominantly in the area of e-commerce systems [431, 433, 434] and websites [435]. These studies aimed to increase users' perceived trustworthiness and, consequently, enhance UX. In trust research however, maximizing trust is not the major goal. Here, the challenge is to precisely adjust users' subjective trust levels to a system's actual performance (*"calibration of trust"* [424]) while taking the operational and environmental context into account [401]. Thus, although trust may need to be raised in many situations, an upper limit should not be exceeded to prevent users from overreliance. In the domain of automated driving, recent studies addressing trust can broadly be divided into two areas. Those dealing with distrust to reduce automation disuse, and those that address the problem of overtrust/overreliance to prevent misuse [424]. For both issues, various resolution strategies have been proposed. Trust may be raised by increasing system transparency, using various techniques such as why-and-how information [436], symbolic representation [437], augmented reality [46] or anthropomorphic agents [438, 439]. An often proposed solution to deal with overtrust is the provision of uncertainty displays in different forms and modalities [440, 441, 96]. In this context, a problem that we see in many trust studies is that a distinction between the two constructs (trust and UX) is not made. For example, was the aim of an experiment actually to address trust/reliance or were mainly UX aspects evaluated which potentially overlap with trust?

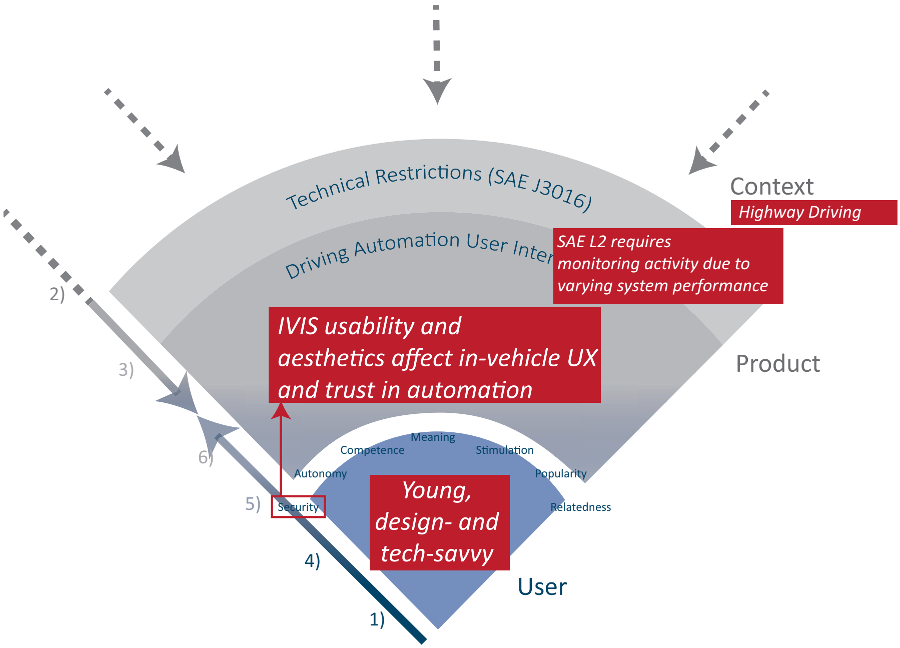

Figure 5.1: Application of the need-centered approach with the "DAUX Framework" in SAE L2 for Hypothesis/ Concept Development.

Further, so called *halo-effect* (see Subsection 2.2.1), caused by a cognitive bias [204, 205, 206] exist. Thus, Lindgaard et al. [435] claim that these are a reason for the interrelation of usability, aesthetics, and trust in websites. Hence, there might be not only the paradox of *"what is beautiful is usable"* [202, p. 127], but also *what is beautiful is trustworthy*?

5.1.1.2 Implications for Design

A central question that arises is, how the two constructs, trust and UX, are correlated in the context of AVs in SAE L2? Similiar to [435], we expect *halo-effects* of aesthetics and usability as biasing factors for trust, what could become highly relevant for the future implementation of automated driving technology. Thereby we hypothesize the need of security as the most critical to satisfy, hence, needs to be specifically regarded in UX design.

Figure 5.2: IVIS Design in SAE L2, A/C menu of the nice (left) and ugly (right) IVIS.

5.1.2 Design

As a central user interface in SAE L2, able to evoke emotions and available already in lower level of driving automation (e.g., TESLA 17-inch display), we chose to investigate the impact of an infotainment system (IVIS), see Figure 5.1.
We implemented four variants of IVISs in HTML/Javascript on a 10.2” tablet (Google Pixel C). The IVISs consisted of a main navigation and three typically available subsystems (a phone/call screen including a list of contacts, a media player including a collection of albums/songs as well as different radio stations, and a climate control), see Figure 5.2.

The visual design was selected from a set of examples created by groups of undergraduate students during a design class. Students were provided a specific menu/navigation structure and instructed to create an IVIS skin. All designs were evaluated using the UEQ [375] on a 7-point semantic differential scale from -3 (negative) to +3 (positive) with at least 5 participants. We utilized the results of the subscale “Attractiveness (Att-UEQ)” and selected the IVISs with the best and worst values. While the nice design has a mean value of ATT-UEQ=1.92 (excellent with respect to the UEQ benchmark dataset [442]), the ugly design shows mean value of only ATT-UEQ=0.45 (bad compared to the benchmark). This process aimed as guidance to confirm our subjective selection of a nice and ugly IVIS, however, was no controlled experiment. All students agreed to contribute with their IVIS design to the experiment and were informed about the conditions. To provide a potentially “bad” usability, we followed the definition provided in ISO 9241-11 [416] that states usability to be the *“extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”*. Thus, we chose to manipulate the IVISs reliability by semi-randomly calculating the chance for a successful button-press action, where at least two and at most 8 clicks were required for a successful action.

Figure 5.3: Study setup showing the driving scenario and an example of the IVIS used to investigate the interaction between UX and trust.

5.1.3 Evaluation of "In UX We Trust"

We conducted a driving simulator study to investigate the interaction (potential correlation and *halo-effects* of UX and trust) between an driving automation's performance/reliability and relevant UX factors (usability/aesthetics) of in-vehicle interfaces, as well as their effect on the perception of AVs in general; aiming to test following hypothesis:

- H3.1: IVIS usability and aesthetic affect in-vehicle UX and trust in SAE L2 automation with varying system performance.

5.1.3.1 Study Setup

The experiment was conducted in a high-fidelity driving simulator (remodeled VW Golf on hexapod platform) and an IVIS on a tablet PC installed on top of the center console (see Figure 5.3).

We applied a full factorial mixed-model design varying the performance of the driving automation system as between-subjects factor, and aesthetics and usability of the IVIS as within-subjects factor (each on two levels). Each participant had to perform various tasks on four different IVISs that represented all combinations of usability (good/bad) and aesthetics (nice/ugly), see Figure 5.4.

Driving Scenario We simulated an AV at SAE level 2 (i.e., combination of longitudinal and lateral control) driving on a 2-lane highway using IPG CarMaker, inspired by the setting used in [440]. The AV drove with a constant speed of 120km/h on the left lane and was confronted with 12 lead vehicles driving at lower speed (70km/h). In such a situation, the driving automation system detected the lead vehicle and reduced the speed to prevent a crash (similar to an ACC system). As soon as the ego vehicle slowed down to 70km/h, the lead vehicle performed a lane change to the right, allowing the ego vehicle to accelerate again to the target speed. In the high-performance condition (group A), all 12 lead vehicles were successfully detected (thus, no manual interventions were necessary). In the low-performance condition (group B), the driving automation system (randomly) failed to detect the lead vehicle in 3 out of the 12 cases (75% reliability), generating the need for interventions – participants thus had to brake manually to prevent a crash (however, they never had to manually engage in lateral control).

Participants and Procedure In total, 48 participants (16 female, 32 male) aged between 19 and 26 (M_{age}= 22.09, SD_{age} = 1.89) years, all undergraduate students, voluntarily participated in the experiment. Each participant was assigned to either group A (high driving automation system performance) or group B (low driving automation system performance), potential differences between the groups considering gender and age were counterbalanced. No participant had to be excluded due to simulator sickness or technical problems. After completing a short questionnaire assessing demographics, each participant conducted a 3-minute test drive to become familiar with the AV. Then, we instructed participants that they will experience four different types of AVs with different IVISs. We further told them that manual braking interventions could be necessary due to automation failures, and that safely completing the drive has the highest priority. Afterwards, participants experienced four consecutive 5-minute lasting trips while experiencing the 4 different IVISs (in randomized order). Within each condition, participants had to complete seven tasks on the IVISs with two levels of complexity. Easy tasks consisted of a single instruction only (such as “call John”), while complex tasks required participants to remember multiple steps (such as “switch to Radio Disney Channel and adjust the volume to 8”). The task instructions were presented auditory (pre-recorded sound files).

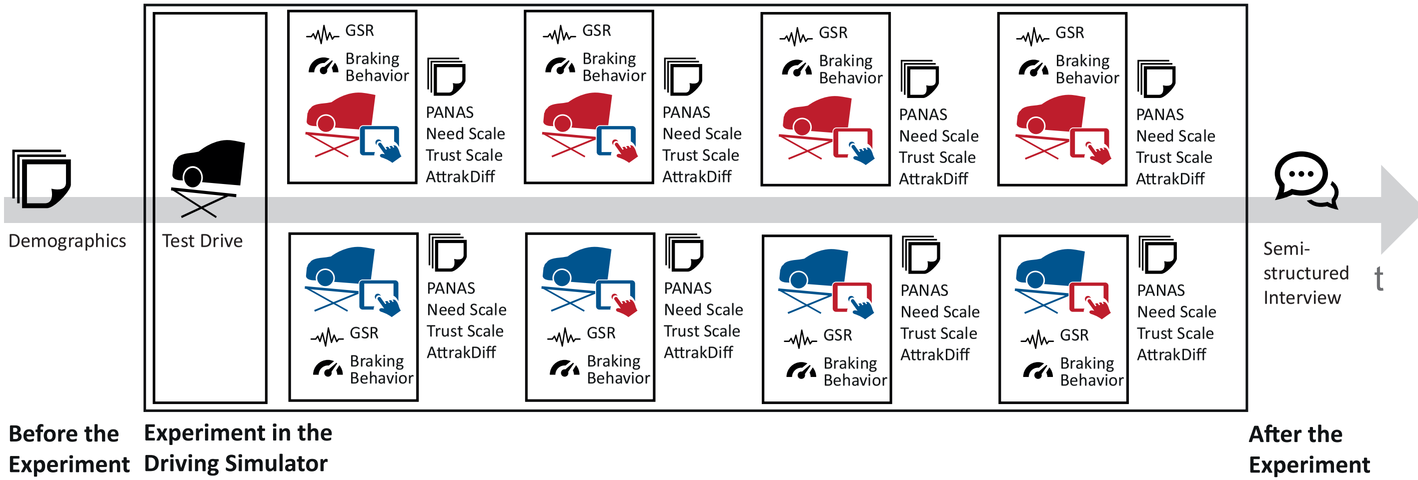

Figure 5.4: Study procedure: The top row represents the drives with low, the bottom row drives with high driving automation performance. The red color indicates decreased qualities (finger: usability, tablet: aesthetics, driving simulator: performance).

Successful completion of a task was indicated with a notification sound and the next task was issued 35 seconds afterwards. In case all seven tasks were completed before finishing the 5-minute lasting drive, the experimental condition was stopped earlier. The selection of tasks from the set was randomized over the conditions, and quasi-randomized within the scenarios (each task was only presented once during the entire experiment). After each condition, participants had to complete a survey including a set of different standardized scales to assess trust and UX in the AV (see Figure 5.4), whereby we repeatedly instructed them to assess the AV as a whole, single system based on their experiences. Additionally, a short semi-structured interview with all participants was conducted after the experiment to reveal further insights into their thoughts and attitudes. The whole experiment lasted approx. 90 minutes for each participant.

Data Collection To be able to evaluate the proposed research questions, we applied the AD UX framework to derive methods, see Figure 5.5. We triangulated a set of experience-, product- and behavioral-oriented measures derived from established theory as emphasized in the following.

Experience-Oriented Measures. System interaction leads to particular (positive and negative) emotions [161] resulting from need fulfillment [63, 178]. Thus, we included the short version of PANAS also with a 7-point Likert scale [158, 443]. PA and NA did not correlate ($r < .12$) and reliability of all subscales was acceptable ($\alpha > .70$, see Table 5.2).
Galvanic Skin Response (GSR) is commonly used as an indicator for the sympathetic nervous system. Changes in skin conductance have been linked to arousal [444, 445], (cognitive) workload [446, 447], usability [448], user experience [449], but also trust [450]. Signal peaks, so called Skin Conductance Responses (SCRs), indicate such activation while the general signal level is subject to bias by individual differences, room temperature, etc. [446]. We utilized a professional 500 Hz physiological measurement system from g.tec medical engineering[1] and attached two skin electrodes to the volar (inner) middle phalanges (muscle limbs) of the non-dominant hand's middle and ring fingers (see guidelines by [451, 452]). Since GSR is sensitive to motion artifacts, we instructed participants to behave naturally but also to prevent waving their hands excessively. We used Ledalab for Matlab [453] to extract all SCRs since the implemented Continuous Decomposition Analysis (CDA) is supposed to be more robust at discriminating single SCRs than traditional peak-detection methods [454]. For the evaluation, we utilized the number of SCRs, which is argued to be less affected by individual differences and other forms of bias [446].
As UX is dependent on the satisfaction of psychological needs [63, 178], we

[1] www.gtec.at

Dep. Variable	Items	Cronbach's α	Ref.
Experience-oriented Aspects:			
Affect			
Positive (PA)	5	.75	[158]
Negative (NA)	5	.85	[158]
Needs			
Autonomy (AUT)	3	.84	[176, 63]
Competence (COM)	3	.86	[176, 63]
Stimulation (STI)	3	.83	[176, 63]
Security (SEC)	2	.77	[176, 63]
Trust			
Trust (T)	6	.91	[354]
Distrust (DT)	5	.87	[354]
Product-oriented Aspects:			
UX Qualities			
Attractiveness (ATT)	2 (Beauty and Goodness)	.65	[206, 216]
Pragmatic Q. (PQ)	4	.77	[206, 216]
Hedonic Q. (HQ)	4	.79	[206, 216]

Table 5.2: Summary of self-rating scales employed.

further utilized the need scale (same version as used in [63] with 7-point Likert scale) and focused on the needs: autonomy (AUT), competence (COM), stimulation (STI), and security (SEC). Also here, reliability of all subscales was acceptable ($\alpha > .70$, see Table 5.2). Intercorrelation between the subscales across all conditions ranged from r=.26 to r=.81.
To evaluate subjective trust we used the trust scale provided by Jian et al. [354]. This scale consists of two subscales for trust (T) and distrust (DT) (7-point Likert) and is widely used to assess trust in automation or robotic systems [441, 455]. Also here, Cronbachs' α resulted in acceptable values while T and DT showed a negative correlation ($r > -.80$).

Product-Oriented Measures. We used the AttrakDiff mini [206] with a 7-point semantic differential scale ranging from 0 (low) to 6 (high). Thereby, the subscale attractiveness (ATT), consisting of two items for beauty and goodness, assesses the overall perception combining both pragmatic (PQ) and hedonic quality (HQ). Since for all subscales Cronbachs' α resulted in acceptable values ($> .60$, see Table 5.2), we calculated mean scale values. All UX qualities are intercorrelated (Pearson's correlation coefficient), ranging from r=.412 to r=.880 across all conditions. HQ and PQ showed least (r<.60), HQ and ATT highest intercorrelations (r>.60).

Behavioral-Oriented Measures. To evaluate driving behavior, we recorded participants' brake pedal actuation and calculated three parameters – the number of brakes representing the quantity of manual interventions, the average duration of a brake pedal actuation, and the average brake intensity (on a scale from 0 to 1).

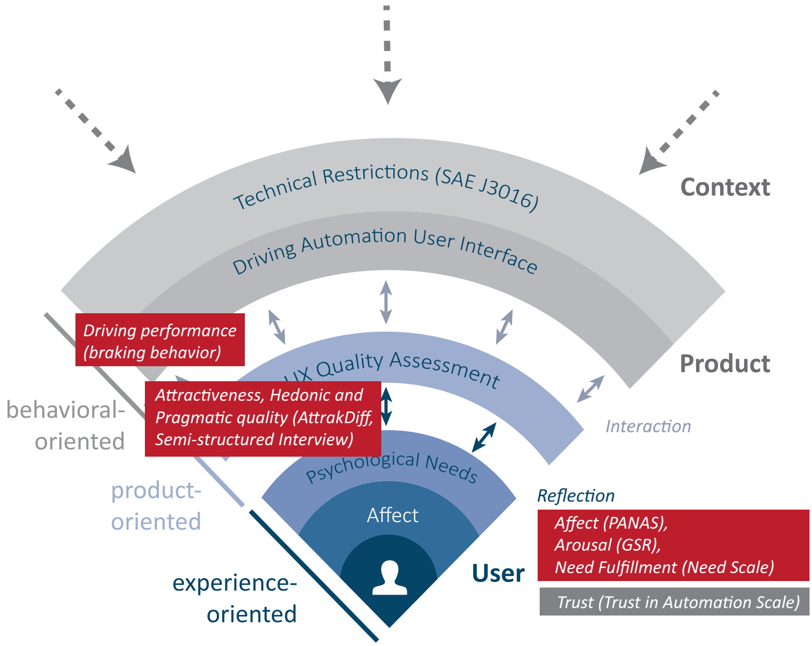

Figure 5.5: Application of the need-centered approach with the "DAUX Framework" in SAE L2 for Evaluation.

5.1.3.2 Results

In the following we present a detailed analysis of the collected data to test postulated hypotheses (all results with $p < .05$ are reported as statistically significant). Since tests for normality (Shapiro-Wilk's, $p > .05$), marginal existence of outliers, and homogeneity of error variances assessed by Levene's test ($p > .05$) were passed for all dependent variables (except for driving performance, see Table 5.2), parametric tests were applied. We performed three-way mixed ANOVAs with the independent variables driving automation system performance as between-subjects, and IVIS usability and aesthetics as within-subjects factors. As the collected driving performance measures did not follow a normal distribution, non-parametric tests (Mann-Whitney-U tests for the between-, and Wilcoxon Signed-Rank tests for the within-subject factors) were applied. To analyze correlations between the subjective constructs of UX and trust, we conducted Pearson's bivariate correlation analyses.

Experience-Oriented Aspects We analyzed the experience-oriented data of utilized scales as well as the objective data on participants' arousal given by GSR. Concerning multivariate tests statistics, we utilized Pillai's Trace.

Questionnaires. Participants' positive (PA) and negative affect (NA) revealed a significant main effect for driving automation system performance, ($V = .36, F(2,45) = 11.33, p < .001$). A look at univariate tests revealed that NA for the low driving automation system performance is significantly higher than for the high driving automation system performance condition($F(1,46) = 23.14, p < .001, \eta^2 = .34$), while PA was not affected. Regarding the within-subject factor IVIS usability, we can observe similar results. Multivariate tests reveal a significant main effect ($V = .16, F(2,45) = 4.38, p = .018$), however, also here only NA showed differences in case IVIS usability is bad ($F(1,46) = 7.26, p = .010, \eta^2 = .14$). Contrarily, IVIS aesthetics, which also has a significant main effect ($V = .21, F(2,45) = 6.007, p = .005$), shows significant differences for both PA ($F(1,46) = 4.24, p = .045, \eta^2 = .08$) and NA ($F(1,46) = 8.63, p = .005, \eta^2 = .16$). Thereby, PA is slightly (but still significantly) higher for the nice IVIS aesthetics in contrast to the ugly IVIS variants. Again, no two or three-way interaction effects could be revealed (see Table 5.3 for means).

				95% Confidence Interval	
Dep. Variable	**Ind. Variable**	M	SD	lower	upper
	system performance				
NA	high	1.04	0.16	0.64	1.44
	low	2.40	0.23	2.00	2.80
	IVIS usability				
NA	good	1.58	1.26	1.27	1.89
	bad	1.86	1.22	1.57	2.15
	IVIS aesthetics				
PA	nice	2.98	0.98	2.69	3.27
	ugly	2.80	1.05	2.49	3.11
NA	nice	1.57	1.21	1.27	1.86
	ugly	1.87	1.27	1.56	2.18

Table 5.3: Significant values of participants' affect.

For users' need fulfillment of Autonomy (AUT), Competence (COM), Stimulation (STI), and Security (SEC), we can report a significant effect for driving automation system performance regarding the multivariate test statistic ($V = .22, F(4,43) = 8.09, p = .025$). Univariate tests reveal only significant differences in participants' need of SEC ($F(1,46) = 12.88, p = .001, \eta^2 = .22$), which was less fulfilled in the group with the low driving automation system performance. Multivariate tests show a significant main effect for IVIS usability ($V = 0.24, F(4,43) = 3.33, p = .018$), univariate tests resulted in a significant decrease of SEC in case of bad IVIS usability ($F(1,46) = 7.43, p = .009, \eta^2 = .14$) and COM ($F(1,46) = 9.54, p = .003, \eta^2 = .17$). Further, also for the within-subject factor IVIS aesthetics, a significant main effect could be revealed ($V = .24, F(4,43) = 3.38, p = .017$). Regarding univariate tests we can observe effects for the need of STI ($F(1,46) = 12.12, p = .001, \eta^2 = .21$), AUT ($F(1,46) = 5.22, p = .027, \eta^2 = .10$), SEC

($F(1,46) = 6.26, p = .016, \eta^2 = .12$) and COM ($F(1,46) = 6.08, p = .017, \eta^2 = .12$). Thereby, all these needs are significantly less fulfilled when driving in an AV with ugly IVIS (see Table 5.4 for means). Here, data analysis did not reveal any two- or three-way interaction effects.

				95% Confidence Interval	
Dep. Variable	**Ind. Variable**	M	SD	lower	upper
	system performance				
SEC	high	3.24	1.20	2.79	3.69
	low	2.10	0.25	1.65	2.56
	IVIS usability				
SEC	good	2.82	1.34	2.47	3.18
	bad	2.52	1.23	2.20	2.84
COM	good	3.13	1.37	2.73	3.52
	bad	2.79	1.36	2.40	3.18
	IVIS aesthetics				
AUT	nice	2.48	1.34	2.09	2.86
	ugly	2.30	1.41	1.89	2.71
STI	nice	2.77	1.12	2.45	3.09
	ugly	2.40	1.27	2.04	2.76
SEC	nice	2.82	1.28	2.48	3.16
	ugly	2.53	1.30	2.19	2.87
COM	nice	3.07	1.26	2.71	3.44
	ugly	2.84	1.43	2.43	3.26

Table 5.4: Significant values of participants' psychological need fulfillment.

Multivariate data analysis (using Pillai's Trace) of users' trust (T) and distrust (DT) revealed a significant main effect for driving automation system performance ($V = .29, F(2,45) = 9.02, p = .001$). Univariate tests on the dependent variables show significant effects for T ($F(1,46) = 18.07, p < .001, \eta^2 = .28$) and DT ($F(1,46) = 15.09, p < .001, \eta^2 = .25$). While T is decreasing in conditions of low driving automation system performance, DT is increasing. Contrarily, T is increasing for high driving automation system performance and DT decreasing. We can report another main effect for IVIS usability ($V = .24, F(2,45) = 7.12, p = .002$). Also here, significant effects for T ($F(1,46) = 14.54, p < .001, \eta^2 = .24$) and DT ($F(1,46) = 9.48, p = .003, \eta^2 = .17$) are visible. Descriptive data shows similar effects like for the between-subject factor driving automation system performance. Further, also IVIS aesthetics shows a significant main effect ($V = .22, F(2,45) = 6.17, p = .004$). However, here only DT could be significantly decreased by a nice IVIS interface, ($F(1,46) = 12.58, p = .001, \eta^2 = .22$); see Table 5.5).

Psycho-Physiological Data. Analysis of GSR data revealed a significant main effect for the within-subject factor IVIS usability ($F(1,38) = 9.85, p = .003, \eta^2 = .21$). Bad IVIS usability leads to significantly more peaks, thus arousal, than good usability. We further can observe a two-way interaction effect for IVIS usability and driving automation system performance($F(1,38) = 4.98, p = .032, \eta^2 = .12$). Descriptive statistic show that if driving automation system performance is low and IVIS usability is bad, participants are significantly more aroused than

				95% Confidence Interval	
Dep. Variable	**Ind. Variable**	M	SD	lower	upper
	system performance				
T	high	3.91	0.21	3.34	4.36
	low	2.55	0.24	2.09	3.00
DT	high	2.34	0.20	1.90	2.79
	low	3.56	0.24	3.11	4.01
	IVIS usability				
T	good	3.40	1.31	3.08	3.72
	bad	3.06	1.35	2.71	3.40
DT	good	2.80	1.26	2.48	3.12
	bad	3.10	1.31	2.76	3.44
	IVIS aesthetics				
DT	nice	2.81	1.26	2.49	3.13
	ugly	3.09	1.28	2.76	3.43

Table 5.5: Significant values of participants' trust.

if driving automation system performance is high and IVIS usability is good. However, when driving automation system performance is low although the IVIS usability is good, the number of GSR peaks is also increasing. No further main effects for driving automation system performance or IVIS aesthetics, and also no further two- and three-way interaction effects could be revealed by our statistical analysis (see Table 5.6 for descriptive statistics).

				95% Confidence Interval	
Dep. Variable	**Ind. Variable**	M	SD	lower	upper
	IVIS usability				
Peaks	good	203.06	65.66	183.99	222.14
	bad	220.45	78.46	196.84	244.07
	system performance x IVIS usability				
Peaks	high & good	194.20	67.20	167.22	221.18
	high & bad	223.95	81.00	190.55	257.35
	low & good	211.93	63.00	184.95	238.90
	low & bad	216.95	77.71	183.55	250.35

Table 5.6: Significant values of participants' arousal.

Product-Oriented Aspects Multivariate tests evaluating the impact of driving automation system performance, IVIS aesthetics and usability on participants' perception of product quality (measured by AttrakDiff) reveals no significant main effect for the between-subject factor driving automation system performance ($V = .21, F(5,42) = 2.24, p = .068$). However, separate univariate ANOVAs on the outcome variables show a significant effect for pragmatic quality (PQ, $F(1,46) = 8.62, p = .005, \eta^2 = .16$). Results for high driving automation system performance were perceived as significantly better than for low performance conditions. Ratings for attractiveness (ATT, Goodness and Beauty) and hedonic quality (HQ) did not differ significantly (see Table 5.7). Additionally, multivariate tests reveal that the overall perceived system quality significantly differs regarding IVIS usability ($V = .44, F(5,42) = 6.47, p < .001$). Univariate tests confirm a significant effect for ATT ($F(1,46) = 14.67, p = .001, \eta^2 = .24$). Regarding the items "Goodness" and "Beauty" separately, there is only a significant effect on "Goodness" ($F(1,46) = 25.45, p < .001, \eta^2 = .36$). Also PQ ($F(1,46) = 25.36, p < .001, \eta^2 = .36$) and HQ ($F(1,46) = 10.60, p = .002, \eta^2 = .19$) differed significantly. Thus, systems with good IVIS usability were perceived better than those with bad IVIS usability across all conditions. Further, we can report a significant main effect for the within-subject factor IVIS aesthetics ($V = .57, F(5,42) = 11.24, p < .001$). Univariate tests reveal significant effects for ATT ($F(1,46) = 50.22, p < .001, \eta^2 = .52$). Here, both items, "Goodness" ($F(1,45) = 20.22, p < .001, \eta^2 = .30$) and "Beauty"($F(1,46) = 58.23, p < .001, \eta^2 = .56$), show significant effects. Also PQ ($F(1,46) = 28.29, p < .001, \eta^2 = .38$) and HQ ($F(1,46) = 52.44, p < .001, \eta^2 = .53$). Thus, across all conditions the nice IVIS was rated better than the ugly IVIS. Moreover, our data confirms the inference model [206, 203] – better aesthetics leads to a significantly higher ratings for goodness and therewith higher ratings for PQ, and not only beauty (evaluative consistency). However, no two or three-way interaction effects could be revealed.

				95% Confidence Interval	
Dep. Variable	**Ind. Variable**	M	SD	lower	upper
	system performance				
PQ	high	4.17	0.18	3.81	4.53
	low	3.42	0.18	3.06	3.79
	IVIS usability				
ATT	good	3.36	1.01	3.07	3.65
	bad	2.96	1.14	2.62	3.30
↪ Goodness	good	3.74	1.23	3.39	4.09
	bad	2.96	1.45	2.54	3.37
PQ	good	4.10	0.92	3.86	4.34
	bad	3.49	1.14	3.17	3.81
HQ	good	2.97	0.83	2.72	3.21
	bad	2.68	0.89	2.42	2.94
	IVIS aesthetics				
ATT	nice	3.72	1.06	3.40	4.04
	ugly	2.60	1.10	2.24	2.97
↪ Beauty	nice	3.72	1.34	3.39	4.05
	ugly	2.24	1.37	3.39	4.09
↪ Goodness	nice	3.72	1.34	3.34	4.10
	ugly	2.98	1.38	2.58	3.38
PQ	nice	4.05	0.97	3.78	4.32
	ugly	3.54	1.04	3.26	3.82
HQ	nice	3.38	0.80	3.14	3.61
	ugly	2.27	1.10	1.95	2.59

Table 5.7: Significant values of participants' UX quality assessment.

Behavioral-Oriented Aspects Since braking data was not normal distributed we performed non-parametric tests. Mann-Whitney U tests with Bonferroni correction (α=.0125) were conducted to confirm expected differences in braking behavior between low and high driving automation system performance. All braking parameters are, across all IVIS conditions, significantly higher in conditions with low than with high driving automation system performance (see Table 5.8).

		system performance		Test Statistic
	IVIS	Mdn (high)	Mdn (low)	Mann-Whitney-U test
Number	bad & nice	0	**5***	U = 510, z = 4.73, p < .001
	bad & ugly	0	5	U = 515, z = 4.83, p < .001
	good & nice	0	**7***	U = 530, z = 5.12, p < .001
	good & ugly	0	6	U = 499, z = 4.47, p < .001
Duration	bad & nice	0	**2.65***	U = 511, z = 4.72, p < .001
	bad & ugly	0	2.47	U = 491, z = 4.30, p < .001
	good & nice	0	**1.99***	U = 438, z = 3.16, p < .002
	good & ugly	0	**2.42***	U = 511, z = 4.70, p < .001
Intensity	bad & nice	0	.72	U = 533, z = 5.19, p < .001
	bad & ugly	0	.72	U = 536, z = 5.25, p < .001
	good & nice	0	.55	U = 515, z = 4.79, p < .001
	good & ugly	0	.65	U = 519, z = 5.19, p < .001

Table 5.8: Participants' braking behavior. *Note: Significances between variables are indicated by *.*

To compare the impact of the IVIS on braking behavior, we calculated separate Friedman tests for low and high driving automation system performance with Bonferroni correction (α=.008). The number of brake actions differs only significantly for the group of the low driving automation system performance ($\chi^2(3) = 11.04, p = .012$). Post-hoc analysis revealed significant differences only between good & nice and bad & nice (p = .022), which led to more brake actions. Further, also braking duration is significantly different in conditions with low driving automation system performance ($\chi^2(3) = 13.40, p = .004$). Post-hoc analysis revealed a significant difference only between good & nice, which shows lowest braking duration median and bad & nice with the highest braking duration median (p = .005), and additionally between good & nice and good & ugly (p = .022). For braking intensity, no significant effects could be revealed.

Correlation of UX and Trust To evaluate a potential correlation between the constructs UX and trust we ran bivariate Pearson correlation analyses of averaged correlation-coefficients after Fisher's Z-Transformation (see Table 5.9). Thereby, we applied Bonferroni Correction and adjust the significance level to α =.016.

Correlations. Participants' product quality perceptions show correlations with the constructs trust (T) and distrust (DT, s. Table 5.9). Although the overall perceived attractiveness (ATT) and almost all sub components correlate positive with T and negative with DT, the sole perception of beauty does not correlate significantly with T or DT. Regarding correlations of participants' psychological needs, we can observe a significant positive correlation of the need for security (SEC) and T, and a negative correlation with DT. The need of competence (COM) correlates positive with T. Moreover, only negative affect (NA) correlates negative with T and positive with DT. Arousal and the construct trust do not correlate across all conditions. Also, no correlation could be identified between arousal and braking behavior.

	Trust (T)	**Distrust (DT)**
UX Qualities		
ATT	.5*	-.48*
↪ Beauty	.27	-.25
↪ Goodness	.59*	-.57*
HQ	.37*	-.36*
PQ	.68*	-.66*
Needs		
AUT	.25	-.16
COM	.30*	-.18
STI	.29	-.25
SEC	.75*	-.74*
Affect		
PA	.06	.04
NA	-.79*	.8*

Table 5.9: Averaged correlations between measures after z-transformation. *Note: Significances are indicated by * (Bonferroni-corrected).*

Semi-structured Interviews. Semi-structured interviews (translated from German) confirm a correlation between perceived pragmatic quality and trust. Thereby, also participants in group with low driving automation system performance expressed to trust the system with good IVIS usability most:

> *"I would trust most in the driving automation system with a running infotainment system. If this is running I can also concentrate on other things around because I know this works"* (P3, low driving automation system performance).

Several participants mentioned the distraction from monitoring the driving automation system as reason for decreased comfort and trust in the condition with bad IVIS usability. For some participants the influence of usability and aesthetics on trust was conscious, e.g.,

> *"the whole vehicle has to look appealing and of high-quality that I agree to drive automated. The whole concept needs to be harmonious."* (P13, high driving automation system performance)

Others, in contrast could not identify why they trusted most in the driving automation system with the good and nice IVIS. For example, one participant in the low driving automation system performance condition rated the driving automation system with good and nice IVIS as most trustworthy, however, reasoned *"because the AV performed best here"* (P5, low driving automation system performance) – actually, automation performed equally good for a in all conditions he experienced. Participants experiencing high driving automation system performance expressed that their trust increased gradually from beginning of the experiment to the end:

> *"At the beginning I was nervous while solving the tasks and I looked always on the street. In the end I relied on that the driving automation system is working"* (P1, high driving automation system performance).

Another participant stated:

> *"The longer I tested the system, the more I trusted in it. The system I trusted most was the AV used in the second drive (nice and good), the interface of the IVIS was the most beautiful. My overall experience was impacted by it, thus, I also trusted more in this AV"* (P21, high driving automation system performance).

5.1.4 Discussion

In the presented need-centered approach, we analyzed driving automation UX in SAE L2 by applying the "DAUX Framework". Based on our related work analysis we expected a correlation of UX and trust because of the need of security. Thereupon, we postulated that aesthetics and usability of an IVIS affect the whole driving experience and trust in automation (H3.1), which we were able to confirm by evaluation.

5.1.4.1 Relevant Psychological Needs

All independent variables show influence on multiple UX qualities. Especially the large influence of visual design on UX regarding users' higher goals confirms results from previous studies investigating the *halo-effect* of usability and aesthetics [435, 202, 207, 208, 203, 206] in the context of AD. As driving automation system performance solely affected pragmatic aspects and thereby only the negative affect (probabilistic consistency), we can assume objective system performance to be a hygiene factor [211, 63, 180] for UX. Experience is only negatively affected if high system performance cannot be achieved. Regarding trust, driving automation system performance led to different results for both trust and distrust, what is also visible for the within-subject factor usability (probabilistic consistency). Aesthetics affected distrust only (with respect to our study sample). Thus, trust cannot be increased by a good design only distrust, however, can be decreased. This can be regarded as evaluative

consistency, as there is no direct relation. The mutual influence of the independent variables on subjective trust indicates that users hardly differentiate between (for the driving task) more (driving automation system performance) and less (IVIS) important subfunctions. Still, results show a clear connection of perception and actual behavior. When looking at driving behavior, we could see that, when UX aspects were degraded, participants actuated the brakes longer, thus de-accelerated to lower speeds and drove more carefully (this statement can be made as braking intensity did not differ, thus longer braking actions with similar intensity consequently lead to lower driving speed). Correlation analysis further confirmed the familiarity of both constructs. All UX quality dimensions (beside the perception of beauty), the psychological need for security and negative affect were correlated with trust/distrust. The influence of usability/aesthetics on trust was further emphasized in semi-structured interviews, even though some participants were not conscious of the impact. Our results do not rely on subjective data only. Obtained GSR data shows that impairment of driving automation system performance and usability led to significantly higher arousal.
We conclude that for SAE L2 the need of security is the most critical. However, instead to fulfill this need to create positive affect, thus, good UX, in SAE L2 designers face the challenge to find the correct balance in addressing this need in an adequate manner as it strongly correlates with trust.

5.1.4.2 Conceptualization of Psychological Needs

Considering the presented results, we suggest the following recommendations for researchers and designers of automated driving systems to appropriately satisfy the need of security:

The mutual influence of all variables reveals a huge problem – *halo-effects* considering the need of security confirm that it is hard for users to (at least initially) assess an AV (SAE L2) based on objective characteristics. This is a known issue for interactive products, but, for AVs, the resulting negative effects might be dramatic. For example, falsely inferring trustworthiness from design aspects due to evaluative consistency could quickly lead to hazardous situations, and the safety critical environment simply does no longer allow system exposure and real-life experiences mediating this effect later on.
Public authorities and/or vehicle manufacturers must create awareness, for example by adopting teaching practices in driving schools, public campaigns, and in addition by UI concepts, highlighting this issue.

Vehicle designers should carefully consider *halo-effects* and it must be prevented to give users the impression that systems perform better than they actually do. Theoretically, our results could suggest that systems should be designed with bad usability and low aesthetics to reduce the chance of overtrust. Yet, it is clear that vehicle manufacturers aim for maximizing UX qualities to maintain competitiveness and enthuse customers for their products. This is also necessary to achieve broad acceptance/proliferation of driving automation on the market. Thus, they urgently need to take other methods into account to better communicate performance aspects to users. Manufacturers of driving automation systems should immediately include solutions that have already been suggested to approach the problem – such as making their systems transparent for the users by communicating system decisions [436], [46, 40], and uncertainties [440, 96], [36], or behavioral measures to avoid misuse (such as preventing automation from being enabled in environments it was not designed for).
Automation performance and possible imperfection need to be made accessible for users. Only if they can deal with it, safe and pleasurable driving experiences can be facilitated.

UX and trust are impaired in all conditions of unreliable driving automation performance. Thus, primary objectives should be to improve automation, and such improvements should become integral part of the user interface. As the need for security seems to be most relevant for driving automation systems [103], the success of AVs will be dependent on the introduction of higher levels of automation where monitoring is no more needed. Recent studies conducted at real test tracks indicate that many drivers are not capable of intervening in upcoming crash situations despite eyes on the road and hands on the wheel [95]. A valid strategy could be to not offer vehicles operating at SAE level 2, which is of interest to the automotive companies, but unfortunately, difficult to achieve given the imperfections of the existing technology.
The driving automation performance is a prerequisite for a positive experience of driving automation. However, SAE L2 implies that automation performance is imperfect and users will have to deal with it. Thus, automation in this level should rather be sold as assistance for manual driving than as “Autopilot” (cf. Tesla) that raises wrong expectations.

5.1.5 Limitations

The presented work has some limitations. As differences between age groups concerning driving automation experience exist, which are in particular related to the need of security and trust [16], future research needs to address this issue by involving a more heterogeneous user group. Age, cultural background, and personality must be included to achieve more generalizable results (as suggested by [100]). Another limitation of our study is the simulation environment. Although many studies addressing trust are conducted with driving simulators [96, 450], [46, 40], their results must be interpreted cautiously. Also the IVIS implemented on a tablet computer was only an example, and since we could reveal strong influence of non-performance based aspects (such as aesthetics), other interfaces present in our simulator might have influenced results too. Future work needs to build up on our results and conduct studies in real AV prototypes and in authentic road conditions. Further, the impact of in-vehicle technology that supports non-driving related tasks [101] and of unobtrusive interfaces for trust calibration, like light designs [456, 457], should be looked at in detail.

5.1.6 Core Findings

In the following, the core findings of this study answering **RQ3.1** are highlighted:

- **UX and trust in automation correlate, thus, mutual influences have to be carefully regarded in design.**
- ***Halo-effects* impact the UX quality assessment and trust in the automated SAE L2 driving automation system.**
- **Designers always need to be aware that design decisions affect overall product perception that may lead to overtrust in SAE L2.**
- **System performance of a SAE L2 vehicle must be made accessible to drivers to ensure safe driving, the basis for a positive driving experience.**

5.2 Conditional Driving Automation (SAE L3)

SAE L3 is a further development step towards full driving automation. According to Marieke Martens, SAE L2 was only *"suitable for testing and research proposes [...] in order to verify readiness for SAE Level 3"* (p. 11), stated in [458]. Nevertheless, SAE L3 is still an intermediate level of automation as well.

Role of User	**Role of Driving Automation System**
Driver **(while the ADS is not engaged)::**	***Driving Automation System*** **(while not engaged)**:
Verifies operational readiness of the ADS-equipped vehicle	Permits engagement only within its ODD
Determines when engagement of ADS is appropriate	
Becomes the DDT fallback-ready user when the ADS is engaged DDT	
DDT fallback-ready user **(while the ADS is engaged)**	***ADS*** **(while engaged):**
Is receptive to a request to intervene and responds by performing DDT fallback in a timely manner	Performs the entire DDT
Is receptive to DDT performance-relevant system failures in vehicle systems and, upon occurrence, performs DDT fallback in a timely manner	Determines whether ODD limits are about to be exceeded and, if so, issues a timely request to intervene to the DDT fallback-ready user
Determines whether and how to achieve a minimal risk condition	Determines whether there is a DDT performance-relevant system failure of the ADS and, if so, issues a timely request to intervene to the DDT fallback-ready user
Becomes the driver upon requesting disengagement of the ADS Level	Disengages an appropriate time after issuing a request to intervene Disengages immediately upon driver request

Table 5.10: Roles of human driver and driving automation system in SAE L3.

Though in this development step users are allowed to use the additional time for NDRTs and are not demanded anymore to monitor the system, they still have the duty to be able to intervene at any time, if the vehicle requests to take-over (TOR, see Table 5.10).

Take-Over Requests (TORs, also referred to as *"request to intervene"* or *"handover"*) are defined in SAE J3016 [47] as:

> *"notification by an ADS to a fallback-ready user indicating that s/he should promptly perform the DDT fallback, which may entail resuming manual operation of the vehicle (i.e., becoming a driver again), or achieving a minimal risk condition if the vehicle is not drivable"* (p. 15).

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They belong to the earliest and most intensively researched topic in the domain of automated driving (see Section 3.2). The transfer of control back to the human driver demands to regain situation awareness quickly in order to resume operation of the dynamic driving task (DDT). It can occur in SAE levels 3 and 4 [82] and is a multi-step process involving both cognitive and physical efforts. Hence, especially in SAE L3, the transfer of control back from the machine (vehicle) to the human driver is both, time- and safety-critical. Hence, experts [458] raise doubts if a safe hand-over is even possible and demand research to determine a *"safe and effective process for re-engaging the driver back in the loop"* (p. 15). Also automotive industry strongly discusses this level of automation. While BMW anounced with Vision iNext able to drive level 3 to 5 [459], VOLVO annouced to skip SAE L3, trying directly to get SAE L4 on the roads [460]. However, most research and discussions on SAE L3 and the involved TORs solely addresses safety aspects, but ignore that these safety issues might also have an impact on UX.

Hence, this case study aims to investigate following research question:

- RQ3.2: How should a user interface be designed to affect UX of driving in SAE L3 in which users have to expect to take over control at any time?

Therefore, the proposed need-centered development approach is applied again. This section is partly based on following publication: [6].

5.2.1 Analysis

By applying the "DAUX Framework", to better understand the experience of SAE L3 and to identify which psychological needs are relevant to satisfy in SAE L3, related work in the area of human factors about conditional automation driving is analyzed and a focus group conducted.

5.2.1.1 Related Work

There are only few papers which regard experiential aspects of SAE L3, thus, UX or strong related concepts like usability, comfort, well-being and emotions. Contrarily, trust, which in literature is often related to UX (see Subsection 5.1.1.1), is much more focused. Also the above presented study in SAE L2 confirmed an inter-correlation between those two constructs (see Subsection 5.1.4, [5]). Further, in [461], participants associated felt enjoyment and relaxation in a *"functioning and trusted [SAE L3] system"* as *"measure of global trust"* (p. 173). Emotions are determining users' final positive or negative affect in a situation, thus UX, cf. the "DAUX Framework". Hence, insights from trust studies can be considered as a basis to understand experience related problems.

Rödel et al. [104], who used the constructs trust and fun to study UX, revealed that trust in automated driving decreases with increasing level of automation, however, trust in highly and fully driving automation is higher than in conditionally automated driving due to hand-over situations. They argue, users can neither keep control, nor fully relax. As we could show in SAE L2 (see Section 5.1, [5]) correlations between the trust construct and the psychological need of security, the detected decrease of trust in previous studies might be interpreted as a lacking fulfillment of the need of security. Thus, *"feeling uncertain and threatened by your circumstances"* [176, p. 339], namely, by the mere possibility of getting demanded to safely take back control at any time. Gold et al. [114] showed that trust and attitude towards the technology of SAE L3 rose after experiencing a drive in a driving simulator with take-over requests. This is also confirmed by Hergeth et al. [336], who showed a positive effect of familiarization with TORs on TOR performance and trust. Further, they revealed that familiarization supports trust calibration, as participants trust decreased in contrast to the group without experiencing and reading descriptions. Hence, prior affect future experiences, and also the pure imagination of a future event, based on knowledge, e.g., by a description, might affect the current experience. This emphasizes the temporality aspect of UX [165]. Hence, to understand how to design a UI which positively affects UX over time, we need to understand the different phases of a SAE L3 drive.

The taxonomy for hand-over and handbacks of Wintersberger et al. [387] thereby gives a guidance for events in a SAE L3 drive which need to considered in UI design, thus, is a basis for a user journey map 5.6. In a prior study [16], UX curves illustrate changes in participants' experience over time of a ride in a SAE L3 system. For the most scenarios (road condition) as well as user groups (younger and elderly users) the experience directly impaired after a take-over request and improved after the hand-overs. Thus, an assistant for hand-overs requires that drivers are able to take over control and also feel comfortable by this, even though, they have been engaged in NDRTs, thus, were out of the loop [462]. Thereby different aspects need to be regarded in the implementation [463]: the multitude of required warnings is dependent on the situation, e.g., what happens if the driver is not suspending the NDRT, the time should be not too short so that drivers can have a stress free take-over, but also not too long so that drivers might ignore a request [387]. Further, according to Yusof et al. [464] comfortable engagement in NDRTs is only possible if the automated driving style matches users' preferences.

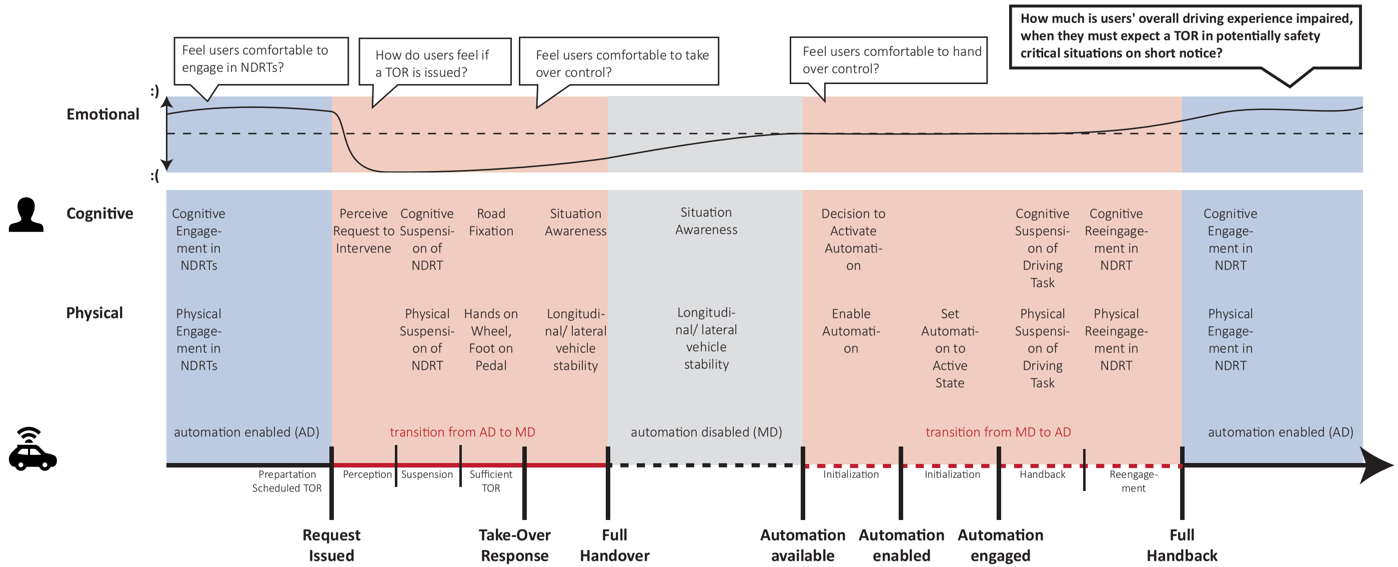


Figure 5.6: User journey map of a driving with a SAE L3 system, adapted from handover and handback taxonomy of Wintersberger et al. [387] and inspired by UX curves in [16].

Regarding the user journey of a SAE L3 drive from a UX perspective, following questions arise (see Figure 5.6): Are potential users willed to comfortably (re)engage in NDRTs and actually use this major benefit of automation? Do users feel comfortable with take- and hand-over control? How much is users' overall driving experience impaired, when they must expect a TOR in potentially safety critical situations on short notice? Hence, should SAE L3 be skipped as VOLVO proposes, not only due to safety but also experiential issues?

5.2.1.2 Focus Group

To get answers on these questions and to close this gap in driving automation research, we aim to understand which psychological needs are relevant to satisfy due to the technical restrictions of a SAE level 3 drive. Therefore, a focus group in combination with a driving simulator drive was conducted.

Study Setup The exploratory focus group study was conducted in the driving simulator lab, using a pure qualitative approach studying the deviation between expectation and reflection after experiencing a drive in the driving simulator.

Participants and Procedure. We invited 6 participants (age between 20 and 65 years with different backgrounds and technology affinity, however, all of them familiar with the topic of driving automation). To avoid confusion about the ability of automated driving in SAE L3, a video explaining the different levels of automation was presented in the introduction. Thereby, the focus on SAE L3 was clearly communicated. As positive feelings and the quality of UX are based on users' need fulfillment [176, 63, 178], [7], cf. "DAUX Framework", participants were asked to describe their expectations in SAE L3 driving one by one using the UX cards method [191, 103]. These cards represent the 7 basic psychological needs, identified as relevant for a positive experience with technology [176, 63]: *autonomy, competence, stimulation, security, popularity, relatedness* and *meaning.* Cards are translated from English to German to avoid language problems. After discussing general expectations, each participant experienced three (5 minute) drives with two TORs in the driving simulator in a highway scenario with moderate traffic, once without an NDRT, once while reading a magazine, and once while watching a video on a tablet PC. Afterwards, we again employed the UX cards method in an open discussion between participants. Statements were noted on post-its and located on a pin-wall with the printed UX Cards. In the very end of the session, participants were asked to score all needs from totally fulfilled to to totally not fulfilled with voting dots on the pin-wall and to agree on the most important four needs (see Figure 5.7).

Results Insights from the focus groups are summarized in statements from participants' expectations before and reflections after really experiencing a driving simulator drive with SAE L3.

Expectations. Before the drives, participants were mostly excited about automated driving systems and seemed to overestimate their capabilities. They especially expected the need for *autonomy* –*"feeling like you are the cause of your own actions rather than feeling that external forces or pressure are the cause of your action"* [176, p. 339] – to be satisfied as they would have the free choice of engaging in arbitrary NDRTs: *"If I can do what I want to do, because the car is driving on his own, then I feel independent"* (P4). This was accompanied by expectations of feeling *competent*, *stimulated* and doing something *meaningful*. Participants emphasized to engage in more *"useful and exciting"* activities than driving. Their expectations in the need of *security* was diverse, while some expressed to be supported by the option to take-over any time (related to the need of *autonomy*), others expected to feel insecure because of potential system failures and not being informed at all or too late for being able to intervene on time. The need of relatedness was concordantly identified as irrelevant for the driving experience, however, probably affected by a NDRT: *"if there are people in the car you can chat with, or if I am on my smart-phone, or do a face-time call"* (P5). The need of popularity was also rated as rather irrelevant, only affected by the awareness to be *"one of the first persons with an autonomous vehicle driving on the factory premises"* (P4). The mere possibility of TORs at any time was not mentioned as possible experience quality defect of a conditionally automated vehicle.

Reflections. Participants' expectations changed after experiencing SAE L3 in the driving simulator. While some felt relatively secure, others especially claimed the need of *security* not to be satisfied. They expressed the permanent fear of upcoming TORs. This made them feel less *autonomous*, and they expressed to feel dependent on the vehicle – in case TOR is issued, there is no option to ignore it: *"Somehow, you are waiting all the time for a TOR, and cannot really relax [...]. You never know, when the next is coming"* (P2). This need was rated by most participants as not fulfilled. Further, performing complex cognitive tasks in an efficient and effective way seemed impossible to them, thus, they would not feel *competent* while engaging in NDRTs, as they could not concentrate: *"I was never fully concentrated, always a bit distracted. Often, I had to restart reading as I always had a look if I had to intervene."* (P3) Another participants stated:

> *"It felt more like a loss of competency, the efficiency was not increased as the the situation was unusual and would demand consistent availability. 'Sprinkling' is rather possible than effectively working"* (P6)

Hence, as another participant commented, competence can be experienced but

Figure 5.7: Participants' voting on UX cards [191]. Autonomy, security, competence, and stimulation are selected as the most important.

only to a limited extent. Handling the TOR safely might support their need of *competence*, but when being interrupted while engaged in NDRTs, safe TOR responses were hard to imagine. However, participants still think, pleasure and stimulation can be created by the possibility to engage in NDRTs (like watching YouTube):

> *"You get more leisure time which, however, you can only use for unimportant things, because you cannot concentrate per 100% on it. Watching a movie is better than reading [...]"* (P3)

Nothing really *meaningful* can be done, thus, the need of *meaning* was identified as non-relevant, as well as popularity and relatedness.

After the discussions, all participants agreed: to create a positive experience the need of *security, autonomy, competence* and *stimulation* are the most relevant needs to be satisfied in SAE L3 driving (see Figure 5.7).

5.2.1.3 Implications for Design

Of course this exploratory study, discussing participants expectations and reflections after a very short drive in the simulator can still only be regarded as first impression of how a real drive with a SAE L3 vehicle will be. The scenario of five minutes included three TORs, what might not always be the case.

However, we argue, as user you never know, a TOR can occur at any time, also three times within five minutes. Hence, results give first insights into how the technical restrictions in SAE L3 in the context of highway driving impact users' experience.

The exploratory study confirmed results and interpretation of related work (e.g., [104]). The overall experience seems to be affected by the mere possibility of a TOR, thus, the needs for *security, autonomy* and *competence* are identified as crucial for a positive experience in SAE L3. Thereby, comfortable and efficient engaging in NDRTs is doubted. Nevertheless, participants hoped to be *stimulated* by NDRTs, thus having *"joy while driving"* [94, p. 165]. Thus, we hypothesized the needs of security, autonomy, competence and stimulation as the most critical to satisfy. These have to be specifically regarded in UX design.

5.2.2 Design

In contrast to the Study in SAE L2, which investigated the general impact of a UI on driving automation UX, we aim to develop a system to satisfy relevant needs in SAE L3. Therefore, we conducted an ideation workshop. Combining first ideas with results from academic studies to substantiate design decision, we derived a concept called ATHENA. The process and the UI are described in the following section.

5.2.2.1 Ideation Workshop

To explore the design space, how a user interface can positively affect a SAE L3 driving experience, we used the "How-Might-We" questions - method. Instead of a Point of view (POV), which is an actionable problem statement based on insights into users and their needs, also described as *"micro-theory"* [465, p. 4], we utilized the identified psychological needs in combination with the user journey (see Figure 5.6) to formulate questions which open design opportunities. Thereby, we aimed to ideate for the whole journey, addressing the temporality aspect of UX.

In total, 5 PhD (Automotive HCI) and 2 undergraduate students (UX design program) participated in the brainstorming workshop. After a short summary of the results of the analysis and introduction into brainstorming rules, the HMWs of each need and user journey phase were successively presented. Then, applying the brainwriting-technique for respectively 5 minutes, participants created ideas on their own. Afterwards, everybody presented and allocated their

How Might We	Autonomy	Security	Competence	Simulation
...give drivers while automated driving the feeling that they...	...choose their activities on their own and self-determined?	...safe from dangers and uncertainties?	...to master challenges and solve problems?	...have fun?
	autonomy of decision	transparency	transparency	gamification
...give drivers at the moment of perceiving a issued TOR the feeling that they...	...are not forced and other-directed?	...safe from dangers and uncertainties?	...to master challenges and solve problems?	...have fun?
	early information	reassurance	motivation	gamification
...give drivers while suspending their NDRT the feeling that they...	...are not forced and other directed?	...safe from dangers and uncertainties?	...to master challenges and solve problems?	...have fun?
	autonomy of decision	NDRT definition	-	-
...give drivers while taking up the driving position the feeling that they...	...are not forced and other-directed?	...safe from dangers and uncertainties?	...to master challenges and solve problems?	...have fun?
	well adapted interior	well adapted interior	well adapted interior	-
...give drivers while guiding and controlling the vehicle manually the feeling that they...	...are not forced and other-directed?	...safe from dangers and uncertainties?	...to master challenges and solve problems?	...have fun?
	autonomy of decision	driver assistance	motivation	*"pleasure of driving"*

Table 5.11: "How might we"-questions and identified idea clusters of the ideation workshop.

post-its on a pin board to be clustered in the end of the workshop. Amongst others, clusters involve ideas about ensuring users' autonomy of decision, e.g., drivers should at any time be able to decide if they want to drive automated or manually, want to work or be entertained. Further, the system should be transparent about system performance and should have a calming effect to satisfy the need for security. Users' need of competence and stimulation can be

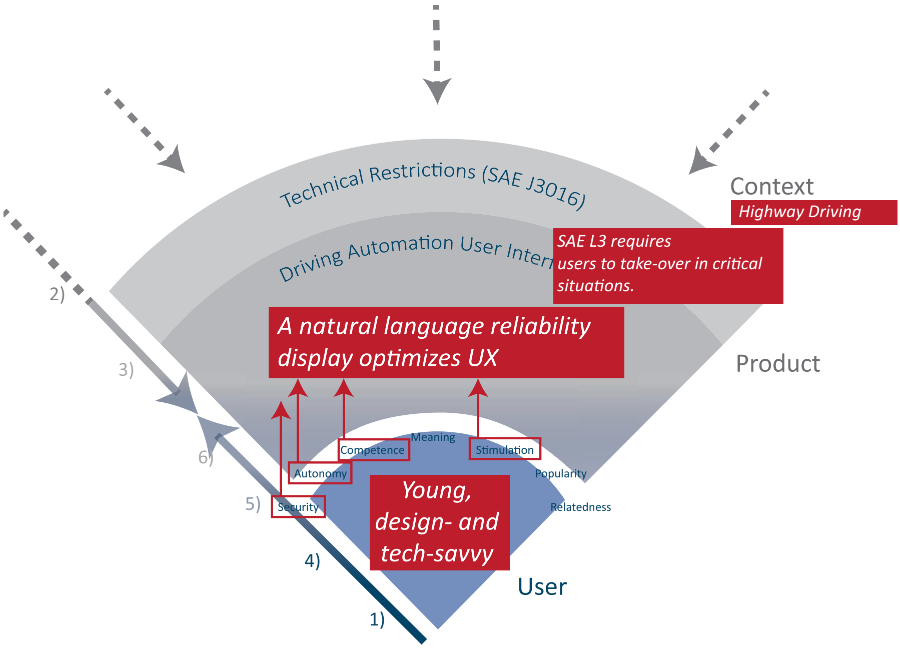


Figure 5.8: Application of the need-centered approach with the "DAUX Framework" in SAE L3 for Hypotheses/ Concept Development.

satisfied by motivation and gamification. Thereby, a often mentioned concept was the implementation of an avatar, supporting the user during the different phases of a SAE L3 drive (see Table 5.11).

5.2.2.2 ATHENA UI

Utilizing the identified clusters of the ideation workshop as inspiration, we finally developed ATHENA, a natural language reliability display [6], see Figure 5.8. It aims to support the user during the drive in the different phases of a SAE L3 drive [387] by addressing the relevant psychological needs of autonomy, security, competence and stimulation. Design decisions are based on relevant related work in the field.

Several studies have already proven positive effects of reliability (uncertainty) displays on driving and TOR performance, trust calibration, and effective NDRT engagement [440, 360, 421], [36], which is expected to increase user experience [96]. Thereby, users are dynamically informed about the current system performance and the likelihood of a system failure, a possible take-over request

or required driver engagement [97]. By the increased system transparency we aim to satisfy the needs of *security*, because users don't feel uncertain as they are informed, and *competence*, as they can regulate their concentration, especially during enabled automation.
We decided for an auditory reliability display, thus, users are not required to move their focus from a NDRT to a visual display [96]. According to the results from Naujoks et al. [466], in contrast to alerts, speech improves the cooperation between automation and humans. In less critical situation, in which the vehicle is still able to manage the situation without intervention, drivers less often suspend the engagement in NDRTs. As the results of our analysis showed a link between effective NDRTs engagement and the satisfaction of the need of competence, as well as Kunze et al. [96] we expect positive effects on UX. But also drivers' autonomy of decision is ought to be supported, e.g., if they feel confident to further engage in NDRT or if they prefer monitoring or intervene. Further, Nees et al. [467] revealed that speech alerts result in better memory for alerted events, which supports the claim of Alvarez et al. [468] who stated that voice user interfaces have a high effectiveness with low cognitive workload, which is especially useful for situations in which users' cognitive workload is already high. This is in coherence with Hester et al. [469] who showed that with task-relevant voice alerts, like *"Driver Take Over"* before a possible crash, more collisions were avoided in contrast to other alert systems.
Moreover, we utilize the already proven positive effects of anthropomorphic interfaces. Studies could show increased trust and acceptance, improved usability, higher relaxation and perceived sympathy [438, 470, 471]. Further, Large et al. [472] could show an improved journey experience regarding pleasure and sense of dominance (or control). Moreover, they interpret participants' lower arousal as more relaxation and assessed it as important positive effect for the driving context, as drivers in an automated system (SAE L2/3) are required to be able to take over control at any time. Drivers' reassurance aims to satisfy the need of security.
Nevertheless, regarding driving context and user preferences in the design of anthropomorphic agents it is essential to achieve the listed positive effects [473]. According to Waytz et al. [438] anthropomorphism is not evoked by superficial but human properties like character, gender and name. Thereby, acceptance of voice systems is higher if personality and mood of the agent are adapted to the user. Thereby, also positive effects on safety could be revealed [474, 475], however, to reduce cognitive load in saftey critical situations Braun et al. [475] recommend to adapt the voice to the driving context. Commands should be in critical more clinical than in less critical situations. Gender of the voice is highly debated, e.g., concerning of a possible gender bias, however studies showed a slight preference towards female agents [476, 477]. All these insights in mind, ATHENA was designed and developed.

As a name is important [438], we decided for ATHENA after the Greek goddess of wisdom and Odysseus' protectress by accompanying him on his journey

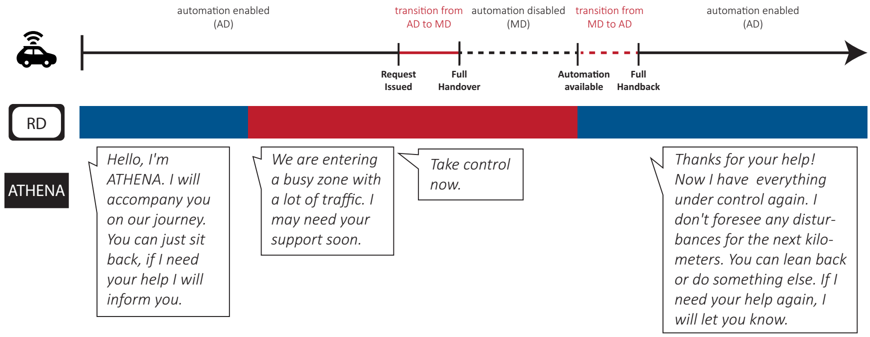


Figure 5.9: User journey map of a driving with a SAE L3 system supported by ATHENA (example statements translated from German) or visual Reliability Display (RD) in different phases of automation reliance.

home. Analogously, ATHENA should also provide support to a driver's journey. The character is designed to be trustworthy and friendly but still professional, patient and supportive. ATHENA is implemented as reliability/uncertainty display, informing users whether or not an upcoming intervention is likely, however, ATHENA does not only dynamically communicate the current level of automation reliance or required driver engagement [97]. The interface also tries to make drivers more relaxed in phases of high automation performance (reassurance and autonomy of decision - supporting the need of *security* and *autonomy*), gives early information about system reliability (transparency - supporting the need of security), clear instructions for the hand-over and hand-back, and provides encouraging feedback after experiencing TOR (motivation - supporting the need of *competence*). E.g., statements like *"I may need your help" or "thanks for your help"* are formulated to empower the driver. Further, ATHENA's character changes during the different phases. During automated driving (less safety critical), ATHENA behaves more like a friend to increase trust and to support the satisfaction of the needs *security, autonomy* and *stimulation*. In phases with low reliability and in TORs situations (more safety critical), ATHENA represents a default character (friendly, helpful) to reduce users' cognitive workload and makes them concentrate on the road environment [475]. We defined a set of statements (see Figure 5.9 for examples) and hired a professional actress to record them.
The evaluation of ATHENA (to optimize UX of conditional driving automation in the context of highway driving) is described below.

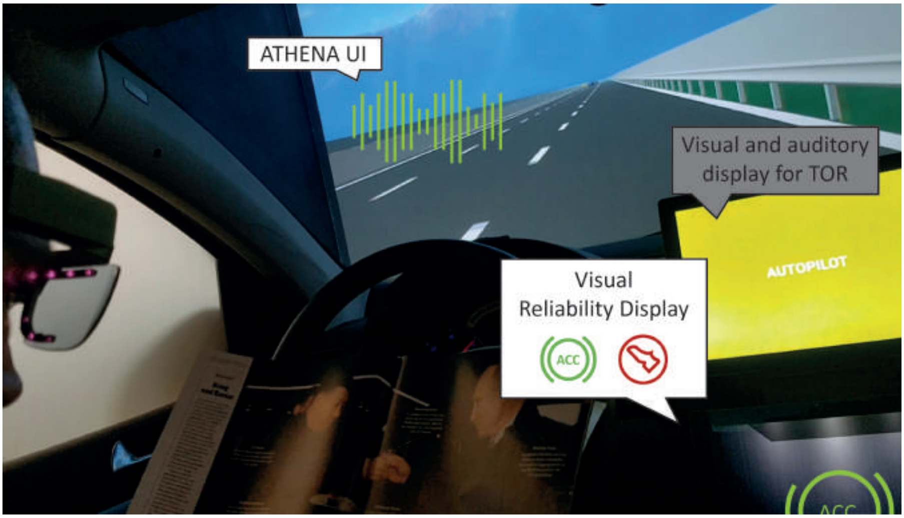


Figure 5.10: Study setup showing the driving scenario and interfaces in the car.

5.2.3 Evaluation of "ATHENA"

To evaluate the impact of ATHENA on UX in SAE L3 we conducted a driving simulator study aiming to reveal differences between the conditions concerning need-fulfillment, affect, product perception and driving performance in the context of highway driving by applying the "DAUX Framework". We wanted to investigate the following hypothesis:

- H3.2: A natural language reliability display affects SAE L3 driving automation UX in which users have to expect to take-over control at any time.

5.2.3.1 Study Setup

The experiment was again conducted in a high-fidelity driving simulator (remodeled VW Golf on hexapod platform) and two tablet PC installed on top of the center console, one to issue take-over requests and the other for the reliability display (see Figure 5.10). We applied a full factorial within-subject design to compare the ATHENA UI with a visual Reliability Display (visual RD), a simple reliability display on an IVIS (red icon = low reliability, green icon = high reliability), and a baseline (no UI), i.e., SAE L3 without extra support by a UI.

Driving Simulation We simulated an AV at SAE level 3 (i.e., combination of longitudinal and lateral control) driving on a 2-lane highway using IPG CarMaker. As we applied a within-subject design three different scenarios were implemented. Each is 26 km long, lasted with an average speed of 130km/h from 10-12 minutes and contained three TORs with different levels of urgency: 1) different road markings, 2) closed lane because of a construction side which was announced by traffic signs (ends after 1 km), and 3) emergency break of a vehicle in front with 7 seconds time to collision. The emergency scenario forced drivers to break before they were able to change the lane. All scenarios contained a critical sector, low reliability indicated as red icon in the display or by the critical statements of ATHENA, however, a take-over request was not issued. The row of the occurring TORs was randomized in the different scenarios to avoid learning effects.

Participants and Procedure In total 18 participants (12 female, 6 male), aged between 19 and 65 (M_{age}= 25.11, SD_{age} = 10.35) years, voluntarily participated in the experiment. After assessing demographics and a short test-drive to get familiar with the driving simulator, all participants had to complete the 12-minute trip in each condition (randomized order). During the drives they could freely choose (but were not forced) to engage in different NDRTs (magazines, YouTube on tablet PC, making use of the private smartphone). After each drive a post-test questionnaire and interview were conducted (see Figure 5.11).

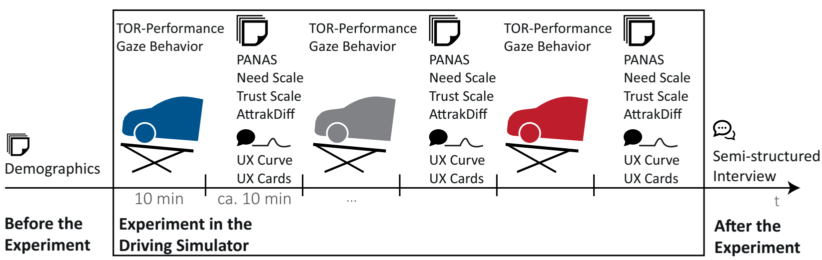


Figure 5.11: Study procedure.

Data Collection To be able to evaluate ATHENA, we applied the "DAUX Framework" to derive methods. We triangulated a set of experience-, product- and behavioral-oriented measures according to the "DAUX Framework" as emphasized in the following (see Figure 5.12).

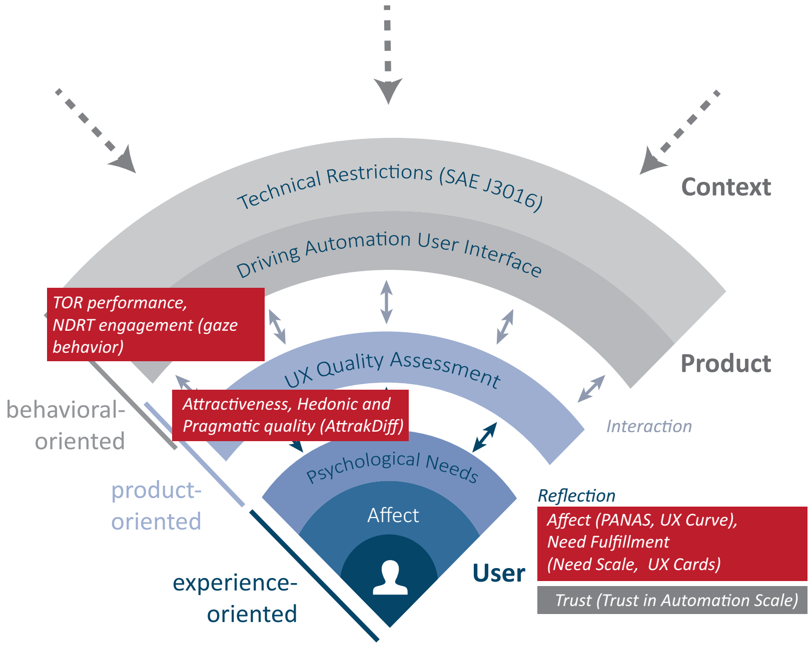


Figure 5.12: Application of the need-centered approach with the "DAUX Framework" in SAE L3 for Evaluation.

Experience-Oriented Aspects. We used the short version of the Positive (PA) and Negative Affect (NA) Scale (PANAS) [158] to gain insights into participants affect associated with driving experiences using a 7-Point Likert Scale. According to Pearson's correlation coefficient PA and NA did not correlate ($r<.23$) and reliability of both subscales was acceptable ($\alpha>.70$), see Table 5.12.

Further, according to the "DAUX Framework", our aim was to evaluate which psychological needs are fulfilled in the different conditions (ATHENA, no UI, visual RD) and reveal potential correlations with affect and product-quality assessment. Therefore, we utilized the need scale from Sheldon [176] as described by [63] using also a 7-Point Likert scale. Also here, reliability of all subscales was acceptable ($\alpha > .70$, see Table 5.12). Only security showed a bad reliability for the visual RD. Hence, items (*"Glad that I have a comfortable set of routines and habits"* (SIC1) and *"Safe from threats and uncertainties"* (SIC2) are not averaged. Intercorrelation between the subscales across all conditions ranged from $r=.28$ to $r=.81$. Especially need for autonomy and security (SIC1) correlated highly in all conditions.

Dep. Variable	Items	Cronbach's α	Ref.
Experience-oriented Aspects:			
Affect			
Posistive (PA)	5	.70	[158]
Negative (NA)	5	.77	[158]
Needs			
Autonomy (AUT)	3	.81	[176, 63]
Competence (COM)	3	.81	[176, 63]
Relatedness (REL)	3	.89	[176, 63]
Meaning (MEAN)	2	.81	[176, 63]
Stimulation (STI)	3	.85	[176, 63]
Security (SEC)	2	.46*	[176, 63]
Trust			
Distrust (DT)	5	.88	[354]
Trust (T)	7	.92	[354]
Product-oriented Aspects:			
UX Qualities			
Attractiveness (ATT)	2	.74	[206, 216]
Pragmatic Q, (PQ)	4	.81	[206, 216]
Hedonic Q. (HQ)	4	.74	[206, 216]

Table 5.12: Summary of self-rating scales employed.

Reliability of the subscales trust and distrust collected by the Trust Scale [354] was good ($\alpha > .70$, see Table 5.12) but show strong correlation (r>-.88).

Further, participants were asked to draw their experience and describe how it changed over time (UX curve method [233]). This was combined with the UX cards methods [191]. Participants should reason why they think the experience improved or impaired at a certain point of the drive using the psychological needs described on the UX cards. During explaining their reasons, relevant needs (fulfilled or not) and the timing of the journey were noted.

Product-Oriented Aspects. As product-oriented measurement we included the AttrakDiff [216] questionnaire. Since for all subscales Cronbach's α resulted in acceptable values (> .70, see Table 5.12), we calculated mean scale values. All UX qualities were intercorrelated, ranging from r=.412 to r=.880 across all conditions. HQ and PQ showed the least (r>.25), only significant in the condition with no UI (r=.58), and PQ and ATT highest intercorrelations (r>.55), also highest value in the condition with no UI (r=.75).

Also the post-test interview aimed to reveal qualitative insights about different aspects of users' product assessment.

Behavioral-Oriented Aspects. To investigate participants' behavior, we calculated participants TOR performance, calculating the response time between issued TOR and first manual driving action (2 degree change of the steering wheel or 5% change in brake/acceleration pedal actuation [387]).
Further, we collected gaze-behavior using a head-mounted eye-tracker (Pupil Labs 120 Hz Binocular). In post-processing we calculated participants' aver-

age gaze duration, gaze number and percentage on an area of interest (road, IVIS or NDRT). Further, we calculated the total average duration on a certain NDRTs differentiating between smartphone, newspaper, tablet and other activities. However, due to technical problems, only 7/18 full data sets were available for analysis.

5.2.3.2 Results

In the following we present a detailed analysis of the collected data.

Experience-Oriented Aspects The following section describes results of quantitative and qualitative methods regarding experience-oriented aspects.

Questionnaires. Since data was normally distributed (Shapiro-Wik's, $p > .05$) and only marginal outliers were detected, parametric tests were applied for experience-oriented questionnaire data. We performed one-way repeated measures ANOVA (all results with $p < .05$ are reported as statistical significant) with the supporting UI as independent within-subject variable. Concerning multivariate test statistics, we utilized Wilks-Lambda. The assumption of sphericity ($p > .05$) was met for all dependent variables.

Looking at participants' affect with the PANAS questionnaire [158], the multivariate test reveals a significant effect of a certain system on positive and negative affect, $F(4, 66) = 2.87$, $p = .030$, partial $\eta^2 = 0.15$. Regarding univariate tests, we see that there is a significant difference for the negative affect, $F(2, 34) = 6.12$, $p = .005$, partial $\eta^2 = 0.27$. ATHENA created significantly less negative affect than the condition with no UI (p=.002). No significant differences could be revealed between ATHENA and the visual RD, and the visual RD and the no UI. Further, there was also no significant effect for the positive affect (see Table 5.13).

				95% Confidence Interval	
Dep. Variable	**Supporting UI**	M	SD	lower	upper
PA	ATHENA	**2.97***	1.14	2.40	3.53
	visual RD	2.87	0.97	2.38	3.35
	no UI	**2.76***	1.01	2.26	3.26
NA	ATHENA	1.64	1.23	1.03	2.26
	visual RD	2.10	1.06	1.57	2.63
	no UI	2.54	1.47	1.82	3.27

Table 5.13: Values of participants' affect. *Note: Significances between variables are indicated by *.*

The multivariate test of participants' need fulfillment using Sheldon's needs scale [176] reveals that there is a significant difference between the used sys-

tems, $F(12, 58) = 2.40$, $p = .068$, partial η^2=0.2.72. However, analyzing univariate tests, a significant effect can be revealed for the need of security, $F(2, 34) = 5.46$, $p = .009$, partial η^2=0.24. Driving with ATHENA fulfilled the need for security significantly more than driving in an AV with no UI (p=.010). The same effect was also visible for the visual RD (p=.046). Further, although the need for competence is most fulfilled for ATHENA, $F(2, 34) = 2.46$, $p = .101$, partial η^2=0.126, no significant effects for competence, as well as for autonomy and stimulation were identified.
As the reliability of the subscale for security was weak for the visual RD condition, we run an additional analysis separating the two items SEC1 and SEC2. The multivariate test reveals also here no significant difference, $F(14, 58) = 1.57$, $p = .118$, partial η^2=0.2.72. Further, univariate tests only reveal a significant effect for SEC2 $F(2, 34) = 4.12$, $p = .025$, partial η^2=0.24. During driving with ATHENA participants felt more *"safe from threats and uncertainties"* than in the AV with no UI (p=.028). The visual RD was not able to create this effect.

				95% Confidence Interval	
Dep. Variable	**Supporting UI**	M	SD	lower	upper
AUT	ATHENA	2.60	1.57	1.81	3.76
	visual RD	2.63	1.24	2.01	3.25
	no UI	2.57	1.40	1.87	3.27
COM	ATHENA	3.54	1.51	2.79	4.29
	visual RD	2.99	1.23	2.38	3.61
	no UI	2.82	1.19	2.23	3.42
STI	ATHENA	3.36	1.43	2.65	4.07
	visual RD	3.43	1.43	2.72	4.12
	no UI	3.03	1.62	2.23	3.84
SEC	ATHENA	**3.22***	1.51	2.47	3.97
	visual RD	**2.92***	1.22	2.31	3.52
	no UI	**2.42***	1.57	1.63	3.20
↪SEC1	ATHENA	3.28	1.87	2.35	4.21
	visual RD	3.00	1.50	2.26	3.74
	no UI	2.78	1.57	1.87	3.74
↪SEC2	ATHENA	**3.17***	1.69	2.33	4.01
	visual RD	2.83	1.86	1.91	3.76
	no UI	**2.06***	1.77	1.18	2.93

Table 5.14: Values of participants' psychological need fulfillment. *Note: Significances between variables are indicated by *.*

Moreover, looking at the results from the Automation Trust Scale [354], the multivariate test reveals a significant difference, $F(4, 66) = 3.20$, $p = .018$, partial η^2=0.16. According to the univariate tests, we can report significant differences for trust ($F(2, 34) = 6.87$, $p = .003$, partial η^2=0.29) and distrust ($F(2, 34) = 4.53$, $p = .018$, partial η^2=0.21). Post-hoc analysis shows that participants' trust is significantly higher with ATHENA than with visual RD (p=.004), and no UI (p=.003). Between visual RD and no UI, no significant effect is visible. Distrust is significantly lower for ATHENA than at the condition with no UI (p=.006).

				95% Confidence Interval	
Dep. Variable	**Supporting UI**	M	SD	lower	upper
T	ATHENA	**3.74***	1.23	3.13	4.35
	visual RD	**3.25***	1.13	2.69	3.81
	no UI	**2.98***	1.47	2.25	3.71
DT	ATHENA	**1.92***	1.27	1.28	2.55
	visual RD	2.44	1.31	1.79	3.10
	no UI	**2.68***	1.59	1.89	3.47

Table 5.15: Values of participants' trust. *Note: Significances between variables are indicated by *.*

UX Curves. Applying the UX Curve [233] in combination with the UX Card [191] method also revealed differences between the three conditions, see Figure 5.13. Driving with ATHENA (n=11) or the visual RD (n=10) was sketched by more participants as consistently positive experience than the experience with no supportive UI (n=7). In this condition more changes of the experience between the positive and the negative area are sketched (n=9; in contrast to respectively 7 for ATHENA and the visual RD). Moreover, as already revealed in [16], TORs led to abrupt gradual reduction of the journey experience. This effect is more distinct in the condition of the visual RD and with no supportive UI, as the consolidated curves in Figure 5.13 show. Curves extend more into the negative area. A consistently negative experience over time is only reported once respectively for the AV with no UI and the visual RD, but not for ATHENA.

In post-processing, mentioned psychological needs and participants' statements while sketching the UX Curve were allocated into the user journey of Figure 5.6, see Figure 5.14. This facilitates the comparison of the impact of the supporting systems on the user experience of a journey over time.

During phases of enabled automation, more participants reported the need of security to be fulfilled with ATHENA than with the visual RD.

> *"I felt much securer than on the other journeys, there was no need to concentrate on a display. The voice made me feel securer because I got continuously feedback when something could happen. This increased my trust [...]. You can do something different but nevertheless you are aware of everything around you."* (P1, ATHENA)

Fewer participants mentioned this need in the condition of ATHENA and the visual RD as not fulfilled than in the condition with no UI. Here, especially at the beginning of the journey, security is stated to be not fulfilled, but gets more and more irrelevant over time. For the visual UI the need of autonomy is more relevant, which is debated controversially (almost same share of mentions of being fulfilled and not fulfilled): e.g., *"by the feedback of the UI you feel less dependent, because you know what will happen."* (P9, ATHENA) in contrast

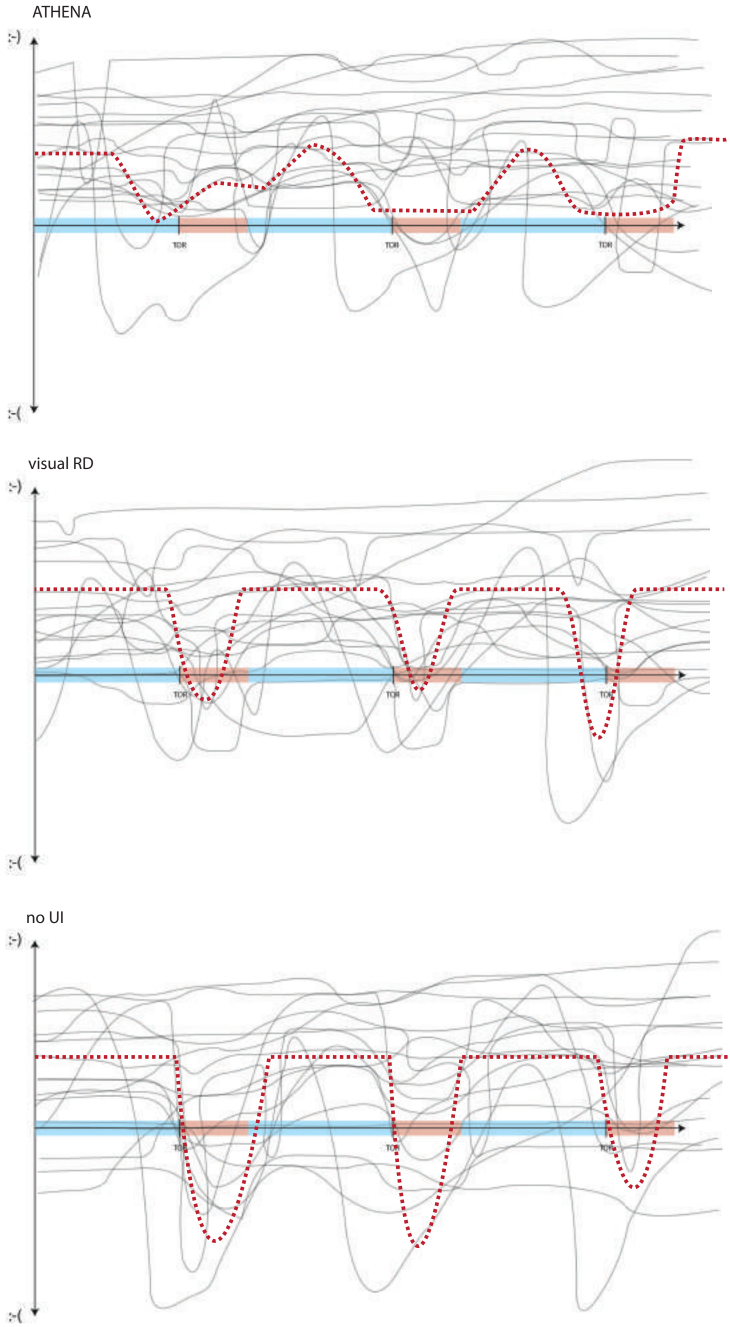


Figure 5.13: Participants' UX Curves and estimated trendlines of the different conditions. Less curves of ATHENA reach into the negative area, however, experiences get already impaired before the TOR.

TOR 1		Automation enabled			TOR Preparation			Request Issused			Automation disabled			Handback		
		ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI
Fulfilled	SEC	7	1	4				5	1		2		4			
	AUT	3	4	1							3	1	1			
	COM	8	5	2							7	3	3			
	STI	6	5	2												
	REL	1	1													
Not Fulfilled	SEC	-3	-3	-5	-1	-2		-3	-5	-12				-1		
	AUT	-5	-4	-2				-2	-1	-3						
	COM	-2	-3	-5	-1					-6		-1		-1		
	STI		-2	-1						-3						
	REL															

...

TOR 2		Automation enabled			TOR Preparation			TOR Issused			Automation disabled			Handback		
		ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI
Fulfilled	SEC	7	2	5				5					1			
	AUT	3	5	2							5	1	1			
	COM	7	5	5							2	3	1			
	STI	6	5	5				1	1							
	REL	1	1													
Not Fulfilled	SEC		-2	-2	-3			-1	-6	-11	-2					
	AUT	-7	-4	-2				-2	-1	-1				-2		
	COM	-2	-4	-5					-2	-4		-1				
	STI	-1	-2	-3	1					-1						
	REL															

...

TOR3		Automation enabled			TOR Preparation			TOR Issused			Automation disabled		
		ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI	ATHENA	v. RD	no UI
Fulfilled	SEC	6		5				2				1	3
	AUT	3	5	2							2	1	
	COM	8	4	5							4	1	1
	STI	5	4	5								1	
	REL	1	1										
Not Fulfilled	SEC	-2	-2		-1				-7	-12	-1		-1
	AUT	-5	-3						-2	-3			
	COM	-1	-3						-1	-4			
	STI		-2							-1			
	REL												

Figure 5.14: Number of mentioned psychological needs with the UX Cards and UX Curve method in the different phases of the user journey of a SAE L3 drive.

to *"I felt restricted, because I had the feeling only to be able to intervene if the vehicle wants me to"* (P17, ATHENA). For the baseline condition with no UI, fulfillment of autonomy increased with each phase of enabled automation. With ATHENA, the need of autonomy was continuously mentioned as rather not fulfilled than fulfilled. E.g., one participant stated:

> *"It should only tell me when something happens and when not. I don't want to chat. While manually driving there was no problem, but she was talking with me like to a child. You get infantilized, what impacts felt autonomy and competence"* (P8, ATHENA).

Another participant stated:

> *"You totally rely on the announcement, especially while driving automated you only wait for a new announcement, you are totally dependent on the system"* (P11, ATHENA).

Or P15 said: *"You can do other stuff, however, you always have in your mind that you might to take over soon"*.
Contrarily, the need of competence and stimulation were more often mentioned

as fulfilled with ATHENA than with visual RD, in which there were also more positive than negative mentions, and with the baseline condition. In this, again a positive development over time is visible, positive mentions increase and negative ones decrease.
In the TOR preparation phase statements to need fulfillment only exist for ATHENA (security and competence), and at the beginning of the journey also for the visual RD: *"I was always warned very early and was therefore unsure because I did not realize why"* (P14, ATHENA).

> *"When the symbol came I was super alarmed and immediately concentrated on the road again, that was like driving myself. Here, I had a stronger feeling that I had to be careful."*(P7, visual RD).

This changed in the phase when the take-over request was issued. In the baseline conditions, participants were not warned in advance. Hence, strong differences are visible, especially between the baseline with no UI and ATHENA. At the drive with the AV with no UI, at each TOR feeling insecure was bemoaned by a high number of participants, what comes with a decreased fulfillment of other needs, especially competence. Participant P17 (no UI) described his first take-over:

> *"The TOR went super fast, I had to dodge really ugly. That was actually too fast to put something away that you had in your hands. I had leafed through the magazine and then had no idea what was going on around me when the takeover came. The problem with the first takeover was that everything went too fast. I made a slight detour, so my competence was somewhat limited. Security was shit because I didn't see where I was going and it all went too fast. I made myself completely unpopular with one of them because I almost drove him in."*

Contrarily, ATHENA has fewer negative and even positive mentions on the need of security during TORs, e.g.:

> *"Also during the take over I felt very safe. I already had my hands on the steering wheel before I had to, so that I was ready right away. This time I wasn't scared either."* (P1, ATHENA).

Not being scared is also mentioned by further participants, what is in coherence with the positive mentions on competence during disabled automation: *"The takeover did not come abruptly, I had the feeling that I could manage the situation well because I could already prepare myself "* (P16, ATHENA). Further participants stated: *"Voice feedback after successful take-over also has a positive effect on competence"* (P3, ATHENA), *"Competence was higher because the system said when it needed me and when it didn't"* (P5, ATHENA). For the visual RD, security and competence are better rated than with no UI, e.g., *"as one is prepared"* (P13, visual RD) here as well, but still criticized: *"security was okay, but if I had held the newspaper differently, then I would not have seen* *the warning and then the need would not be fulfilled either"* (P18, visual RD), *"competence was not satisfied, one really only saw by chance and was suddenly confronted with the fact that one had to do something"* (P11 visual RD). In the phase of the hand-back, only single participants bemoaned the fulfillment of security, autonomy and competence with ATHENA. Participants criticized ATHENA's *"well-done"* statement:

> *"It would be nice to change the voice, because it was very sweet. A bit like I was a child. 'You have done well', hey, I drove a car, nobody has to tell me that I did well. I would prefer a short technical announcement that the car continues to drive automatically"* (P17, ATHENA).

Although all 7 psychological needs were presented to the participants via UX Cards, most mentions are coherent with the identified needs from the focus group: security, autonomy, competence and stimulation. However, also relatedness was mentioned. On the one hand, participants saw this need fulfilled by NDRTs like messaging with the smartphone in phases of enabled automation. On the other hand, relatedness towards ATHENA as anthropomorphic UI was perceived as positive: *"You feel connected to the voice, she praises you too, that was quite nice"* (P16, ATHENA). Further, as Figure 5.14 also shows, there is a positive development over time. Especially, except for the issued TOR, the fulfillment of the need of security improved in all condition:

> *"Security has become better and better over time, because then you could estimate how much time you have between the first warning and the actual takeover"* (P16, ATHENA).

For the visual RD and no UI, participants stated: *"Towards the end I felt more secure because I was then familiar with the system"* (P14, visual RD), and *"At the beginning I was very insecure, but in the end I was positive. If you do that more often, it will get better anyway"* (P13, no UI).

Product-Oriented Aspects The following section describes results of quantitative and qualitative methods regarding product-oriented aspects.

Questionnaires. Since data was normally distributed (Shapiro-Wik's, $p > .05$) and only marginal outliers were detected, parametric tests were applied for experience-oriented questionnaire data. We performed one-way repeated measures ANOVA (all results with $p < .05$ are reported as statistical significant) with the supporting UI as independent within-subject variable. Concerning multivariate test statistics, we utilized Wilks-Lambda. The assumption of sphericity ($p > .05$) was met for all dependent variables.

Regarding AttrakDiff [206], results of the multivariate test show that there is a significant difference in the product-quality assessment, $F(6, 64) = 2.40$, $p = .037$, partial η^2=0.18. Univariate tests reveal difference for all dependent variables: PQ ($F(2, 34) = 3.88$, $p = .030$, partial η^2=0.19), HQ ($F(2, 34) = 3.44$, $p = .044$, partial η^2=0.17) and ATT ($F(2, 34) = 3.93$, $p = .029$, partial η^2=0.17). Post-hoc analysis reveals that ATHENA has a better pragmatic quality (PQ) than the visual RD (p=.048) and the baseline system with no UI (p=.014). The assessment of the AV with no UI and visual RD do not differ significantly. Also the ATHENA's hedonic quality (HQ) is rated significantly better than the visual RD (p=.028), however, no significant differences between the AV with no UI (p=.156) and ATHENA as well as between no UI and visual RD could be revealed. The overall attractiveness is also highest for ATHENA. The assessment differs significantly from the AV with no UI (p=.015) but not from the visual RD (p=.120).

				95% Confidence Interval	
Dep. Variable	**Supporting UI**	M	SD	lower	upper
PQ	ATHENA	**3.94***	1.34	3.28	4.61
	visual RD	**3.22***	1.33	2.56	3.88
	no UI	**3.03***	1.31	2.38	3.68
HQ	ATHENA	**3.39***	1.00	2.89	3.86
	visual RD	**2.97***	0.90	2.52	3.42
	no UI	3.13	0.84	2.71	3.54
ATT	ATHENA	**3.64***	1.28	3.00	4.28
	visual RD	3.28	1.11	2.72	3.83
	no UI	**3.00***	1.38	2.31	3.69

Table 5.16: Values of participants' UX quality assessment. *Note: Significances between variables are indicated by *.*

Semi-structured Post-Test Interview. Asking participants about their favorite AV system, 10 participants would like to use ATHENA, 3 the visual RD and 4 the AV with no supportive UI. ATHENA is rated as *"trustworthy"*, *"reliable"*, and it is praised that users are early alarmed about an upcoming TOR and are not surprised. One participant stated:

> *"I would most likely buy the voice system. Maybe the voice calmed me down, it just made me feel the safest"* (P15).

ATHENA as character herself was controversially perceived and impacted participants' product assessment. While some experienced the anthropomorphic character as positive and reassuring, other would prefer a more technical voice:

> *"I'd be most likely buy the second system [visual RD]. Audio-visually, but only through sounds, not through the voice. Maybe it was the character of the voice [ATHENA], but it didn't seem competent to me. The car ride was too playful, it was like the assistant had the parent position. With a different voice and shorter texts that would perhaps be another thing, the long announcements were not optimal."*

Moreover, ATHENA's applicability was scrutinized in cars with more passengers or music.

Participants who favored the visual RD, rated as positive not to be interrupted by voice alerts.*"I can do whatever I want in my car, that's what the system is for"* (P7). Further, it was rated as good *"because you're supposed to keep your eyes on the road, [...]. You tend to trust the voice and not to look at the street at all"* (P11). Thus, another participant recommended to combine the visual RD with ATHENA. The visual RD was criticized as *"too distracting"* (P10), *"you had to focus it and you couldn't really look the other way"* (P15).
A participant who preferred the AV with no supportive UI stated: *"It is more like a Lane Keeping Assistant. I think I can recognize the dangers better than a system."* (P14). Another stated to favor this system as it is more *"like normal car driving"* (P6).

Behavioral-Oriented Aspects In the following, behavioral data is reported.

TOR Performance. Since data was not normally distributed (Shapiro-Wik's, p <.05) and outliers were detected, non parametric Friedman tests were applied for analyzing TOR performance. Pairwise comparisons were performed with a Bonferroni correction. Regarding mean response time of all TORs of a participant did not show any significant differences between the conditions, as well as participants' first and second TOR. Looking at the emergency TOR only, reveals a significant effect ($\chi^2(2) = 8.33, p = .016$). With ATHENA (Mdn=2.26 sec) participants were significantly faster to take-over at the emergency situation than with the visual RD (Mdn=2.74 sec) and no UI (Mdn=2.72 sec).

Gaze-Behavior. Regarding gaze behavior, only 7/18 full data sets could be analyzed due to technical problems. As assumptions for parametric statistical test are not met (normality and outliers), non-parametric Friedman ANOVAs were performed. But after Bonferroni correction (α=.0166), no significant effects, only tendencies from descriptive data, can be revealed.
Thereby, it can be reported that the IVIS (reliability and TOR display in the center console, see Figure 5.10) was least focused in all conditions (average gaze duration < 1 second). Only short checks were conducted, also in the AV with visual RD, see Figure 5.15. Nevertheless, here, the average number of gazes on the IVIS and on the road is higher than with ATHENA or no UI. Hence the visual RD led to a more active gaze behavior for monitoring the dynamic driving task changing gazes between IVIS and road. Number of gazes on the NDRT do not differ much between all three conditions, see Figure 5.16.

Regarding average gaze duration on the road, longest gazes can be reported for ATHENA (M_t=6.63 sec) in contrast to the visual RD (M_t)=3.63 sec) and the AV with no UI (M_t)=4.70 sec). Also the average gaze percentage of gazes on the road during the whole trip is highest for ATHENA with 45.52%, with the visual RD participants only looked at the road in average 35.44% and with no UI in 30.34% of the driving journey on the road. Contrarily, the average percentage of gazes on a NDRT is highest for the AV with no UI (67.08%), with

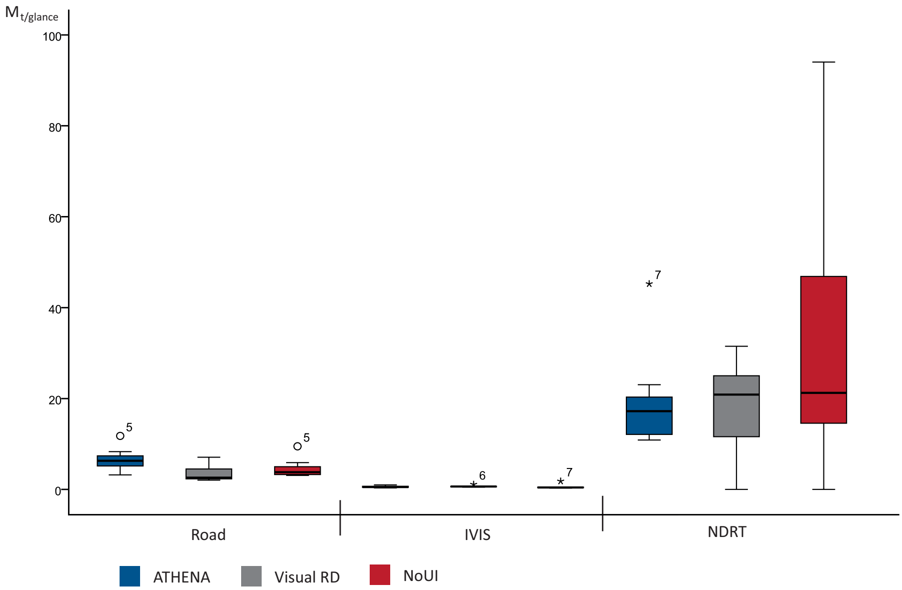


Figure 5.15: Average gaze duration on different areas of interest.

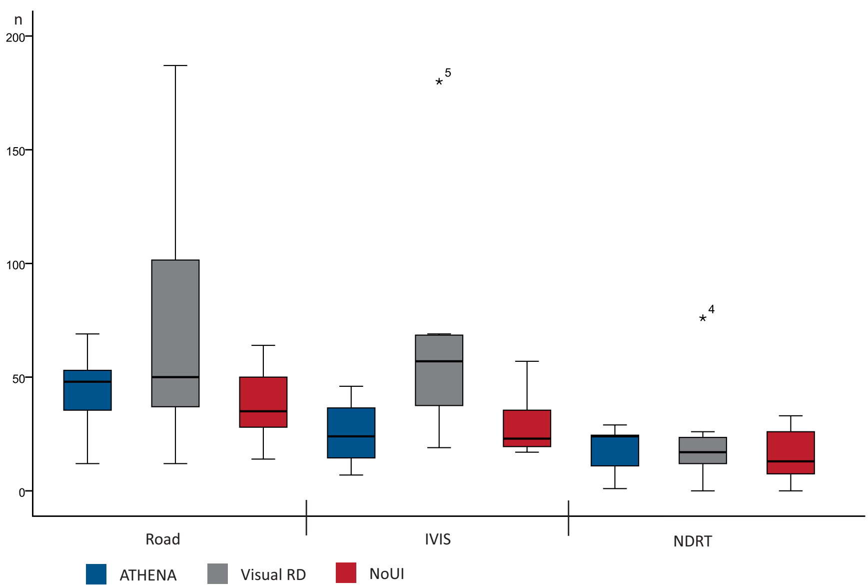


Figure 5.16: Average gaze number on different areas of interest.

ATHENA in average 51.94%, and with visual RD 57.04% of the driving journey the NDRT is focused. This is in coherence with the average gaze duration of NDRTs, which is also highest for the AV with no UI (M_t=34.02 sec). With ATHENA, participants concentrated on the NDRTS in average for 19.74 and with the visual RD 17.94 seconds per gaze, see Figure 5.15. Regarding the type of NDRT, longest gazes are spent for the newspaper (M_t= 48.17 sec) and the smart-phone (M_t=49.74 seconds), however, only in the baseline condition with no UI.

5.2.4 Discussion

In the presented need-centered approach, we analyzed driving automation UX in SAE L3 by applying the "DAUX Framework". Based on our related work analysis and a focus group, we assumed that the mere possibility of a TOR affects the whole journey experience. Thus, we hypothesized that an anthropomorphic auditory reliability display affects the driving automation UX in SAE L3 (H3.2). A positive effect, can only be partially confirmed.

5.2.4.1 Relevant Psychological Needs

Users' expectations towards conditionally automated driving before and after a first experience in the driving simulator showed that the whole journey experience is dominated by the mere possibility of an upcoming TOR. Before experiencing an AV (SAE L3) in the driving simulator, participants' expectations towards *UX while being driven* was higher than afterwards. Then, participants expressed to feel insecure, incompetent to handle the TOR or concentrate on NDRTs, and not to feel free to engage in the activities they really want to. Nevertheless, they still expect pleasure from NDRTs. This result confirms Rödel et al.'s [104] assumption that users can neither keep control, nor fully relax. As systems are already in development, users' expectations, especially fears, have to be taken in account in design, nonetheless, as expectations impact the actual experience and its evaluation. Thus, in addition to safety aspects, conditional driving automation and TORs have to be investigated from an experience-perspective. This makes it especially critical for car manufacturers to be able to get this level, as next step of driving automation, established on the market.
Systems need to be developed which support users to be able to experience the benefits of conditional driving automation: the engagement in NDRTs without having to monitor the system. Therefore, identified psychological needs of security, autonomy, competence and stimulation have to be regarded in the design process.

5.2.4.2 Conceptualization of Psychological Needs

Considering presented results, we suggest the following recommendations for researchers and designers of automated driving systems to appropriately satisfy the needs of security, autonomy, competence and stimulation:

We developed an anthropomorphic auditory reliability display, called ATHENA, aiming to address identified relevant needs. The automated vehicle as product equipped with ATHENA was evaluated better according to all UX qualities than with no UI and the visual RD. Most participants would also decide for ATHENA, as post-text interviews showed. However, contradictory to our initial hypothesis, ATHENA could not improve users' positive affect. The UI was only able to reduce negative feelings, most satisfied the need for security and led to higher trust and less distrust. Other needs did not significantly differ in fulfillment from driving without support of UI or a visual reliability display. This confirms [176, 63, 103], and results from the SAE L2 case study (see 5.1.4) that security is a hygienic factor, thus, prerequisite for UX. With ATHENA, especially in phases of enabled automation, participants stated to feel secure due to the continuous feedback. Although the preparation phase of the TOR led to a feeling of insecurity, participants were less scared when the TOR was actually issued, as participants were prepared. This can also be confirmed by the reaction times of the emergency TOR, participants took over control faster than with no UI or the visual RD. With no additional support by a UI, participants' need of security was least fulfilled when a TOR was issued, what is accompanied with a loss of competency. ATHENA, contrarily, fulfilled the need of competence best but differences to the other conditions were not significant. However, also qualitative statements of UX curves confirm that participants felt much more competent in managing the take-over and the dynamic driving task and reassured by the positive feedback of ATHENA after a successful take-over. The visual RD had similar effect on competence due to the preparation, whereas to continuously check the visual display was assessed as rather critical. This is confirmed by the most active gaze-behavior of the eye-tracking data switching between road and IVIS.
Continuous feedback about the journey and current system performance (reliability display) helps to fulfill the need of security and competence. A visual display has the disadvantage of visual distraction. Using an anthropomorphic auditory display is more promising, but not sufficient to increase positive experience.

Although participants in the focus group stated their need for autonomy to be impaired in SAE L3 driving, ATHENA could not compensate this effect. Qualitative statements from the UX curves and UX cards showed that the need is important for a positive driving experience in SAE L3, however, not as often mentioned as the need of security, competence and stimulation. Further, the concept of an reliability display (visual or auditory) was on the one hand expe-

rienced as supporting due to transparency, on the other hand as restricting, as participants had the possibility of a TOR always in their minds, thus, felt less autonomous. This could also be confirmed by the tendencies of the eye-tracking results, mean gaze duration on the road was longest, and on NDRTs shortest for ATHENA. Further, ATHENA as anthropomorphic UI was experienced as infantilizing. However, this was highly individual. While some liked the personal feedback, designed like a friend, was talking, others felt infantilized. This was also confirmed by the post-test interview. Contrarily, with no UI, the need of autonomy was more often mentioned as fulfilled as not fulfilled and even increased though the journey lasted only a few minutes.
In the design of a voice user interface as anthropomorphic reliability display, effects of a phenomenon called reactance [478] – a defense reaction against internal and external restrictions and infantilizing – need to be carefully regarded. Further, users' individual preferences have be taken in account.

UX curves and UX cards showed a positive development over time regarding need-fulfillment of security and also autonomy. Thus, expected problems with conditional automated driving might only be problematic at the introduction of this level of automation on the market, or reoccure after critical situations or accidents. Thus, supporting interfaces might be only necessary at the beginning, and should be capable of being switched off.
The problem with psychological needs of security and autonomy might balance itself over time. To prove this longterm and real-road studies are necessary, further, the impact of experienced accidents (in real, or reported, e.g., by media) is still unclear and needs to be investigated.

Moreover, one should regard the paradox that participants engaged more in NDRTs without no UI than with a UI (ATHENA or visual RD) although they felt more unsecure and distrusted the system. This contradicts to studies which use gaze behavior as measure of trust in automation (cf. [383]). Our participants did not monitor because they were not forced to, however, they did not feel good with the situation. With ATHENA, which updated participants about current system performance, gazes were longer on the road and reaction times were faster in taking-over controls than without having a UI. Thus, such systems aiming to keep the driver in the loop should be considered as possibility to increase objective and subjective safety to improve the overall experience, as already discussed above. Nevertheless, keeping the driver in the loop, as ATHENA or the visual RD does, contradicts to the promise of the possibility to engage in NDRTs in SAE L3. This discussion then leads to the overall question, should we skip SAE L3? According to VOLVO this should be done due to safety reasons [460]. Our results also give some evidence from experiental perspective. If a system which keeps the passive passenger (fall-back ready user [47]) in the loop to be prepared to become an active driver can only

reduce negative affect, shouldn't car manufacturers stay at SAE level 2 where the responsibility is totally with the driver and introduce systems to keep the driver in the loop in a positive way(e.g., Pokémon Drive [479])? Of course, ATHENA is only an example UI. Other solutions might satisfy the needs better and create a positive experience.
Rather than skipping SAE L3, we recommend from experience perspective a mix of SAE L2 and L3. Driver should be kept in the loop by pleasurable experience, conveyed by high UX quality, and still allow users to engage in NDRTs to some extent.

5.2.5 Limitations

The presented study has some limitations. Especially, the missing eye-tracking data from 2/3 of the participants does not allow a full conclusion about monitoring and engagement in NDRTs. Tendencies can only be added for discussion, however, derived statements have to be proved in future work. Work concentrated on younger participants, results cannot be generalized to other user groups. Security concerns are more prominent to elderly than to younger users [16]. As individual differences are visible in the preference towards a supportive UI, other factors like cultural background and personality have to be taken in account. Only a short time span is regarded, long-term and habituation effects of take over as well as the influence of real road conditions contrarily to the driving simulator experience are still unclear [238]. A next step is to study SAE L3 on a test track, what is already ongoing [22], and with a wizard-of-oz car in the field (cf. [240]).

5.2.6 Core Findings

In the following, the core findings of this study answering **RQ3.2** are highlighted:

- **A possibility to engage in NDRT without the need of monitoring is the main benefit of SAE L3. Comfortable engagement should be assured.**
- **Designers of an anthropomorphic display must be aware of users' individual preferences to prevent reactance.**
- **Keeping the driver in the loop with a reliability display helps to improve driving experience by at least reducing negative affect, however, contradicts the promise of SAE L3.**
- **The introduction of SAE L3 is not only questionable from a safety- but also from an experiential perspective.**

5.3 High/Full Driving Automation (SAE L4/5)

With increasing automation more responsibilities are transferred from the human to the system, hence, already in SAE L3 the ADS performs the entire dynamic driving task when engaged. This also applies for higher levels of automation, thus SAE L4 and L5, however, users can fully concentrate on NDRTs because if TORs occure (only in SAE L4), they will be neither safety nor time-critical. However, what sounds like a long-cherished desire for some, might be scaring for others, and achieving this goal is highly dependent on a widespread user acceptance. These higher levels of automation may eliminate some of the before discussed problems but pose new challenges for the automotive industry in general, and vehicle brands in particular. When the driver becomes a passive passenger, driving related interactions disappear. As soon as long-established touchpoints between the consumer and the vehicle vanish, the passenger becomes a "ghost in an empty shell", disconnected from the essential elements of the driving task. As large parts of in-vehicle experiences could be substituted by other industries (entertainment, web, furniture, home appliances, etc.; [65]), the emerging question then is how, and by whom will this shell be filled with life? How can we deal with drivers' perceived loss of control [94]? How can vehicle manufacturers maintain the influence on their consumers' user experience, without loosing their market position.

This case study aims to investigate the following research question:

- RQ3.3: How should a user interface be designed to affect UX of driving in SAE L4/5 with limited controllability?

As the role of the user does not change between SAE L4 and 5 we expect similar experiences during driving in a specific operational design domain, e.g., our use case of highway driving. Thus, the presented case study is applicable to both levels.

This section is based on following prublications: [7, 8, 9].

5.3.1 Analysis

To answer which psychological needs have to be specifically regarded in UXD for ADS in SAE L4/5 for a positive UX of driving, we conducted a related work analysis and an exploratory inductive study using the laddering interview technique.

Role of User	Role of Driving Automation System SAE L4	Role of Driving Automation System SAE L5
***Driver/dispatcher* (while the *ADS* is not engaged):**	***ADS*[SAE L4](while not engaged):**	***ADS*[SAE L5](while not engaged):**
Verifies operational readiness of the ADS-equipped vehicle	Permits engagement only within its ODD	Permits engagement of the ADS under all driver-manageable on-road conditions
Determines whether to engage the ADS		
Becomes a passenger when the ADS is engaged only if physically present in the vehicle		
***Passenger/dispatcher* (while the *ADS* is engaged):**	***ADS* (while engaged):**	***ADS* (while engaged):**
Need not perform the DDT or DDT fallback	Performs the entire DDT	Performs the entire DDT
Need not determine whether and how to achieve a minimal risk condition	May issue a timely request to intervene	
May perform the DDT fallback following a request to intervene	Performs DDT fallback and transitions automatically to a minimal risk condition when: • A DDT performance-relevant system failure occurs or • A user does not respond to a request to intervene or • A user requests that it achieve a minimal risk condition	Performs DDT fallback and transitions automatically to a minimal risk condition when: • A DDT performance-relevant system failure occurs or • A user does not respond to a request to intervene or • A user requests that it achieve a minimal risk condition
May request that the ADS disengage and may achieve a minimal risk condition after it is disengaged	Disengages, if appropriate, only after: • It achieves a minimal risk condition or • A driver is performing the DDT	Disengages, if appropriate, only after: • It achieves a minimal risk condition or • A driver is performing the DDT
May become the driver after a requested disengagement	May delay user-requested disengagement	May delay user-requested disengagement

Table 5.17: Roles of human driver and driving automation system in SAE L4/L5.

5.3.1.1 Related Work

The need for permanent monitoring vanishes, and UX will more and more be affected by engagement in NDRTs and the behavior of the automation. For example, [99] claim that the driving style (sportive, ecological, etc.) is highly relevant for the overall user experience of ADSs, and this is underpinned by the results of [100]. Further on, NDRTs will likely influence UX quality. Preferences of NDRTs during automated driving were analyzed by [101], but how to support users in the engagement of NDRTs, e.g., like office work [32] is still an open question [480]. As in highly and fully automated driving (SAE L4/L5), the entire driving task including the fallback authority [387] is transferred to the automation, a high pragmatic quality will then be mostly required for additional systems and services. Pettersson [102] evaluated users' expectations of future automotive technologies by emphasizing study subjects to draw the desired interior of automated vehicles on the floor. They reveal a tension between the wish to engage in NDRTs (as main benefit of ADSs) and a still existent distrust into the system, which hinders users to engage in NDRTs. The authors demand future research to be more "user focused" instead of continuing being "driver focused", what leads to several implications on car interior and HMI design. Pettersson and Ju [69] further reviewed current challenges in human-vehicle interaction design and argue that such interactions must be the primary consideration for future in-car experiences. They discussed how automated driving changes interaction design and concluded, that such a design is not only dependent on users' preferences, but also on societal norms (which need to be further investigated). Acceptance and UX of ADS for mobility on demand was analyzed by Distler et al. [103], who also applied a similar psychological need-based approach. Results indicate safety as a prerequisite for a good user experience, and pragmatic quality (including perceived usefulness, effectiveness, etc.) to become a hygienic factor [180]. This means, e.g., these issues will be only noticed by participants if the required quality is not delivered.

5.3.1.2 Laddering Study

As we speculated users' attitude towards automation to vary dependent on the operational context, we conducted a detailed investigation of user needs utilizing our driving simulator.

Study Setup The experiment was conducted in a high-fidelity driving simulator (remodeled VW Golf on hexapod platform). We used a within-subject split plot design, where each participant experienced three fully automated driving scenarios (each lasting 3 min) in the driving simulator.

Driving Scenario. We presented contextual variations of driving scenarios – three different road types (highway, rural, and urban) with three levels of traffic volume (light, moderate, and heavy) – to participants and investigated how the environment influences users' attitude towards automation (see Table 5.18). SAE L4 is restricted to specific environmental settings (SAE On-Road Automated Vehicle Standards Committee, 2018) and thus essential for the experience of ADS. Further, as mixed traffic is predicted to be a problem in the next decades [481], varying traffic volumes from free roads to heavy traffic jams come along. Also today our driving experience as driver/passenger is highly impacted by the traffic volume. Thus, we assume this not to be only a problem from the technological, but also from a user-centered perspective.

Participants and Procedure. In total 30 participants (9 female; 21 male) aged between 22 and 41 ($M_{age} = 26.867$, Std = 3.98), all undergraduate students and university staff, participated in the experiment. None of the participants had to be excluded due to simulator sickness or technical problems. The driving simulator give participants a "compressed" experience, taking them into the different world within seconds. We argue, although it is a short time period, it gives a more realistic view on participants' perception than existing survey studies (e.g., [104]) utilizing narratives building only on users' pure imagination. All participants faced each road type and traffic volume once in quasi-randomized combination (see Fig. 2), leading to 90 data records (10 for each possible combination of road type and traffic volume). To further increase immersion, we always narrated the same short introductory story to the participants ("imagine you are visiting a friend..."). After each drive, they first had to state whether they would prefer to use automation in the respective scenario. Afterwards, we asked them to justify/explain their decision verbally using the laddering technique, see Figure 5.17.

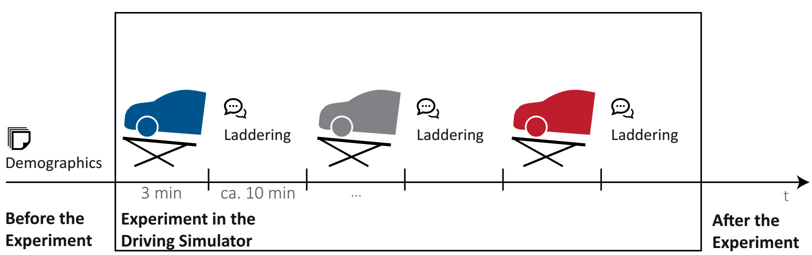


Figure 5.17: Study procedure of the analysis study.

	Highway	Rural Road	Urban Road [Road Type]
Light			
Moderate			
Heavy [Traffic Volume]			

Table 5.18: Examples of scenarios using different road types (columns) and varying traffic volume (rows).

Data Collection. Although users are prone to link their (positive and negative) experiences to product aspects, it is not easy to uncover the underlying reasons. According to [482], users will choose a certain product if product aspects fit to their personal values (Means-End theory). To be able to reveal underlying reasons (fulfillment of psychological needs) relevant for potential users, we utilized the laddering technique [419] in a retrospective semi-structured interview. By "probing", participants were asked why or why not they are willing to use automation in a certain context. Based on their answer, the interviewer continued asking the question "why" to unfold the reasons behind until the level of needs has been reached (approach adopted from [420]). Thereby, users' personal opinions and the underlying values and needs are revealed. This technique can help to make the unconscious conscious. After transcribing the data from the laddering interviews, we conducted a content analysis by coding the expressed justifications for and against automated driving in a certain scenario. To do so, we categorized statements based on the universal psychological needs (autonomy, security, stimulation, competence, meaning, relatedness, and popularity) and highlighted whether or not the expressed needs were mentioned in a positive or negative way. All propositions ($n = 172$) from in total 90 interviews were coded by one researcher, a subset ($n = 55$) was coded by a second researcher to guarantee validity of the content analysis. An agreement of 78.2% could be achieved, calculating the interrater reliability by using Cohen's kappa indicates substantial agreement ($\kappa = 0.74$). Afterwards, we calculated Chi-Square tests to investigate the relationship of a specific scenario (road type/traffic volume) and the negative/positive fulfillment of the psychological needs. All results with $p < 0.05$ are reported as statistically significant.

Results Overall, we can report a high acceptance of ADSs. Regardless of the scenario, participants stated to prefer automated driving in 66 of the 90 interviews (73.3%). However, based on the content analysis, we could identify that the number of participants' negative statements on AD was slightly higher ($n = 89$) than those of positive mentions ($n = 83$). Autonomy ($n = 60$), security ($n = 65$), stimulation ($n = 31$) and meaning ($n = 14$) were the most crucial underlying psychological needs, competence was only mentioned 2 times. While autonomy had roughly the same number of positive and negative mentions, security was mentioned 42 times positively and only 23 times negatively. On the contrary, stimulation was mentioned mostly in a negative ($n = 28$) than in a positive ($n = 3$) way. In the following, we present a detailed investigation of our results by relating participants' qualitative statements to the contextual parameters road type and traffic volume (see Figure 5.18). Numbered interview statements are presented in Table 5.19 (road type) and Table 5.20 (traffic volume), and referenced throughout the results section (in the following style [road type or traffic volume | statement number]).

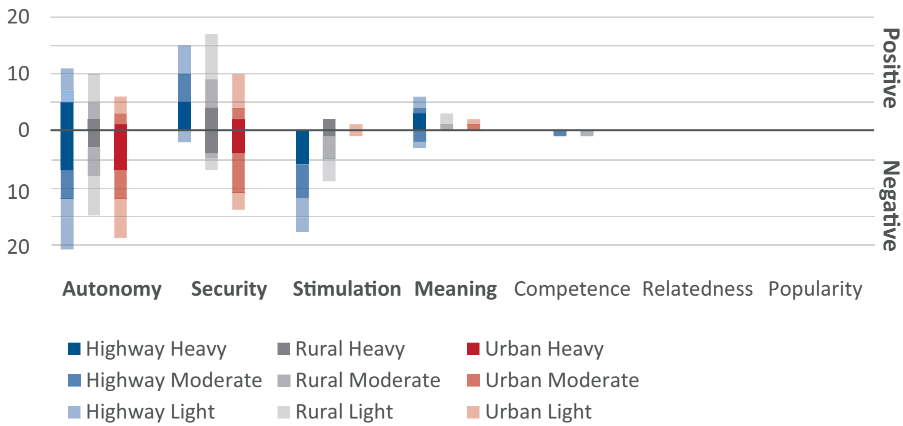


Figure 5.18: Number of mentions concerning need fulfillment, categorized along the independent variables road type (colors: blue, grey, red) and traffic volume (saturation: heavy, moderate, light).

Road type (Highway, Rural, Urban). Regarding the independent variable road type, only slight differences between the three scenarios (highway, rural, urban) are present with respect to participants' preference of enabling/disabling automation (see statements in Table 5.19). When driving on a highway or rural road, 76.7% (n = 23) would enable and 23.3% (n = 7) disable automation. In an urban area, only 66.7% (n = 20) would like to drive (fully) automated and 33.3% (n = 10) rather manually. However, when considering the underlying needs, interesting differences between the scenarios become visible.

During highway driving the need for security received 15 positive but only 2 negative mentions – participants stated to feel *"safe"*, *"comfortable"*, *"relaxed"*, and *"to trust"* the system. One reason for this can be seen in the low complexity of the driving environment [highway|1]. Participants also mentioned that there were no oncoming vehicles and no intersections. Also, driving behavior of the vehicle, if it acts more risky or conservative, sporty or cautious, seems to contribute to the need of security [highway|2]. In addition, three participants believed the ADS's to perform better than human drivers, for reasons such as *"[...]if weather conditions are not good"*. As already stated, a lack of safety/security was mentioned only twice – for both participants it was the first condition experienced, what could also be seen as familiarization with the system [highway|3]. The need for autonomy was another important concept in highway driving. It occurred nearly the same number of times in a positive (n = 11) and in a negative (n = 13) way. Participants complained not being able to intervene and desired to participate in the driving task on an operational level [highway|4–7]. On the other hand, participants liked the possibility to engage in NDRTs. Thus, the need for autonomy correlates with the need for meaning (6 positive mentions) as the free time can be used for something useful. Especially working (to improve the individual efficiency and effectiveness) was mentioned several times [highway|8–9]. Many participants stated to feel *"bored"* and *"tired"* and accordingly the need for stimulation received the highest number of negative mentions (n = 18) among all scenarios [highway|10]. This was further accompanied by a loss of meaning [highway| 11]. Five participants explicitly preferred manual driving in this context. For them, the UX of driving was important [highway|12–13]. Contrarily, for the other participants that mentioned a loss of stimulation, the UX while being driven is essential [highway|14]. On rural roads, security received the highest number of positive mentions (n = 17), where again driving behavior (n = 8) was the main reason for participants to feel safe, especially when they could identify themselves in the driving style [rural|1–2]. Similar to highway driving, the low complexity of the environment (less intersections, no pedestrians) positively contributed to the need for security (n = 5). However, the argument can also be flipped (higher complexity due to oncoming traffic, curves, etc.), thus some participants (n = 7) mentioned security also in a negative way [rural|3]. Again, driving behavior plays an important role – some stated the automation to drive too fast or to perform too risky overtaking maneuvers.

Road Type	Interview Statements (Numbered)
	Security:
	1 (+) *There is not too much to do for the ADS but just keeping the distance and following the vehicles.*
	2 (+) *It keeps the lane, the distance - not only from the car in the front but also the car from behind – this is why I feel safe.*
	3 (-) *It is a friable feeling at the beginning because you have first you get used to it, to trust in the system. Because I have never tried it* before.
	Autonomy:
Highway	4 (-) *It is weird not to touch the steering wheel, not to touch anything, I want to decide how I want to drive, faster or slower!*
	5 (-) *I should be able to decide which lane I want to go or to take control of the car to drive manually to the left lane by myself.*
	6 (-) *Just for some small changes, like going to the left lane or shortening the following distance!*
	7 (-) *I would like to gain control of the car and drive manually.*
	8 (+) *I would like to drive automatically because I can use the time for more useful things. This is also the reason why I like more to drive with the train than with a car. Driving time is lost time for me. It is a necessary evil which costs time*
	9 (+) *If I sit in the office or in the car and I can work it would be the same for me*
	Stimulation/Meaning:
	10 (-) *It was okay, but quite boring - just following the traffic - nothing actually happened.*
	11 (-) *I am bored compared with traditional manual driving. While driving by yourself you watch the situation, but now you don't do anything. You feel like you are useless.*
	12 (-) *It was boring, the vehicle drove very slowly and always on the left lane. I am not the person who stays on the left lane with 100km/h.*
	13 (-) *It was boring - on the highway the challenge is to overtake to drive fast.*
	14 (+) *I could imagine driving automatically, because I could do any other activities like sleeping or working. This would save time and would lead to efficiency [...] but like this, it was boring.*

Road Type	Interview Statements (Numbered)
Rural	**Security:**
	1 (+) *I would do the same for overtaking - it's pretty good. Yes, now I trust this system.*
	2 (+) *This driving experience was very nice. I felt very safe. The distance to the other cars was perfect - was not too close but also not too far away. My car decelerated every time when there was a speed limit. And also when the car passed the other cars in front of me, I felt safe because I was also able to see the other traffic which on the other lane might drive into my lane.*
	3 (-) *In the rural area I'll feel safer without overtaking - because we cannot feel safe when something happen in the front area or other cars coming over - we need to fully concentrate on it.*
	Autonomy:
	(see Highway)
	Stimulation/Meaning:
	4 (-) *I would not use automation on this road because it makes more fun to drive manually, I would use it on autobahn because driving there is boring – or maybe I would like to use it in USA.*
	5 (-) *If you drive on your own, you have something to play. You can look at the dashboard how fast you are, which motor speed.*
	6 (-) *If you spend 80000 ? for a vehicle you also want to have fun with this car. You get adrenalin if you drive fast in the curves. I think you only by this you have this feeling, if you have the control. This is what it gives you the kick!*
Urban	**Security:**
	1 (-) *I don't trust it as much as on the highway, because here in the city there are too many parameters I can't change, like people are crossing the street - I think too much would be happening around.*
	2 (-) *Not as safe as the previous one! I was not that relaxed because I need to see the red lights, while on the highway there is nothing like that, you just have to keep the lane and take care of cars in the lane.*
	3 (-) *I would be cool if there is a system which shows that it recognizes the traffic lights and pedestrians. I want to be sure that the system does not hit the persons in the street, as well if there is a car coming from the side I want to know that it does not hit me.*
	4 (-) *I would like to have more drivers that are anticipatory. I want to feel earlier that the car reacts on events outside the car.*
	5 (+) *I would especially use this in the city, because it is complicated for me to drive in urban areas with all the traffic lights, pedestrians. I am sure the vehicle can handle this, and I do not want to concentrate on this [...].*
	Autonomy:
	6 (-) *I don't have a feeling of controlling the car, yes, I feel out of control!*
	7 (-) *Other persons are around me, in my opinion, not too much control is not a problem on highways where there are no persons, and vehicles are traveling in the same direction, but here it is not okay for me!*

Table 5.19: Interview statements categorized by road type, needs and positive/ negative (+/-) mentions.

The need for autonomy is often mentioned in highway driving (10 positive mentions), even though the share of negative mentions is smaller (n = 5). Also, the underlying reasons are similar – some wanted to engage in NDRTs, while others miss the possibility to participate in the driving task. The need for stimulation shows a similar picture – it was mostly mentioned with negative association, although (compared to highway driving) only 9 participants complained about a loss of stimulation. This always comes along with a loss of driving fun [rural|4–6]. While rural driving was perceived similarly to highway driving, need fulfillment on urban roads is fundamentally different. Here, security received the highest number of negative (n = 14) and the lowest number of positive mentions (n = 10) – mostly because of the high complexity of the environment. 9 participants stated not being able to relax due to a lack of trust [urban|1–2]. These participants assessed their own performance in an urban area to be better than the performance of an automated vehicle. Thus, they expressed the wish for feedback about the system state [urban|3]. Moreover, driving behavior [urban| 4] plays an important role (n = 6). participants that positively mentioned security believed automation to perform better than human drivers. Some participants even mentioned the benefits of "cameras and sensors" [urban|5]. On urban roads, the need for security (negatively) correlated to the need for autonomy. Only five participants could imagine to engage in NDRTs, while 15 participants complained a loss of autonomy – mostly because they did not trust the vehicle, or felt being out of control [urban|6,7]. Participants described in detail how they monitored the environment and the vehicle's actions – engaging in NDRTs was no option for them. With only one mention, the need for stimulation was not important in urban driving – neither in a positive nor in a negative way. On the one hand, urban driving is not a source of fun, but on the other hand, people can hardly imagine to transfer the driving task to automated systems as they fear safety issues. Chi-Square tests reveal a significant association between road type and positive/negative fulfillment of the need of security, $\chi_2(2) = 10.08$, $p < .05$ – highest number of negative mentions in the urban scenario, least in the highway scenario. In addition, for the fulfillment of the need of stimulation we can report a significant effect, $\chi_2(2) = 6{,}65$, $p < .05$ – contrarily, highway receives the highest number of negative mentions and the urban scenario the least.

Traffic volume (high, moderate, low). Regarding the independent variable traffic volume, slight differences between the three situations (high, moderate, and light) are present with respect to participants' preference of enabling/disabling automation. In heavy traffic, 70% wanted to use automation, compared to 66.3% for moderate and 83.3% for light traffic. In all the scenarios with a high traffic volume, almost the same number of participants mentioned the need for security positively (n = 8) and negatively (n = 11). Again, the driving behavior is an important factor [high|2]. On the one hand, participants fear the increased probability for failures [high|1], but on the other, they stated manual driving in heavy traffic stressful [high|3] and thus welcome AD [urban|4]. In addition, the need of autonomy received a similar number of positive (N = 8) and negative mentions (n = 10). Participants desired to use the additional time for NDRTs [high|5]. In heavy traffic, some participants miss the need for autonomy because they believed to be faster on their own [high|6,7]. In contrast, others do not trust the vehicle and observed every behavior of the vehicle to be ready to take over control in case of an upcoming hazard. Only two participants stated not to be *"bored"* (need of stimulation) due to the high traffic

Traffic Volume	**Interview Statements (Numbered)**
High	**Security:**
	1 (-) *The speed was not so fast and the traffic volume was too much. Even though the automation is quite good, I was concerned about the safety just because there were too many cars on the road*
	2 (-) *The car should drive as I would drive, more carefully and anticipatory, especially in the urban area with a lot of traffic.*
	3 (+) *If I had driven on my own, it would have been more stressful. You have to take care on too many things at one time. Back, front, where are pedestrians?*
	4 (+) *In this kind of traffic, you just wanted arrive where you will get. So here I really enjoy AD [...], here with many cars, speed limit, the system does everything for me - for this situation I'll definitely buy it.*
	Autonomy:
	5 (+) *It was comfortable, because you cannot drive anyway like you want because there is one car after the next. This very convenient if you do not need to drive.*
	6 (-) *I wanted to move to the left lane because there it was a little faster. The headway was a little bit too long.*
	7 (-) *The vehicle was maybe too slow. I think there was one situation you could have gone faster.*
	Stimulation/Meaning:
	8 (+) *I was not even bored because there was a lot of traffic, and there is happening a lot. But at the same time I was more relaxed to look around and do other things - what is maybe weird because it was a lot of traffic.*
Moderate	**Similar to high traffic**
Low	**Security:**
	1 (+) *I didn't need to go through any maneuvers. The car behaved by itself well. I felt safe all the time. It was comfortable - I don't have to pay attention to anything like traffic. And I don't have to do anything like accelerating, braking or gear shifting.*
	2 (+) *In this context with light traffic, I think it was safe, but I am wondering how it will be like in case there is much more traffic.*
	Stimulation/Meaning:
	3 (-) *In current situation, I am not sure if I would be willing to use ADS –on a free road I really like driving!*
	4 (-) *I also want drive on my own. Because I like the freedom, you can drive faster if you want and if the roads are free.*
	5 (-) *Especially in Germany where you could drive 200km/h when there is no traffic it is a nice driving experience. [...] You feel self-determined and autonomous if you can drive 160 km/h or 170km/h. It is nice to accelerate and having to drive on your own and determine on your own when I want to drive faster or slower dependent on your mood.*

Table 5.20: Interview statements categorized by traffic volume, needs and positive/ negative (+/-) mentions

volume [high|8]. However, more participants (N = 7) mentioned the need of stimulation in a negative way. For a moderate traffic volume, we can observe similar effects on participants' needs for security and autonomy as for heavy traffic, but participants complain more about the need of stimulation (N = 10) if there is less traffic on the road. A big difference is visible in scenarios with light traffic. Here, 19 participants stated the need for security to be fulfilled. They mainly felt *"comfortable"* and *"safe"* [light|1]. One participant addressed the traffic volume as context factor explicitly [light|2]. In addition, in light traffic participants see the advantage of an increased autonomy by being able to decide what they want to do. Further, they would like to stay in control because of the same reasons mentioned already in heavy and moderate traffic. Negative mentions of stimulation increase with less traffic. Especially the loss of *"pleasure of driving"* is criticized [low| 3–5]. Chi-Square tests did not reveal any statistical significant differences.

Multi-level effects. Regarding interaction effects of both independent variables road type and traffic volume, we can observe that people especially feel safe in a rural road with light traffic (n = 8), while an urban area with moderate traffic leads to trust and safety issues (n = 7). An automated drive in an urban area with heavy traffic has an even higher negative impact on the need of autonomy (n = 6), and the least number of positive mentions for need fulfillment at all. Highway driving with light traffic negatively affects the need for autonomy (n = 6). While highway driving shows significant losses in stimulation with the impact of traffic volume (n = 6, in all scenarios), a rural road only lacks at moderate and high traffic to fulfill the need of stimulation. Urban driving does affect stimulation neither positively nor negatively, thus this need plays little role in the urban scenario. Regarding the relationship of road type and traffic volume concerning the number of mentions of specific need fulfillments, Chi-Square tests did not reveal any significant effects.

5.3.1.3 Implications for Design

Overall, we see a general openness to use an automated vehicle in SAE L4 or 5 across all operational contexts. However, the number of negative statements on need-fulfillment shows that there is still skepticism in the society. Exploring first driving automation concepts and the impact of UIs on users' experience will be the crucial factor for a success of this technology on the market. Hence, appropriate UIs have to fulfill relevant user needs to alleviate last doubts. As this doctoral thesis focuses on the context of highway driving with light to moderate traffic, we identified the needs of stimulation, meaning and autonomy as relevant: Considering the need of stimulation (especially *"pleasure of driving"*), we can see that automated vehicles lack to fulfill this psychological need (regardless of the scenario). Especially with increasing vehicle speed (such

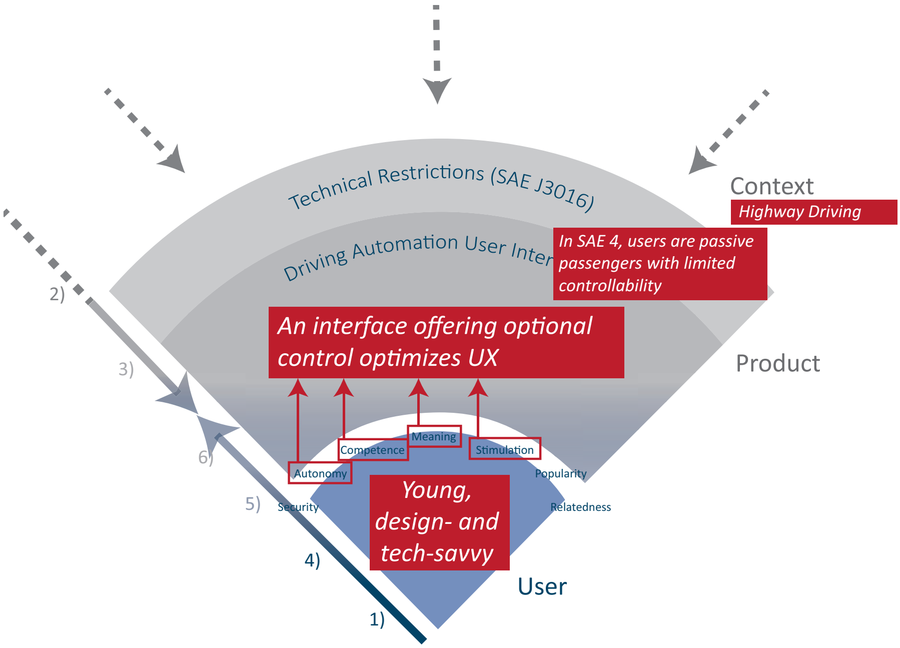


Figure 5.19: Application of the need-centered approach with the "DAUX Framework" in SAE L4/5 for hypotheses and concept development.

as present on highways or rural roads) and road curvature (rural driving), automation more and more lacks in the provision of stimulation and participants emphasize to miss the *"pleasure of driving"*. Results from [94] confirm this. They revealed that for some motorists speed control is an important factor to insure *"joy of driving"* (p. 165). Further, our participants bemoaned the *meaningless* interaction which resulted in boredom. Further, beside the gained autonomy being able to engage in NDRTs, participants felt *"out of control"* as they wished to engage in the dynamic driving task. However, even though automated driving offers additional time for engagement in NDRTs, in our study, people often wanted to intervene into the driving task when they believed to be faster than the automation – for example by performing overtaking maneuvers or changing to lanes with higher flow speed in crowded areas. Thus, users' perceived usefulness and performance expectations have to be met by appropriate design solutions for ADS [103]. This could also rely on the subjective perception of the value of time, which is dependent on the satisfaction derived from activity or the subjective meaning of an event. Hence, we hypothesize the needs of autonomy, competence, meaning and stimulation as most critical to satisfy. These have to be specifically regarded in UX design, see Figure 5.19.

5.3.2 Design

The concept is inspired by [483], who showed the negative effects of automation (amputation of user capabilities) by the example of a coffee grinder (automated vs. manual). A hybrid solution utilizing the benefits of automation (e.g., increased comfort) and balancing the disadvantages (e.g., meaninglessness of an interaction) led to an increased fulfillment of users' needs of stimulation, autonomy, meaning, and competence, thus, improved UX. As this is in coherence with our results from the need profiles from the laddering study , our aim was to replicate such a situation in the context of automated driving. The features were identified within a brainstorming session.

Based on the presented result of our exploratory inductive laddering study, we assume that optional cooperative control (OC) alias "Driving Hotzenplotz" might fulfill the psychological needs of stimulation, meaning, and autonomy especially in highway driving with higher speeds. OC was implemented in a way that the automation performed the primary task of driving, but participants still had the possibility to overrule the longitudinal system with the gas/brake pedal. Thereby, still engaging in NDRTs is possible, however, if users get bored or have the need to control the vehicle, e.g., to meet own performance expectations, they can feel the stimulation of acceleration and still be in control. Highway driving allows higher speeds than other scenarios and offers possibilities for overtaking frequently. We assume that the immediate feedback of acceleration can fulfill the needs for stimulation and autonomy. Additionally, we offered the possibility to perform lane changes and overtaking maneuvers with the indicator (similar to automated overtaking assistants as proposed by Tesla or BMW). Tactical decisions emerging from this option could satisfy the needs for competence and autonomy while giving the driver the feeling of being in control. Thus, lateral control is performed automatically as it has no impact on the experience in an environment with low road curvature. A similar concept for rural driving, e.g., an interesting mountain road, would need to offer different control option as in this context e.g., steering may have a greater meaning for users. As highway driving often comes with increased trip lengths, resulting in fatigue and concentration problems, the advantages of fully automated driving should remain. The driver may perform additional activities and there is no need for monitoring system functions, speed and lane selection are pure optional tasks only performed on demand. In case the driver releases control the vehicle maintains a cruising speed of 130 kilometers per hour. Hence, personal preferences of the user are regarded.

The evaluation of the effectiveness of OC in the context of highway driving to optimize UX of high/full driving automation is described in the following section.

5.3.3 Evaluation of "Driving Hotzenplotz"

To evaluate the impact of highly automated driving (SAE L4/L5) with (OC) and without optional cooperative control (AD) on user experience in a short-term highway driving scenario and compared the results to manual driving (SAE L0/L1, MD), we conducted a driving simulator study aiming to reveal differences and inter-correlations between need-fulfillment, positive affect, and product perception in the context of highway driving by applying the "DAUX Framework". We wanted to test following hypothesis:

- H3.2: An interface offering optional control affects SAE L4/5 driving automation UX with limited controlability.

5.3.3.1 Study Setup

Driving Simulation The experiment was performed on a Hexapod simulator (moving platform) utilizing a closed 3-lane highway (German setup with two leftmost lanes each 3.5m wide and a truck lane with 3.75m on the right) course with moderate traffic (stable or near free flow, level of service C).

Participants and Procedure In total, 27 participants (9 female, 18 male) aged between 19 and 35 ($M_{age} = 23.185$, Std = 4.14) years, all undergraduate students, participated in the experiment. 48.1% of our participants stated to drive with a car on a daily basis, 22.2% once a week, 11.1% irregular, 7.4% rarely, 3.7% never and the rest did not answer. After assessing demographics and general driving behavior, participants had to complete a 10-minute trip in each condition (randomized order, within-subjects design). Participants were equipped with a tablet to complete the survey consisting of a set of different questionnaires assessing the respective driving mode after each condition. Afterwards, we conducted a semi-structured interview with all participants, see Figure 5.20. Out of 30 participants, three had to be excluded due to simulator sickness (2) and technical problems (1).

Data Collection To capture UX in a holistic way, we again applied the "DAUX Framework" for evaluation, see Figure 5.21.

Experience-Oriented Measures. We used the Positive (PA) and Negative Affect (NA) Scales PANAS [158] to gain insights into partiicpants' affect associated with driving experiences. Users' affect determines if users' experience is positive or negative. The PANAS-X [484] sub-scales for a*ttentiveness, serenity, fatigue,*

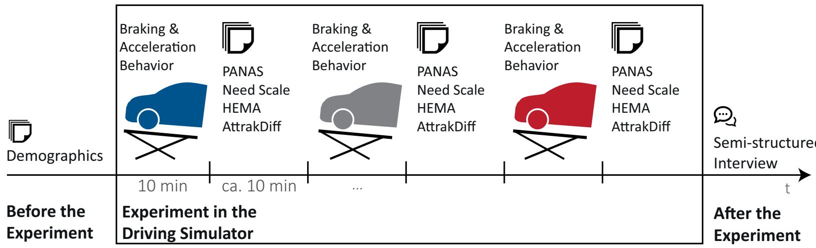


Figure 5.20: Study procedure of the evaluation study.

and *boredom* were utilized in addition as we believed them to be relevant in the context of car driving. Subscales show satisfying reliability values (see Table 5.21). PA and NA do not correlate (τ = 0.074), however, PA significantly correlates with attentiveness (s = 0.725, p $<$ .001), fatigue (τ = -0.509, p $<$ .001), and boredom (τ = 0.539, p $<$ .001), and NA with serenity (τ = -0.369, p $<$ .001).

Further, according to the "DAUX Framework", our aim was to evaluate which psychological needs are fulfilled in the different conditions (MD, AD, OC) and reveal potential correlations with affect and product-quality assessment. Therefore, we utilized the need scale from Sheldon [176] as described by [63] using a 7-Point Likert scale. For each participant, we computed the scales' means and calculated internal consistencies per scale (Cronbach's alpha, see Table 5.21) as well as scale intercorrelations with Kendall-Tau due to the non-parametric nature of Likert scales (and failed tests for normal distribution). Reliability of all subscales was acceptable (a $>$ 0.70). However, psychological needs showed correlation among each other, but redundancies of the correlations (average τ = 0.236) were not critical [178].

Moreover, hedonia and eudaimonia were assessed by including the HEMA questionnaire, again utilizing a 7-Point Likert scale [485, 183]. While eudaimonia is directly connected to need fulfillment (competence, self-actualization and popularity), positive affect, and meaning of an action, hedonic UX is a momentary pleasure resulting from the use of technology (connected with the psychological need of stimulation). Like Mekler and Hornbaek [183], we applied the scale for activities (not for motives), and asked participants: *"To what degree did you approach this driving experience with each of the following intentions?"* Also here we can report acceptable reliability scores (see Table 5.21) and observed no high correlation between these two constructs (τ = 0.202).

Product-Oriented Measures. As product-oriented measurement, we included AttrakDiff [216] and focused on the pragmatic and hedonic quality of stimulation in our analysis, as these subscales had an acceptable reliability (see Table

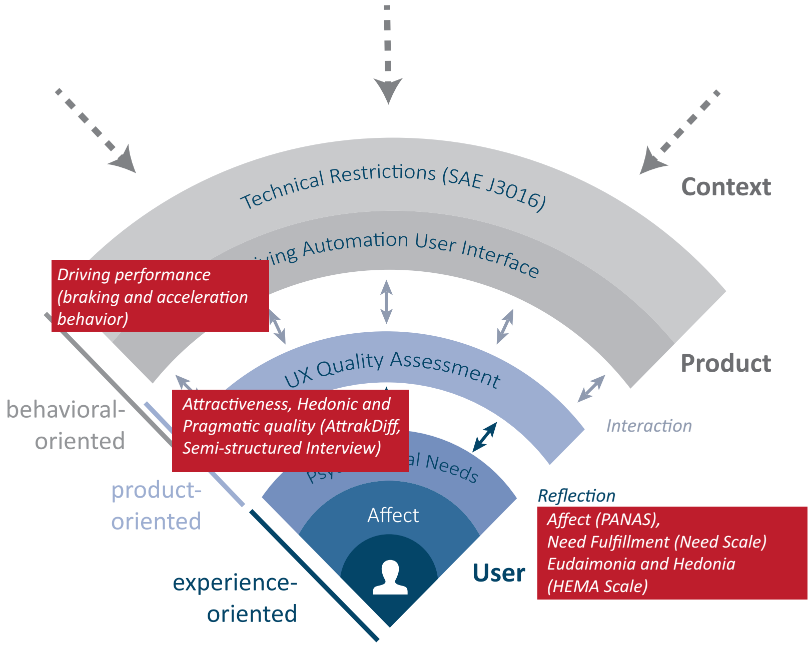


Figure 5.21: Application of the need-centered approach with the "DAUX Framework" in SAE L4/5 for evaluation.

5.21) and are correlated to each other (again not high enough for redundancy $\tau = 0.231$). Attractiveness and hedonic quality of identification had to be excluded, as the Cronbachs' alpha was not sufficient. Further, we conducted semi-structured interviews to gain insights about participants' reasons for their product evaluation.

Behavioral-Oriented Measures. In addition, to regard behavioral aspects, we recorded quantitative data on participants' driving behavior (number of lane changes, gas and brake actuation, and speed, only for the conditions MD and OC).

5.3.3.2 Results

All results with $p < 0.05$ are reported as statistically significant. As the collected measures did not follow a normal distribution, non-parametric tests (Friedman tests and Wilcoxon Signed-Rank post-hoc tests for the within-participant factors) were applied.

Dep. Variable	Items	Cronbach's α	Ref.
Experience-oriented Aspects:			
Affect			
Positive Affect (PA)	10	.91	[158]
Negative Affect (NA)	10	.88	[158]
Attentiveness	4	.90	[484]
Serenity	3	.82	[484]
Fatigue	3	.89	[484]
Boredom	2	.75	[484]
Psychological Needs	7	.82	[176, 63]
Autonomy (AUT)	3	.89	[176, 63]
Competence (COM)	3	.87	[176, 63]
Relatedness (REL)	3	.89	[176, 63]
Meaning (MEAN)	3	.78	[176, 63]
Stimulation (STI)	3	.75	[176, 63]
Security (SEC)	3	.72	[176, 63]
Popularity (POP)	3	.87	[176, 63]
HEMA			
Eudaimonia	4	.90	[485, 183]
Hedonia	5	.78	[485, 183]
Product-oriented Aspects:			
UX Qualities			
Pragmatic Quality (PQ)	6	.83	[206, 216]
Hedonic Quality of Stimulation (HQS)	6	.77	[206, 216]

Table 5.21: Summary of self-rating scales employed.

Experience-Oriented Aspects AD showed a significantly lower positive affect than MD and OC (Friedman's ANOVA: $\chi^2(2) = 110.04$; $p < .001$). Negative affect was rated low over all conditions, but still a significant difference between MD and AD is visible ($\chi^2(2) = 14.64$; $p = .001$). Multiple sub-scales of PANAS-X revealed statistically significant differences. Attentiveness was rated higher for MD than for OC and AD, and further OC higher than AD ($\chi^2(2) = 84.03$; $p < .001$). Also serenity (feeling relaxed and calm) showed differences between MD and AD ($\chi^2(2) = 20.61$; $p < .001$), while OC does not differ to the other two conditions. Fatigue as indicator for feeling drowsy/tired was rated highest for AD, and here all conditions differ significantly to each other ($\chi^2(2) = 79.42$; $p < .001$). Additionally, AD was rated to be more boring than MD and OC ($\chi^2(2) = 13.03$; $p = .001$, $T = 0.34$, $p = .029$), despite all conditions showing the same median value (see Table 5.22).

	MD (Mdn)	AD (Mdn)	OC (Mdn)
Positive Affect	4	2	3
Negative Affect	2	1	1
Attentiveness	4	2	3
Serenity	3	4	4
Fatigue	2	3.5	2
Boredom	2	2	2

Table 5.22: Values of participants' affect.

Regarding psychological need-fulfillment, the results of Friedman's ANOVA reveal significant differences between the conditions ($\chi^2(2) = 39.34$; $p < .001$). Wilcoxon and Bonferroni post-hoc tests show, that AD ($Mdn = 2$) fulfills significantly less needs than MD (Mdn = 5, T = -0.22, p = 0.001) and OC (Mdn = 4, T = -0.33, $p < .001$). A difference between MD and OC was not present. These effects also exist when comparing the different needs individually (see Figure). Autonomy ($\chi^2(2) = 68.30$, $p < .001$) and competence ($\chi^2(2) = 19.50$, $p < .001$) was significantly lower rated for AD (autonomy: Mdn = 2; competence: Mdn = 3) than for MD (autonomy: Mdn = 6, competence: Mdn = 5) and OC (autonomy:Mdn = 5, competence: Mdn = 5). In addition, meaning was less fulfilled during AD (Mdn = 3), but here only a difference to MD (Mdn = 4.0, T = - 0.46, p = .013) is visible. No significant effects could be determined for the other needs (stimulation, security, popularity, and relatedness), see Figure 5.22.

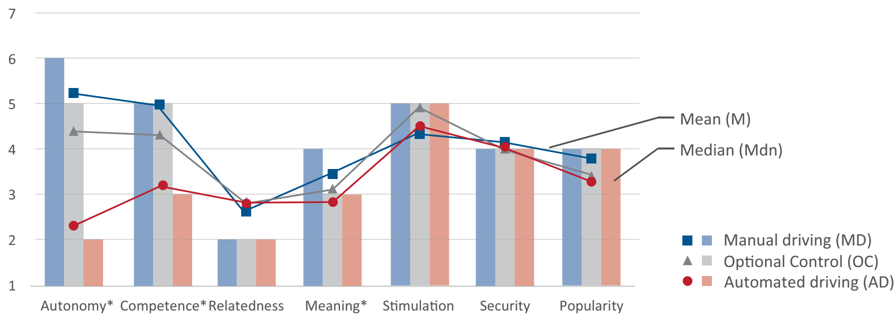


Figure 5.22: Values of participants' psychological need fulfillment. *Note: Significances are indicated by *.*

The HEMA scale shows an advantage of MD with respect to eudaimonia, while AD and OC had higher ratings for hedonia. Friedman's ANOVA ($\chi^2(2) = 31.66$; $p < .001$) and following post-hoc tests revealed significant differences for eudaimonia between AD and MD (T = -0.65, $p < .001$), and AD and OC (T = -0.50, p = .001). Similar effects for hedonia could not be discovered (see Table 5.23).

	MD (Mdn)	AD (Mdn)	OC (Mdn)
Eudaimonia	5	3	4
Hedonia	3	5	5

Table 5.23: Values of participants' ratings about hedonia and eudaimonia.

Product-Oriented Aspects Considering the pragmatic quality as product-oriented measure for UX, no difference was visible (Mdn = 5 for all three conditions). Hedonic quality of stimulation, on the other hand, showed significant effects ($\chi^2(2) = 20.75$; $p < .001$). Participants rated HSQ higher for AD (Mdn = 5, T = 0.27, p = .025) and OC (Mdn = 5, T = 0.40, $p < .001$) than for MD (Mdn = 4), while there were no differences between AD and OC (see Table 5.24).

	MD (Mdn)	AD (Mdn)	OC (Mdn)
Pragmatic Quality	5	5	5
Hedonic Quality (Stimulation)	4	5	5

Table 5.24: Values of participants' UX quality assessment.

We further conducted interviews (translated from German) with all participants to get additional insight in their personal mindsets. Asking them about their preferences in total 48% claimed OC to be the most enjoyable driving condition. Their reasons support our hypotheses as they stated to be in control and part of the driving process while still feeling relaxed and safe:

> *"it is more relaxing because you can hardly make errors, at the same time you still have the feeling be in control [...] there is no need to concentrate all the time"* (P9).

Another participant said:

> *"I would prefer Hotzenplotz at longer journeys, I am glad if there are times in which I do not have to do anything. But I also like to accelerate and takeover"* (P7).

Also participants emphasized that it was not as tiring as fully automated driving. In total 44% stated fully automated driving to be boring:

> *"It was really dull, I did not trust the system enough that I was able to relax, at one point I got tired but still wanted to monitor the system"* (P29).

Contrarily, 14.8% preferred the condition of AD, mainly because of the comfort to do nothing and the possibility to perform other side activities like working or watching a movie.*"At the beginning, it was really exciting. After a while I felt really relaxed"* (P28). Overall only 11% rated pure MD to be the potentially best method of car driving. They explicitly want to have full control and stated it to be most fun while fearing a decrease in safety due to the use of automation. *"I like driving, I do not want to do nothing, I also do not go to the beach in my holiday"* (P10). Some of them criticized not to know the system boundaries and that people might risk to test them out or trust the system too much. One participant expressed:

> *"I did not know what I was allowed to do and what not. I tried it, but then I had an accident. It was not possible for me to appraise the system correctly. Where are the boundaries between manual and automated driving?"* (P18)

Behavioral-Oriented Aspects Even if the usage of OC was just optional, almost all participants performed multiple lane changes ($M = 17.6$, $SD = 9.8$) and adjusted their speed frequently. We applied a Wilcoxon test to compare the actuation of the gas pedal between OC and MD. Gas pedal actuation (floating point number between 0 and 1) did not show significant differences between MD ($M = 0.29$, $SD = 0.10$) and OC ($M = 0.26$, $SD = 0.10$), $Z = 284.00$, $p = 0.150$. Brake pedal actuation, on the contrary, showed some significant differences ($Z = 324.00$, $p < .001$). During MD ($M = 0.07$, $SD = 0.08$) only 4 participants never pressed the brake pedal in contrast to OC with 13 participants ($M = 0.01$, $SD = 0.02$), here perfect automation (also automated braking) was immediately activated when no pedal was pressed. The speed of MD ($M = 139.30$ km/h; $SD = 19.69$) and OC ($M = 138.36$ km/h; $SD = 12.19$) did not reveal significant differences. Results indicate that in contrast to AD, users actively intervened in OC (gas and speed), however, did not feel the need to press the brake pedal as in MD only. These results confirm that the system provided in the OC condition was frequently used by participants.

Intercorrelation of UX aspects By calculating bivariate correlation with Kendall's Tau, we can observe a correlation between the general fulfillment of needs and the positive affect assessed by PANAS in all conditions (MD: $s = 0.535$, $p = .001$; AD: $s = 0.408$, $p = .007$; OC: $s = 0.363$, $p = .017$, PA and NA did not correlate in the individual conditions). Contrarily, negative affect does not correlate with the needs. This confirms results of existing work [63, 178], stating that positive affect is dependent on the users' need fulfillment. As no participants had a high negative affect in any of the conditions, a correlation between NA and need fulfillment is not visible. Regarding the results of the product-oriented measures, we can report differences between AD, OC, and MD after calculating bivariate correlations between need fulfillment and HQS/PQ (HQS and PQ do not correlate in the individual conditions). On the one hand, in AD as well as for OC, HQS correlates significantly with users' general need fulfillment (AD: $s = 0.416$, $p = .006$; OC: $s = 0.402$, $p = .010$). PQ does not have any significant effects on AD or OC. During MD on the other hand, PQ is significantly correlated ($s = 0.442$, $p = .004$) to user needs, while HQS is not. Regarding behavioral aspects, we see that OC is actively used by the participants, although there was no need for it. Based on these results, which show that participants already have an intention to use the OC system, and the positive results of the experience and product-oriented measures, we interpret correlations between all these three aspects.

5.3.4 Discussion

In the presented need-centered approach, we analyzed driving automation UX in SAE L4/5 by applying the "DAUX Framework". Thereby, our exploratory approach of the analysis aimed to reveal correlations of need fulfillment and specific driving scenarios (road type/traffic volume). Based on the qualitative results we postulated that cooperative control can enhance driving automation UX, which we were able to confirm by evaluation.

5.3.4.1 Relevant Psychological Needs

If there are no NDRTs to perform, people will be bored, get tired, and would frequently like to intervene. This is also especially critical for SAE L2/L3 (even though we tested here SAE L4/L5), in which drivers have to be kept in the loop for a safe take-over (see also Sections 5.1 and 5.2). The insights from the analysis helped us to understand that, e.g., lack of autonomy is not a general problem of automation [94, 65]. In a different environment, e.g., rural road, the psychological need of autonomy is mentioned in a less negative way. Further on, our approach revealed why a need is fulfilled or not. For example, also in urban driving, users' need for autonomy was not fulfilled - but here participants are not bored, they rather feel insecure. Based on the qualitative analysis, autonomy seems to correlate with a lack of stimulation in highway driving. In an urban area, however, a correlation exists between security and autonomy.
Thus, fully automated driving without any possibility to participate in the driving task might not be a good solution for all environments and all users. It may be accepted by potential users in urban environments, but in settings with higher speed (such as rural or highway driving), it fails to provide stimulating activities and makes people feel bored and out of control [94]. Automation amputates the users from meaningful interactions [483], thus the needs of autonomy, competence, meaning and stimulation have to be carefully regarded when designing for high and full driving automation.

5.3.4.2 Conceptualization of Psychological Needs

Considering presented results, we suggest the following recommendations for researchers and designers of automated driving systems to appropriately satisfy the need of autonomy, competence, meaning and stimulation:

As the results of our evaluation of participants' first impressions (during a highway drive with moderate traffic and short travel time) confirms, cooper-

ative/shared control interfaces that combine advantages of manual and automated driving will be more suitable in such a context to fulfill users' needs. Especially autonomy and competence were rated significantly lower for AD, compared to pure manual driving (MD) or cooperative vehicle control (OC). Manual driving further has a higher positive affect (PANAS) than fully automated driving - a result confirmed by investigation of the negative affect, where the result is reversed. PANAS-X scales show that MD has a higher need for attention, while drivers experiencing AD are more prone to fatigue and boredom. Cooperative control as hybrid solution resulted in nearly the same ratings for the psychological needs of autonomy and competence, and even received the highest value for stimulation (similarly to the hybrid coffee grinder concept presented by [483]. Interestingly, MD (which resulted in less hedonic quality than all other conditions) was rated highest for eudaimonia - we suppose this to be a habituation effect as users are already experienced with manual vehicle control for a long time. The full engagement in all driving tasks provides pleasure by supporting users' self-actualization/meaning, while OC is something new and innovative, which leads to fun and excitement. Providing solely the possibility for fully manually driving in between of fully automated driving without support might overwhelm users and raise safety problems caused by users' deskilling. Thus, systems are needed to support users. Further, the possibility to perform meaningful side activities while being driven may compensate this – fulfillment of the need of meaning, autonomy and competence can emerge from engagement in NDRTs (see Section 5.2) – but might not be fully compensating for all users as the wish was articulated by participants also to be important in the future. However, this needs to be investigated more deeply in future studies.
We conclude that a cooperative control interface in the context of driving automation has the potential to eliminate the loss of control problem of ADS [94] while maintaining the advantage of increased comfort and safety [98]. Assistant systems like the *"guardian angel"* [219], which override the human driver if it detects critical situations, could thereby help.

Further, we were able to confirm intercorrelations between experience and product-oriented assessment of UX, similar to existing studies [63, 178, 180, 183], see Subsections 2.1.2 and 2.2.1. Moreover, results confirm our initial assumption that with lower levels of automation (here represented by MD), primarily the pragmatic quality is crucial for users' need fulfillment and, thus, positive affect. In MD, more interaction with the vehicle is required and the user is more demanded on the operational and tactile level - which requires high information processing capacity and occupies working memory. With higher level of automation (here AD), hedonic quality becomes more important, as the user only interacts on tactical/strategical levels [57]). We found similar results for OC, which goes hand in hand with the ergonomic framework for shared control by [486]. If the driving task is too complex for the vehicle, users

have to take over, and their level of control changes from solely strategical to operational/tactical. Further, drivers perceive to reach a destination faster by going with a a manual vehicle than with an ADS [42]. If they believe that overruling of the automation would result in shorter travel time, but cannot intervene, they will feel less autonomous despite engagement in side activities. This may lead, as suggested by [103], to a decrease of the perceived usefulness and, as consequence, lower pragmatic quality - which is regarded as hygiene facto [211, 63, 180] for the acceptance of ADSs (see also Subsection 2.2.2).
Based on our results, we claim, similarly to [98], that takeover should also be voluntarily possible, based on the subjective internal and emotional state of the driver and deliver aids to maintain the comfort of driving automation.

5.3.5 Limitations

We included several contextual parameters in our explorative analysis, but a holistic contemplation of all possible parameters influencing UX is hard to achieve. In future work, additional factors such as trip duration, trip type (business, leisure, commute, etc.) or number of passengers need to be included. Hence, we should evaluate if satisfying other needs (such as relatedness or competence) are able to account for negative effects of ADS. Further, Eckoldt et al. [94] suggest unfulfilled needs could be compensated by a good relationship to other passengers or drivers. However, also concepts which create a relationship between the driver and the system, like the friendship between Michael Knight and K.I.T.T (in the Knight Rider series), can be an option to fulfill users' need of relatedness. Further, it need to be investigated if the possibility to engage in NDRTs as another context parameter has an impact on users' need fulfillment. While competence and autonomy will no longer be fulfilled by solving the driving task, but can still be fulfilled by successful office work [32, 33]. As with increasing automation hedonic quality will get more important, we have to deal with the shift from *"joy of driving"* to *"joy while driving"* [94]. Thus, we have to investigate how the need for security can be satisfied. This particular need seems to be the most important precondition of a good driving automation UX [487, 103, 488]. In the analysis, we saw differences between users' mindsets and personalities, which had an effect on the individual experience and thus acceptance of ADS. In future work, the diversity of users has to be analyzed by developing personas or assessing personality types, such as used in [100]. Additionally, results from analysis and evaluation are solely based on short-term sessions in the simulator to get participants' first impressions. Of course, a driving simulator cannot mimic real world behavior, which would result in further problems that we do not understand at this time. Nevertheless, by this methodology, we are able to derive and test ideas in a controlled environment and with rather high level of immersion (also in a short time period of 3x10 min) as compared to scenario descriptions, which rely on participants' pure imagination of an experience. Clearly, both longer trips and long system exposure (frequent use) may alter users' perceptions and consequently UX [165].

5.3.6 Core Findings

In the following, the core findings of this study answering **RQ3.3** are highlighted:

- **Certain activities and context factors lead to individual need profiles which have to be carefully considered while designing experiences for ADS.**
- **Highly/fully automated highway driving leads to boredom and a feeling out of control. Users still value pleasure of driving, hence, designing for "UX *of* driving" is also important in higher levels of automation.**
- **Optional cooperative control can improve UX *of* driving and prevent deskilling [489]. However, driving assistance systems with the ability to override the driver if necessary are imperative to preserve the main promise of driving automation, namely to increase road safety.**
- **Control possibilities over the automation, e.g., initiating overtaking or co-deciding where to park, should be always provided.**

6 Discussion and Derivation of Recommendations

Driving automation UX comes with many challenges like unsolved human-related issues of automation, individual requirements of the different levels of automation, and the uncertainty concerning individual and societal acceptance. The latter is especially important for the establishment of driving automation systems on the market. As positive user experiences with a product can support acceptance, everyone is currently talking about UX as the Holy Grail, but, in the development of driving automation systems UX research is still *"old wine in new bottles"* [132], as Bargas-Avila and Hornbaek postulated already back in 2011.
This doctoral thesis combined UX theory and insights from UX practice (RQ1) to develop an optimized approach for user interface development (RQ2). We applied the presented "DAUX Framework" in three case studies, each in a different level of automation to develop example interfaces that improve user experience in driving automation (RQ3). The postulated research questions and answers we got on them will be discussed in the following sections.

6.1 What Could We Learn from UX Practice (RQ1)?

Our investigations on UX practice show that UX is an emerging topic which also receives more and more attention in the automotive context for driving automation systems. Nevertheless, in driving automation human-factors/HCI research, it is still a side topic in contrast to safety, acceptance, and trust (see Subsection 3.2.2), though constructs are interrelated: Safety is a prerequisite for positive driving experiences which impact user acceptance and trust in automation. This has been already highlighted by related work [104], [16], and could be confirmed by the presented case studies (e.g., see Section 5.1). This shows the importance to investigate driving automation also from an experiential perspective and emphasizes the research gap which the presented doctoral thesis aims to close.

However, our detailed analyzes revealed that the state-of-the-art of UX practice still lacks quality. The literature review in academia about UX in general and interviews with UX professionals confirm the fundamental challenge that there is still no consistent understanding of the definition and concept of UX (cf. e.g., [129, 132, 153, 415]). We could show that there is a weak link between UX theory and applied methodological approaches. Researchers are not clear about the aspects UX involves, thus, also not about how to set up UX studies. This fuels discussions within and between teams and disciplines, and leads to a unilateral focus on pragmatic aspects (e.g., safety, usability, and functionality) and technology-centered development instead of user-centered processes. Hence, the presented fundamental challenge is also the reason for organizational and methodological challenges. While organizational challenges in the industry are difficult to solve from outside, academic UX research should set a good example. Nevertheless, similar discussions about UX and its value were also prevalent in our research team. Splitting up the umbrella term UX in its elements defined by UX theory (cf. [145]) helped us to create a consistent understanding and guided the triangulation of researchers with different backgrounds and experiences. Thereby, technological, human-factors, and experiential perspectives complemented without excluding each other. As according to holistic approaches of UX definition multiple elements lead to UX (cf. chapter 2), we argue, the collaboration of different disciplines is essential for successful UX research and design.

Further, while UX researchers tend to use more than one method, a sound sequential and concurrent triangulation approach on how to combine different methods as well as self-reported, behavioral and psycho-physiological data, is still missing. This is especially important for driving automation UX. The special characteristics of an in-vehicle UX created by a constant stream of many different experiences demand to investigate UX from different angles [133]. This again highlights the importance to unbundle the umbrella term UX in its elements using UX theory. For UX, traditional methods like semi-structured interviews and questionnaires are often used, collection methods from other constructs can enrich UX studies and help to move from investigating only the expressible to tacit and latent aspects of UX [242]. Thus, in our case studies, in addition to self-reported data from interviews and questionnaires, we involved methods collecting behavioral data like driving or TOR performance but also psychophysiological measures like Galvanic Skin Response (GSR).

While general UX studies often used high-fidelity prototypes or market-ready products, driving automation UX studies have to deal with the immaturity or non-existence of driving automation systems especially of higher levels. Most driving automation UX studies were performed in the lab using a driving simulator or a wizard-of-oz setup. Thus, context as an important impact factor of UX and the system itself has to be simulated (see Section 2.3). To provide a more realistic experience than solely by static text or sketches as AV representation (cf. [104]) the presented case studies were all conducted in a high-fidelity driving simulator (hexapod, moving platform), using simulation software and storytelling to bring users in the context of highway driving. Although there is a need to confirm results for the real world, the study results of all three case studies are comparable as they are gained by a controlled and repeatable experiment. Further, while general UX studies showed a positive development regarding the conduction of long-term studies, academic and industrial driving automation UX studies are mostly conducted in single sessions. Although we are aware of the problematic, also the case studies were performed due to organizational issues only in single sessions. Hence, long-term effects of developed user interface examples on UX, and consequences on individual and societal acceptance, have to be investigated in future studies, see Section 7.4.

6.2 How Could UI Development be Optimized (RQ2)?

Based on UX theory and insights from UX practice this thesis aimed to optimize the development of UIs of driving automation systems. Therefore, to address the identified fundamental challenge and with it also related to organizational and methodological challenges in UX research practice, the "DAUX Framework" embedded in a need-centered development approach was proposed (see chapter 4). The framework unfolds the different layers of an experience based on UX theory, thus, unbundles the umbrella term UX in its components as Tractinsky [145] recommends. By visualization of the different layers of UX, the "DAUX Framework" raises awareness for the core of a positive experience, and finally creates a consistent understanding of what UX means in the context of driving automation. This facilitated communication about connected and involved aspects of UX in our interdisciplinary team and especially supported sequential and concurrent triangulation for optimized development of driving automation UIs. The benefits of the proposed triangulation strategies are discussed in the following.

6.2.1 Sequential Triangulation by Need-Centered Development

Based on insights of UX theory, related driving automation studies (e.g., [193, 195, 103]) and, due to the emphasis on the importance of needs of UX practitioners in industry, a need-centered development approach was suggested. As the satisfaction of users' psychological needs, which differs regarding context and technical restrictions of the different levels of automation, is the core of positive experiences, these have to be centered in the development process. This is also highlighted in the visualization of the "DAUX Framework". Basic psychological needs identified by Sheldon et al. [176] are of course broad concepts, but easy to understand as they can be related to personal every-day experiences. But reasons for satisfaction or non-satisfaction of a certain need can differ, as we could also show in the analysis of SAE L4/5 (see Section 5.3). Thus, a fine-grained analysis of implications of context factors, level of automation, individual user differences, and intended product character, is necessary. Our case studies firstly identified relevant psychological needs for a certain context and level of automation and user group. Insights regarding need-fulfillment were used as a source of inspiration for hypothesis/concept development, which was then tested in an evaluation phase. The combination of need-centered analysis, design, and evaluation thereby fosters sequential triangulation [258], thus, iterative user-centered design [67].

By applying this approach we were able to prove the existence of *halo-effects* [204, 205, 206, 203] and intercorrelation of the constructs trust and UX in the case study of SAE L2. We identified by a related work analysis the need of security as most relevant. In the evaluation phase of different IVIS qualities, the need for security was then verified as subjectively perceived as fulfilled or not fulfilled as well as other needs related to the IVIS versions, with implications on users' braking behavior, UX quality assessment, affect and trust.
Conducting a qualitative analysis, regarding users' needs during conditional driving automation (SAE L3) helped to understand the impact of TORs on the overall journey experience. But, in combination with evaluation using qualitative and quantitative methods, we revealed that the proposed interface example, which aimed to balance drawbacks and using benefits of this level of automation, was not able to create positive affect. Only negative affect could be decreased. Thereby, the fulfillment of the need for security by the example UI confirms the assumption to be a hygienic factor, as also already revealed by related studies [103]. This emphasizes the need for sequential triangulation and iterative user-centered design. An analysis alone might imply wrong assumptions for product design. In the presented case study, our design decisions were not able to satisfy further relevant psychological needs which might be able to create positive affect. Thus, more iterations are necessary to improve UX of the presented interface by better fulfilling these.
The case study of SAE L4/5 highlighted how important it is to regard need-fulfillment in different contexts. Individual need-profile [178] emerged from road-type and traffic volume. The developed interface example, which was able to improve driving automation UX on highways by satisfying identified relevant needs, might not satisfy these in a different context.

6.2.2 Concurrent Triangulation by the "DAUX Framework"

To further improve driving automation UX practice, the need-centered development approach with the involved "DAUX Framework" aims to guide concurrent triangulation. Besides the focus on users' psychological needs, it additionally gives a guideline on how to study UX in evaluation studies. The visualized layers of UX, based on UX theory, automatically imply a strategy for concurrent triangulation of *behavioral, product-* and *experience-oriented* methods. Hence, researchers and practitioners can derive which methods must be involved to study UX at a certain level of automation. Thereby, different disciplines, contributing with their individual expertise, can collaborate to reach the overarching goal, creating positive experiences by fulfilling users' needs. Further, adequate data triangulation meets expectations from academia and industry on quantitative objective results about UX for summative evaluation but also reveals insights about reasons for a certain UX quality. These are important to inform design for an iterative development process (formative evaluation). Therefore, besides mixing different perspectives on UX, also different data types (quantitative and qualitative) have to be triangulated.

Applying this approach led to several insights. In SAE L2, results from concurrent triangulation showed that users' trust did not match with objective system performance which also led to implications on users' driving performance. UX and trust have often been mixed in existing driving automation (e.g., [104]) but also in UX studies (e.g., [274]). We argue that UX researchers and designers have to differentiate between them, but also give attention to both, especially in lower and safety-critical levels of automation. Influences of the visual representation conveying a degree of professionalism impact evaluation results on concepts aiming to calibrate trust (e.g., reliability displays [96], [36]. Such effects can be only revealed by concurrent triangulation. Further, results retrieved from different perspectives imply to question the usefulness of introducing SAE L3 on the market not only from safety but also from an experiential perspective. Users felt (experience-oriented) and rated the system better when they did not engage in NDRTs but monitored the driving performance (behavioral-oriented). If researchers only had regarded product-quality, results would have shown that users rate the AV with ATHENA better than without UI and might lead to wrong assumptions. Only regarding behavioral aspects would show effects on safety but would miss revealing that such an interface keeping the driver in the loop does only reduce negative affect but is not able to create pleasure, which is essential that users are willing to use a system. Similar interacting effects between components of UX could also revealed by applying the concurrent triangulation strategy in SAE L4/5. The framework helped to understand if users' needs could be fulfilled while interacting with the example UI of the AV and lead to actual positive affect, a good UX and thus a positive assessment of the product quality.

Applying both triangulation strategies in all three case studies reveals several insights regarding driving automation UX methodology. Overall, the need-centered approach applying sequential triangulation supported the development of valuable user interfaces by explaining, exploring, and validating results. Concurrent triangulation implied by the embedded "DAUX Framework" optimizes UX practice by regarding UX from different angles to cross-validate findings and enrich researchers' understanding of the overarching phenomenon of driving automation UX which is influenced by a stream of multiple experiences. Hence, case studies can be seen as examples on which future research in industry and academia can orientate to improve driving automation UX. Due to methodological improvements of driving automation UX practice, we are also able to derive recommendations for driving automation UI development, discussed in the following section.

6.3 How to Design Driving Automation UIs (RQ3)?

The application of the "DAUX Framework" in the different case studies, each in a different level of automation, showed that each level of automation is highly individual. Technical restrictions users have to deal with differ, thus, recommendations for UI development have to be automation-level specific. However, UX designers must be aware that they are not designing for specific vehicles categorized in different auomation levels. According to SAE J3016 [47]:

> *"The levels apply to the driving automation feature(s) that are engaged in any given instance of on-road operation of an equipped vehicle. As such, although a given vehicle may be equipped with a driving automation system that is capable of delivering multiple driving automation features that perform at different levels, the level of driving automation exhibited in any given instance is determined by the feature(s) that are engaged"* (p. 2).

Weather and road maintenance conditions (e.g., lane markings and construction sites) can change the level of automation of a vehicle due its ODD. With the engagement of specific driving automation features performing at different levels also users' role changes from an active driver to a passive passenger. Consequently, an AV needs to adapt its user interfaces to the level which is currently engaged to create positive experiences. By the presented case studies we developed example interfaces. Of course, many other possibilities exist to fulfill users' needs to create positive experiences, nevertheless, recommendations how to design driving automation UIs can be derived. These are discussed in the following, see Table 6.1.

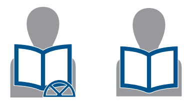
Engaged Level of Automation	**SAE L2**	**SAE L3**	**SAE L4/L5**
			
Technical Restrictions	Users are still drivers and have to monitor system performance and intervene if necessary.	User have to be fall-back-ready. They are allowed to engage in NDRTs, however, have to expect to receive a request to take-over control in a timely manner.	There are no technical restrictions anymore, users can do what ever they want.
Relevant Psychological Needs	Security	Security, Autonomy, Competence, Stimulation	Autonomy, Competence, Meaning, Stimulation
REC'S	**R-L2-1**: Objective safety is the prerequisite of positive driving automation experiences.	**R-L3-1**: Objective safety is the prerequisite of positive driving automation experiences.	**R-L4/5-1**: Objective safety is the prerequisite of positive driving automation experiences.
	R-L2-2: Creating a subjective feeling of safety to improve driving experiences and preventing overtrust have to be balanced in design.	**R-L3-2**: User interfaces keeping the driver in the loop, e.g., reliability displays, improve driving automation experiences.	**R-L4/5-2**: Control possibilities on driving automation should be provided for users.
	R-L2-3: High quality of all in-vehicle systems improves overall driving automation experience, but emerging halo-effects have to be carefully regarded in UI design.	**R-L3-3:** Comfortable engagement in NDRTS should be supported, e.g. by combination of both visual and auditory interfaces.	**R-L4/5-3**: Beside UX while being driven, UX of driving should be supported to create positive driving automation experiences, e.g., optional cooperative control.
	R-L2-4: To prevent halo-effects causing overtrust user interfaces, e.g., reliability displays, have to create awareness for users' responsibility.	**R-L3-4**: Anthropomorphic systems can improve driving automation experience, however, have to be carefully designed to prevent reactance.	**R-L4/5-4**: User interfaces which allow cooperative control have to be supported by assistant systems to ensure safety.

Table 6.1: Recommendations for driving automation UI development.

6.3.1 Recommendations for SAE L2

At this level, we identified the need of security as the most critical to be regarded in user experience design. Thereby, it has to be differentiated between objective safety and subjectively felt safety. Both are connected to the need of security, the hygienic factor for UX [176, 178, 103]. Only if users arrive safely at their destination, the need of security can be fulfilled and positive experiences enabled. Thereby, the temporality aspect of UX has to be carefully regarded. One negative experience or stories from others (also reported by media, e.g., Tesla accidents [14]) will affect future experiences regarding the subjective feeling of safety. Hence, systems have to be designed to ensure objective safety as this is the prerequisite of positive driving automation experiences (**R-L2-1**).

Further, creating subjective safety should be carefully balanced to prevent overtrust (**R-L2-2**). Our results showed subjective feeling of safety is not necessarily connected to the objective performance of the automation. Although e.g., there is heavy rain and low visibility, the fulfillment of users' need of security might be supported by diverse aspects of a car objectively not connected to safety, e.g., UX quality of other in-vehicle systems. Our study showed that *halo-effect* can create overtrust [424, 401]. While these effects are positive for e-commerce businesses, for car manufactures they can have fatal consequences as recent incidents such as the accidents with Tesla Autopilot or the Uber self-driving taxi [423]) showed. To prevent such effects, of course, car manufacturers should not reduce UX quality of exterior, interior, and UI design. Our results showed that high visual aesthetics created positive affect, thus, high quality is important to maintain competitiveness. However, the phenomenon of *halo-effect* should be kept in mind during design processes (**R-L2-3**). Concepts have to be developed that create an awareness of the user's responsibility and also emphasize safety criticality (**R-L2-4**). In particular, if the vehicle can also be driven in higher levels of automation, the change in the user's responsibility must be made directly perceptible. Reliability displays, making current system performance of users accessible, have already been proven to have positive effects on trust calibration and user experience [440, 97, 96], [36].

As we concentrated at this level on the need for security, it makes it difficult to create positive affect, as the fulfillment of this need can be seen as hygienic factor [176, 178, 103]. Nevertheless, users' enthusiasm for the new technology and new brands, like Tesla, can be assumed to approach users' needs of stimulation and popularity and creating positive experiences (cf. YouTube videos of users' reactions on Tesla). Further, approaches of manual vehicles (e.g., Clique Trip [193, 192]) are still relevant to create positive driving experiences also for this level of automation.

6.3.2 Recommendations for SAE L3

In SAE L3, we identified the needs of security, autonomy, competence, and stimulation as the most relevant to be fulfilled for positive driving automation experiences. Again as already for SAE L2, objective safety is the prerequisite for a positive experience. The most safety-critical part in this level are take- and hand-overs (**R-L3-1**), which need to be designed in a way that users' safety is assured. Furthermore, TORs are also from an experience perspective critical. Due to the temporality aspects of UX, the mere possibility of a TOR affects the whole journey experience. We could show, that a reliability display keeping users in the loop also during automated driving cud improve the driving experience as users felt more secure and relaxed, but also competent in handling the driving task, which also had positive effects on users' reaction times, thus, objective safety (**R-L3-2**).

Nevertheless, keeping the driver in the loop contradicts to the promise of SAE L3, that users are able to engage in NDRTs, which is highly valued by users. Thus, comfortable and safe NDRT engagement should be supported by user interfaces (**R-L3-3**), e.g., a concept which allows user to take-over and steer with a tablet computer which they used during engaged automation [218] could improve UX quality assessment. Further, multi-modality of a reliability display, e.g., visual, auditory and even olfactory relaibility displays can improve comfort and increase NDRT performance [36]. An anthropomorphic agent also showed positive effects on the UX quality assessment of the AV, nevertheless was differently rated by individual users. Thus, such voice user interface needs to be carefully designed to prevent that users feel infantilized and get annoyed (**R-L3-4**).

Overall, also at this level, we had difficulties to create a positive driving automation experience. We could only improve the experience by reducing users' negative affect. As TORs are critical from the perspectives of safety and experience, an introduction of this level on the market should be further discussed [460]. Negative experiences due to actual accidents or critical situations can also affect future experiences and thus also acceptance of highly and fully automated vehicles. As we could show, keeping the driver in the loop could improve the driving experience, car manufacturers should consider staying at SAE L2 with a clear responsibility at any time with the drivers so that they are always prepared to intervene in a safe, relaxed and in an unafraid way.

6.3.3 Recommendations for SAE L4/5

In SAE L4/5, the users become to passive passengers. They can do whatever they want. However, what at first glance sounds perfect, as we revealed, driving on a free highway contains the problem that users feel out of control and amputated from the meaningful interactions of driving. Thus, we identified the needs of autonomy, competence, meaning, and stimulation as the most relevant to fulfill. We could show, providing an interface for optional cooperative control can improve the driving experience [490], as users feel more autonomous, competent and in the position that they do something meaningful. Hence, we argue, control possibilities must still be provided (**R-L4/5-2**), e.g., by the possibility to introduce overtaking if users don't want to follow a truck anymore, or let users decide where the car is parking [16]. Further, *UX of driving* should still be maintained. On the one hand, driving fun is the USP of several car manufacturers, e.g., Ferrari. On the other hand, there will be always users who love the joy of driving who have to be considered by car manufacturers (**R-L4/5-3**).

Nevertheless, in these high levels of automation safety is still a prerequisite for positive experiences. The main benefit of driving automation systems is the societal benefit of increased road safety [50]. If drivers still go with 200 km/h on our highway and have positive experiences, individual safety, and overall increased road safety cannot be assured due to the limited predictability of the human driver. Thus, user interfaces need to be designed to reduce the chance for accidents, e.g., the Guardian Angel [219] system, which overrides the driver in critical situations (**R-L4/5-1, R-L4/5-4**). Trendsetting ideas are in demand. Horse-riding or skiing were once being mobility solutions and have become popular sports. Fun-parks for car driving, for example, are imaginable in the future.

7 Conclusion

The wish for mobility always inspired innovations that have made the world faster, better connected, and human life more convenient. But existing automotive solutions can be and have to be further improved to make traveling even safer, cleaner and more comfortable. The next and already ongoing step is the automation of driving. As individual and societal acceptance are dependent on users' experiences, UX is a major success factor for the introduction and establishment of automated vehicles in the different levels of automation on the market and fundamental to keep individual and societal promises. Therefore, the predominant technology-centered development processes have to be extended by an additional human-centered perspective. Hence, the overall goal of this doctoral thesis was the derive a practical need-centered development approach for user interfaces that support users during their drives to create positive driving automation experiences. The final chapter concludes this doctoral thesis by a summary, highlights contribution of this thesis, and addresses limitations as well as possibilities for future work.

7.1 Summary

The presented work used a three-fold approach to study driving automation UX and develop an optimized development approach for driving automation UIs. After reviewing UX theory and related work in the field, which showed that a satisfactory systematic approach to study driving automation UX is still missing, UX practice of academia and industry was analyzed in more detail. We conducted two literature reviews, one for UX research in general and another for driving automation in general, and a literature study with UX practitioners from industry working on driving automation UX **(RQ1)**. Results indicate that there is still no consistent understanding across departments and disciplines what UX means. This leads to technology- instead of need-centered processes in which organizational issues still prevent a real iterative design process. As it is unclear which aspects need to be studied to access UX, mostly traditional methods like interviews and self-defined questionnaires are conducted, without a clear strategy on how to apply triangulation in a meaningful way to get a more reliable, holistic and well-motivated understanding of UX. The temporality of UX is mainly ignored and quantitative results are favored.

To improve UX practice **(RQ2)**, this thesis presented the “DAUX Framework” which is part of a need-centered development approach. This was inspired by UX theory and related studies. The focus of this approach is on fulfilling users’ needs whose prioritization differs regarding context and situation. Therefore, sequential triangulation, by using qualitative approaches to reveal which needs are relevant in a certain context and level of automation, and evaluation of a developed user interface example by mixing behavioral-, product-, and experience-oriented data as concurrent triangulation strategy are recommended. Thereby, the presented “DAUX Framework” gives a guideline by unbundling and visualizing related components of UX, which automatically implies a certain method selection to study UX from different perspectives.

The need-centered process is then applied in three case studies to develop example user interfaces which improve driving automation UX **(RQ3)**. Each case study regards a different level of automation (SAE L2, L3, and SAE L4/5), however, all investigated the context of highway diving. The framework helped to substantiate hypotheses and facilitated discussions in the interdisciplinary team about the right method selection to study UX relevant constructs for evaluation. Results of the presented case studies are important findings for driving automation UI development.
Regarding SAE L2, overtrust/overreliance has already led to fatal accidents. Thus partial driving automation may not be safely possible without making system performance accessible to drivers, e.g., by reliability displays. The results of our study give insights in how the stream of experiences combining performance, usability, and aesthetics of different vehicle subsystems correlate and influence each other. This emphasizes the importance of a joint contemplation of driving automation UX by an interdisciplinary team of UX, trust and safety researchers.
Further, the safety problem of SAE L3 driving was highlighted by various studies. A lot of effort is invested to reduce take-over times. However, combining methods from safety but also emotional research shows the difficulty also from an experience perspective. In SAE L4 users still wish to have a possibility to intervene. The presented interface for optional cooperative control is no real solution that should be built like our prototype, however, it is an example of how an increased user autonomy can enhance the joy of driving, thus, user experience.

Finally, the results obtained by answering the presented research questions are discussed and requirements for driving automation UI development derived.

7.2 Contributions

By presenting a need-centered development approach for driving automation UX, this doctoral thesis contributes to:

- **Uncovering existing problems and challenges of UX practice in academia and industry:** The systematic literature reviews, as well as the interview study with UX practitioners, revealed that, although UX seems to get more popular, existing practices lack quality. The origin lies in the nature of the umbrella term, which seems to be treated either as *"all or nothing"*, leading to organizational and methodical problems. Uncovering existent challenges offers a starting point to develop methods that solve identified issues. The proposed approach, based on insights from UX practice, is only one solution. Other researchers and practitioners can use revealed information about the state-of-the-art in different ways to improve driving automation UX design.

- **Bridging the gap between academia and industry:** The state-of-the-art analysis included both academia and industry, and revealed that they are facing similar issues. The proposed need-centered approach with the embedded "DAUX Framework" aims to address both parties. As my personal background is in academia, the framework also aims to bring scientific quality concerning reliability and validity into the industry. Case studies, which were conducted in an academic setting to reveal requirements for driving automation UI development, should inspire industry. Ardito et al. [246] recommended a closer collaboration in empiric research to improve development processes. We agree, argue, however, that improvements are necessary on both sides. The presented approach is a first step to create mutual understanding, necessary for reciprocal inspiration.

- **Closing the gap between different disciplines involved in the development process of driving automation systems:** Results revealed that a gap exists not only between academia and industry, but especially between disciplines within teams. The proposed "DAUX Framework" unfolds the umbrella term UX in its components and demonstrates the importance to involve different perspectives, e.g., on safety, design, emotions, to work in collaboration for one goal – improve driving users' driving automation UX by fulfilling users' needs.

- **Creating a consistent understanding about what UX means in the context of driving automation:** By the visualization of the different UX layers based on UX theory in the "DAUX Framework" it gets clear which aspects have to be regarded in UX studies. This facilitates communication in interdisciplinary teams and moves the term UX away from only being a buzzword.

- **Optimizing UX practice by the proposal of guidelines for sequential and concurrent triangulation:** Triangulation is an approach to improve empirical research [256], which could be revealed as lacking in existing studies. The "DAUX Framework" gives a guideline on how to study UX by identifying relevant needs for a specific level of automation and context, and shows how to evaluate developed concepts aiming to address identified needs by triangulating behavioral-, product-, and experience-oriented methods. The guideline still gives researchers the freedom to decide which specific methods to use. Presented case studies are examples of how to apply the proposed triangulation strategies. Of course, dependent on the research question to be answered an individual method mix is required. Therefore, specific expertise are necessary, which highlights the importance to triangulate researchers in UX studies, i.e., collaboration. While the "DAUX Framework" is in particular developed for driving automation UX, the approach can also easily be adapted to develop UIs for other products.

- **Development of driving automation UIs by making automation level-specific UX recommendations:** Presented case studies applied the proposed need-centered approach to develop example user interfaces which aimed to address relevant identified psychological needs of a specific level of automation to create positive experiences. The results of the studies gave insights into important circumstances that need to be carefully regarded in UX design. Based on this, concrete level-specific requirements are formulated which should especially help the automotive industry to design for positive driving automation experiences.

7.3 Limitations

The presented research of this doctoral thesis has several limitations, which are summarized in the following section.

The literature reviews were conducted in 2017 (2010-2016) and in 2019 (2010-2018). Thus, progress in UX research practice, which happened in the last few years is not considered anymore. UX practice quality in industry is also very dependent on the general mindset of a company, the conducted study involved only a small sample of UX practitioners. All of them were working for or with European car manufacturers. Differences in the Asian and the US automotive industry would be interesting to regard as well, especially to new companies like Tesla, Waymo, and UBER. Further, analyzing UX practice in industry from an academic perspective is difficult because deep insights into the daily work are missing. Statements of interviews, so to say at second hand, have to be carefully treated, as employees might be biased and not allowed to talk freely due to confidentiality regulations.

The proposed "DAUX Framework" embedded in a need-centered development approach can optimize driving automation UX practice, however, not fully solve all challenges. By creating a consistent understanding, it sets only the basis to create a common mindset that has positive impacts also on organizational and methodological issues. But still, UX practitioners will face the challenges of fast-pace development processes for which the proposed approach is not providing a solution. The framework does not address the temporality of UX. Moreover, as the presented case studies show, the "DAUX Framework" does not work similarly in every project. It is only a tool to facilitate studying driving automation UX. Further expertise and UX knowledge are still necessary to know how to apply it and to choose the right method mix to answer a postulated research question.

The case studies applying the need-centered approach only regarded the context of highway driving. As the analysis of SAE L4/5 showed, different contextual factors, e.g., traffic volume, lead to different need profiles which have to be considered. The case studies show static user interfaces for the determined context parameter to be able to conduct a controlled experiment in the driving simulator. In reality, user interfaces have to be highly adaptable and react to contextual changes immediately. This emphasizes the necessity to evaluate concepts in real-world conditions. Yet, it is not yet clear if similar effects which we revealed by the diving simulator experiments can also be proven on real roads. Especially experience-oriented insights might differ towards the fact of a real safety-critical environment. Further, long-term effects, especially on individual acceptance, have to be investigated. Therefore, also a broader user group has to be investigated considering individual differences, e.g., personality, gender, age, and culture. Our studies focussed only on younger tech and design-savvy users who mainly grew up and live in Europe. Hence, postulated requirements can only be regarded as proven for the context in which they were revealed.

7.4 Future Work

To extend the presented work, the "DAUX Framework" should be applied in industrial projects supported by academic UX research to evaluate if identified fundamental, organizational, and methodical challenges can be addressed in long term. Thereby, like driving automation UIs, also the approach should be iteratively improved and continually developed. More workshops together with academic and industrial UX researchers should be conducted to keep identified challenges uptodate as they may change over time. This would further strengthen the collaboration between academia and industry. Moreover, a holistic set of methods allocated to the behavioral-, product-, and experience-oriented perspectives should be created and maintained. Similar to the idea of `allaboutux.org`, a platform could help UX practitioners from all over the world to exchange views and experiences to improve UX practice. Further, future work should also investigate driving automation UX in long-term studies and on real roads, which was already highlighted in the limitations. As driving automation systems of higher level do not yet exist, insights from today are only assumptions which need to be proven later if possible. As we claim, positive user experiences are essential creating individual and societal acceptance, large-scale and ongoing acceptance studies have to be conducted to supervise the establishment of driving automation systems on the market. Correlation of UX, trust and acceptance should be further investigated from a theoretical perspective. Furthermore, the usefulness of the "DAUX Framework" should also be tested for other technologies and products.

7.5 Closing Remark

Driving automation comes with many promises like increased road safety, improved traffic flow, mobility for new target groups, and more leisure time. But there is still skepticism in the society which need to be carefully regarded because it can prevent a holistic establishment of driving automation systems on the market. Especially in the crisis of the automotive industry, traditional processes have to be revised and the focus shifted from money-making to the fulfillment of human needs. Thereby, users are not professionals who have to deal with human-related issues of automation. As users spend their private time and money, their expectations on having positive experiences in the car have to be met. This is important to regain trust and to bind customers for the future. Hence, all promises which are given by the concept of driving automation require advanced technology, but in addition intelligent and well-designed UI concepts to support the user during the drive. A focus on users' psychological needs helps to create positive experiences in the different levels of automation. While still many questions regarding driving automation are unanswered and circumstances unknown, the "DAUX Framework" embedded in a need-centered development approach provides a guideline for driving automation research and development. This will iteratively improve driving automation user experiences for the future and bring mobility to the next higher level of innovation.

A Original Publications

In the following all published papers are listed. Equal contribution of co-authors is highlighted by *.

A.1 List of Core Publications

[1]: I. Pettersson*, F. Lachner*, A.-K. Frison*, A. Riener, and A. Butz, "A Bermuda Triangle?," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 2018, vol. 2018-April, pp. 1-16. (Honorable Mention Award)

[2]: A. K. Frison*, Y. Forster*, P. and Wintersberger*, V. Geisel*, S. Hergeth, and A. Riener, "Where We Come From and Where We Are Going: A Review of Automated Driving Studies," *Transp. Res. Part F Traffic Psychol. Behav.*, Under Revision, 2020.

[3]: Y. Forster*, A.-K. Frison*, P. Wintersberger*, V. Geisel*, S. Hergeth, and A. Riener, "Where We Come From and Where We Are Going," in *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct Proceedings - AutomotiveUI '19*, 2019, pp. 140-145.

[4]: A.-K. Frison, "User Experience of Automated Driving: From a Buzzword to a Real Concept for Automated Driving User Interface Development," in *User eXperience Design in the Era of Automated Driving*, Springer-Verlag, 2020, In Press.

[5]: A.-K. Frison*, P. Wintersberger*, A. Riener, C. Schartmüller, L. Boyle, E. Miller, and K. Weigel *"In UX We Trust,"* in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, 2019, pp. 1-13.

[6]: A.-K. Frison, P. Wintersberger, A. Oberhofer, and A. Riener, "ATHENA: Supporting UX of Conditionally Automated Driving with Natural Language

Reliability Displays," in *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct Proceedings - AutomotiveUI '19*, 2019, pp. 187-193. (Honorable Mention Award)

[7]: A.-K. Frison, P. Wintersberger, T. Liu, and A. Riener, "Why Do You Like to Drive Automated?," in *Proceedings of the 24th International Conference on Intelligent User Interfaces - IUI '19*, 2019, vol. Part F1476, pp. 528-537.

[8]: A.-K. Frison, P. Wintersberger, A. Riener, and C. Schartmüller, "Driving Hotzenplotz," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '17*, 2017, pp. 236-244.

[9]: A.-K. Frison, P. Wintersberger, and A. Riener, "Resurrecting the ghost in the shell: A need-centered development approach for optimizing user experience in highly automated vehicles," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 65, pp. 439-456, Aug. 2019.

A.2 Clarification of Contributions in the Core Publications

The following table clarifies my contribution to the core publication and lists the contributions of my co-authors.

Publ.	My Contribution	Contribution of Others
[1]	I came up with the original research idea together with Ingrid Pettersson at the Dagstuhl Seminar "Automotive User Interfaces in the Age of Automation" in 2016. The idea was further developed in collaboration with Florian Lachner who joined later. The publication benefited from iterative refinement and discussions among us first three authors. We contributed equally to process definition, publication identification, paper coding, and paper writing, thus, we are all leading authors of the publication (author order was selected randomly). Together with Florian Lachner, I was responsible for data analysis and processing. Efforts were rewarded by an Honorable Mention Award at CHI.	Andreas Riener and Andreas Butz provided feedback on the project and the publication, as well as supported paper writing.

Publ.	My Contribution	Contribution of Others
[2],[3]	I came up with the original research idea, based on the UX literature review study and invited Yannick Forster and Philipp Wintersberger to collaborate in this project. Victoria Geisel joined later. The literature review strategy was developed in joint workshops. All first four authors contributed equally to process definition, publication identification, paper coding, and paper writing of both publications. Together with Philipp Wintersberger, I was in particular responsible for data analysis and data processing.	Andreas Riener and Sebastian Hergeth provided feedback on the project and the publication. Andreas Riener commented and edited the manuscript.
[4]	I came up with the research idea, study setting, and interview questions. I organized and conducted the interviews, performed the content analysis, and wrote the book chapter.	Andreas Riener provided feedback on the project.
[5]	The original research idea to investigate the correlation of UX and trust evolved over a long time period together with Philip Wintersberger, Andreas Riener, and Linda Boyle. Philipp Wintersberger and I contributed equally to study design and paper writing (bringing together both perspectives: UX and trust), thus, we are both leading authors of the publication. I initiated the methodological approach applying the DAUX Framework, was responsible for the IVIS designs, study conduction, and statistical analysis.	Andreas Riener supervised the project, contributed to study design, and supported paper writing. Philipp Wintersberger implemented with the help from Clemens Schartmüller the IVIS prototype as well as the driving simulation. Clemens Schartmüller supported the study conduction and paper writing, as well as performed the data processing of the GSR data. Linda Boyle and Erica Miller contributed to the study design during my research stay at the University of Washington and edited the manuscript for clarity and readability. Klemens Weigel supported the statistical analysis.
[6]	I came up with the original research idea and study design. I initiated the methodological approach applying the DAUX Framework, supervised the implementation of the prototype, study planning, and study conduction. I statistically analyzed the collected data and was the leading author of the publication which was rewarded with an Honorable Mention Award at AutomotiveUI.	Amelie Oberhofer developed the prototype and conducted the study in her bachelor thesis. Philipp Wintersberger supported study implementation and contributed to paper writing. Andreas Riener provided feedback on the project and the publication, as well as commented and edited the manuscript.
[7]	The original research idea and study design were developed together with Philipp Wintersberger. I initiated the methodological approach applying the DAUX Framework, conducted the study, performed the content analysis, and was the leading author of the publication.	Tianjia Liu implemented the driving simulations in his master thesis, supported study conduction and supported the content analysis by coding a subset of the narratives to ensure high interrater-reliability. Philipp Wintersberger supervised the driving simulation implementation, supported study conduction as well as the content analysis by coding a subset of the narratives to ensure high interrater-reliability, and contributed to paper writing. Andreas Riener provided feedback on the project and the publication, as well as commented and edited the manuscript.

Publ.	My Contribution	Contribution of Others
[8]	I came up with the original research idea and developed the concept and study design. I initiated the methodological approach applying the DAUX Framework, conducted the study, performed the data analysis and was the leading author of the publication.	Philipp Wintersbeger and Clemens Schartmüller supported the implementation of the prototype, study conduction and paper writing. Andreas Riener provided feedback on the project and the publication, and supported paper writing.
[9]	The journal article is a combination of both before reported studies/publications [7, 8]. I came up with the idea and the concept of this publication and was the leading author of the article.	Philipp Wintersberger contributed substantially to the publication. Andreas Riener commented and edited the manuscript.

Table A.1: Overview of core publications included in this thesis and clarification of contributions.

A.3 List of Further Publications

These publications are not directly part of this thesis, however, important contributions during the process of my doctoral studies. Partially, argumentation and formulations of these publications are adopted by this doctoral thesis.

[10]: M. Braun, S. T. Völkel, H. Hussmann, A.-K. Frison, F. Alt, and A. Riener, "Beyond Transportation," in *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '18*, 2018, pp. 175-180.

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B Driving Automation Literature Review Tables

In the following all tables of the literature review, regarding constructs, collection methods and parameters are listed.

Collection Method for Safety (n)	Parameter	n_p
TOR Performance (58)	Reaction Time	70
	Lateral Position	18
	Time to Collision	15
	Speed Parameters	10
	TOR Timing	10
	Acceleration	9
	Braking	7
	Steering Wheel Angle	5
	Distance Front	4
	First Driving Action	4
	Number of Collisions	4
	Disengagements	3
	Lane Change Parameters	3
	Steering	3
	Accuracy	2
	NDRT Engagement	2
	Accident Avoidance Ranking (AAR)	1
	Number of Interactions	1
	N/D	7
Driving Performance (24)	Lateral Position	13
	Speed Parameters	9
	Reaction Time	7
	Time to Collision	5
	Acceleration	3
	Steering Wheel Angle	3
	Braking	2
	Lane Departure Parameters	2
	Number of Collisions	2
	Automation Enabled/Disabled	1
	Distance Front	1
	Overtakings per km	1
	Steering	1
	N/D	1
Eye Tracking / Gaze Behavior (12)	Gaze Percentage	9
	Gaze Duration	6
	Gaze Number	3
	Glancing Behavior	3
	Reaction Time	3
	Pathways	1
	Saccade	1
Observation (12)	Crossing Behavior	2
	NDRT Engagement	2
	Reaction Time	2
	Accuracy	1
	Automation Enabled/Disabled	1
	Braking	1
	Crossing Time	1
	Gaze Number	1
	Number of Collisions	1
	Situation Criticallity	1
	Steering	1
	Time to Collision	1
	N/D	2
Self-Defined Questionnaire (11)	*N/D*	10
	Accuracy	1
Standardized Questionnaire (6)	Scale for Criticallity Assessment of Driving and Traffic Scenarios	2
	Cooper Harper Rating Scale (CHRS)	2
	Auditory Urgency Scale	1
Secondary Task Performance (3)	NDRT Engagement	1
	Reaction Time	1
	N/D	1
Interviews (2)	Semi-Structured Interview	2
Matching (1)	Accuracy	1

Table B.1: Safety Collection methods and parameters.

Collection Method for Trust (n)	**Parameter**	$\mathbf{n_p}$
Self-Defined Questionnaire (19)	*N/D*	19
Standardized Questionnaire (17)	Automation Trust Scale (ATS)	12
	Interpersonal Trust Scale (ITS)	1
	Van-der-Laan Acceptance Scale	1
	Trust in Technology Scale	1
	Trust Perception Scale-HRI	1
	Propensity to Trust Scale	1
	N/D	1
Observation (5)	Body Pose/Movements	4
	Acceleration	1
	Brake	1
	Driving Action	1
	Gaze Duration	1
	Reaction Time	1
	Steering	1
	Waiting Time	1
Interviews (4)	Semi-Structured Interview	3
	Structured Interview	1
Eye Tracking / Gaze Behavior (4)	Gaze Duration	2
	Gaze Percentage	1
	Glancing Behavior	1
	Gaze Number	1
Driving Performance (1)	Braking	1
	Steering	1
Decision Game (1)	*N/D*	1
TOR Performance (1)	Reaction Time	1

Table B.2: Trust collection methods and parameters.

Collection Method for Acceptance	**Parameter**	$\mathbf{n_p}$
Standardized Questionnaire (18)	Van-der-Laan Acceptance Scale	10
	Unified Theory of Acceptance and Use of Technology (UTAUT)	4
	Technology Acceptance Model (TAM)	3
	Car Technology Acceptance (CTAM)	2
	Willingness to Ride Scale	1
	Perceived Behavioral Control (PCB)	1
	System Usability Scale (SUS)	1
	Personal Innovativeness Scale	1
Self-Defined Questionnaire (13)	*N/D*	13
Observation (3)	Automation Enabled/Disabled	1
	Reaction Time	1
	N/D	1
Driving Performance (1)	Proportion of Manually Driven Scenarios	1
Interviews (1)	Unstructured Interview	1
Focus Group (1)	*N/D*	1
Secondary Task Performance (1)	NDRT Engagement	1

Table B.3: Acceptance collection methods and parameters.

Collection Method for Workload (n)	**Parameter**	$\mathbf{n_p}$
Standardized Questionnaire (22)	NASA-TLX	17
	Driver Activity Load Index (DALI)	2
	Rating Scale Mental Effort (RSME)	1
	Scale for Subjectively Experienced Effort (SEA)	1
	Global Mental Workload Measurement	1
Self-Defined Questionnaire (4)	*N/D*	4
Secondary Task Performance (4)	NDRT Performance	2
	Twenty Question Task (TQT)	1
	Surrogate Reference Task (SURT)	1
Observation (1)	*N/D*	1
Interviews (1)	Semi-Structured Interview	1
Eye Tracking / Gaze Behavior (1)	Glancing Behavior	1
Driving Performance (1)	Steering Wheel Angle	1

Table B.4: Workload collection methods and parameters.

Collection Method for General Attitude (n)	**Parameter**	$\mathbf{n_p}$
Self-Defined Questionnaire (15)	*N/D*	15
Interviews (5)	Semi-Structured Interview	4
	Unstructured Interview	1
Standardized Questionnaire (2)	BIG 5	2
Observation (1)	*N/D*	1

Table B.5: General Attitude collection methods and parameters.

Collection Method for Situation Awareness (n)	**Parameter**	$\mathbf{n_p}$
Eye Tracking / Gaze Behavior (7)	Gaze Duration	5
	Gaze Number	4
	Gaze Percentages	3
	Glancing Behavior	2
	Blink Behavior	1
	Reaction Time	1
Self-Defined Questionnaire (6)	*N/D*	6
Standardized Questionnaire (3)	Situational Awareness Rating Technique (SART)	3
Probing (2)	Situation Awareness Global Assessment Technique (SAGAT)	3
TOR Performance (2)	Lateral Position	2
	Reaction Time	2
	Acceleration	1
	Time to Collision	1
Interviews (2)	Semi-Structured Interview	2
Observation (1)	Accuracy	1
	Reaction Time	1
Secondary Task Performance (1)	NDRT Performance	1

Table B.6: Situation Awareness collection methods and parameters.

Collection Method for Stress (n)	Parameter	n_p
Standardized Questionnaire (6)	Short Stress State Questionnaire (SSSQ)	3
	Dundee Stress State Questionnaire (DSSQ)	2
	Driver Stress Inventory (DSI)	1
Heart Rate Variability (4)	HR (BPM)	2
	Physical Position	1
	Root Mean Square of Successive Differences (RMSSD)	1
GSR (2)	AmpSum	1
	ISCR	1
	nSCR	1
	SCR	1
	PhasicMax	1
	N/D	1
Eye Tracking / Gaze Behavior (1)	Gaze Duration	1
	Gaze Number	1
Self-Defined Questionnaire (1)	*N/D*	1
Observation (1)	Body Pose/Movements	1
Interviews (1)	Semi-Structured Interview	1
EMG (1)	*N/D*	1
Driving Performance (1)	Automation Enabled/Disabled	1

Table B.7: Stress collection methods and parameters.

Collection Method for Interaction Behavior (n)	Parameter	n_p
Observation (6)	Walking Behavior	2
	Automation Enabled/Disabled	2
	Glancing Behavior	1
	Pathways	1
	Reaction Time	1
	NDRT Engagement	1
	N/D	2
Standardized Questionnaire (3)	Brief Sensation Seeking Scale (BSSS-8)	1
	Pedestrian Behavior Questionnaire (PBQ)	1
	Theory of Planned Behavior (TPB)	1
Self-Defined Questionnaire (2)	*N/D*	2
Eye Tracking / Gaze Behavior (1)	Gaze Percentages	1
Interviews (1)	Semi-Structured Interview	1
Secondary Task Performance (1)	Single-Choice Quiz	1

Table B.8: Interaction Behavior collection methods and parameters.

Collection Method for Drowsiness/ Fatigue (n)	Parameter	n_p
Standardized Questionnaire (7)	Karolinska Sleepiness Scale (KSS)	4
	Driver Stress Inventory (DSI)	1
	Multidimensional Fatigue Inventory (MFI)	1
	Self-Assessment Manikin (SAM) Scale	1
	Dundee Stress State Questionnaire (DSSQ)	1
Self-Defined Questionnaire (2)	*N/D*	2
Observation (2)	Yawning	1
	Blink Behavior	1
	N/D	1
Driving Performance (1)	Reaction Time	2
	Lateral Position	1
Eye Tracking / Gaze Behavior (1)	Glancing Behavior	1
UX-Curve (1)	*N/D*	1

Table B.9: Drowsiness/ Fatigue collection methods and parameters.

Collection Method for UX	Parameter	n_p
Standardized Questionnaire (4)	AttrakDiff	2
	User Experience Questionnaire (UEQ)	1
	Van-der-Laan Acceptance Scale	1
	Hedonia and Eudaimonia (HEMA) Scale	1
	Sheldon's Need Scale	1
Interviews (4)	Semi-Structured Interview	4
Self-Defined Questionnaire (2)	*N/D*	2
Driving Performance (1)	Acceleration	1
	Braking	1
	Speed Parameters	1
	Number of Lane Changes	1
Observation (1)	*N/D*	3
Heart Rate Variability (1)	HR (BPM)	1
UX-Curve (1)	*N/D*	1
Think Aloud (1)	*N/D*	1
Sorting (1)	*N/D*	1

Table B.10: UX collection methods and parameters.

Collection Method for Productivity (n)	Parameter	n
Secondary Task Performance (6)	NDRT Performance	8
	NDRT Engagement	3
	Accuracy	3
	Body Pose/Movements	1
	N/D	1
Driving Performance (1)	Accuracy	1
	Reaction Time	1
Observation (1)	Accuracy	1
Interviews (1)	Semi-Structured Interview	1
Eye Tracking / Gaze Behavior (1)	Gaze Percentages	1

Table B.11: Productivity collection methods and parameters.

Collection Method for Comfort (n)	Parameter	n_p
Self-Defined Questionnaire (7)	*N/D*	7
Standardized Questionnaire (2)	Multidimensional Driving Style Inventory (MDSI)	1
	Technology Acceptance Model (TAM)	1
	Unified Theory of Acceptance and Use of Technology (UTAUT)	1
	User Experience Questionnaire (UEQ)	1
Driving Performance (1)	Acceleration	1

Table B.12: Comfort collection methods and parameters.

Collection Method for Emotions (n)	Parameter	n_p
Standardized Questionnaire (4)	Positive and Negative Affect Scale (PANAS)	2
	PANAS-X	1
	Affect Grid	1
	Multi-Modal Stress Questionnaire (MMSQ)	1
	Affect Scale	1
Self-Defined Questionnaire (4)	*N/D*	3
	Russel's Circumplex Model	1
Observation (1)	Percentage of Detected Emotions	1
	Facial Expressions	1
Interviews (1)	Semi-Structured Interview	1
Think Aloud (1)	*N/D*	1

Table B.13: Emotions collection methods and parameters.

Collection Method for Usability (n)	**Parameter**	$\mathbf{n_p}$
Self-Defined Questionnaire (4)	*N/D*	4
Standardized Questionnaire (3)	System Usability Scale (SUS)	3
	Input-Output Questionnaire	1
Interviews (2)	Semi-Structured Interview	2
Think Aloud (1)	*N/D*	1

Table B.14: Usability collection methods and parameters.

Collection Method for Cognitive Processes	**Parameter**	$\mathbf{n_p}$
Self-Defined Questionnaire (3)	*N/D*	3
EEG (2)	*N/D*	2
Detection Task (1)	Accuracy	1
	Reaction Time	1
Driving Performance (1)	Lateral Position	1
	Time Headway	1
Standardized Questionnaire (1)	Driver Stress Inventory (DSI)	1

Table B.15: Cognitive Processes collection methods and parameters.

Collection Method for Motion Sickness (n)	**Parameter**	$\mathbf{n_p}$
Standardized Questionnaire (4)	Sickness Questionnaire (SSQ)	3
	Motion Sickness Assessment Questionnaire (MSAQ)	1
Self-Defined Questionnaire (1)	*N/D*	1
Heart Rate Variability (1)	HR (BPM)	1
Driving Performance (1)	Motion Sickness Dose Value (MSDV)	1

Table B.16: Motion Sickness collection methods and parameters.

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