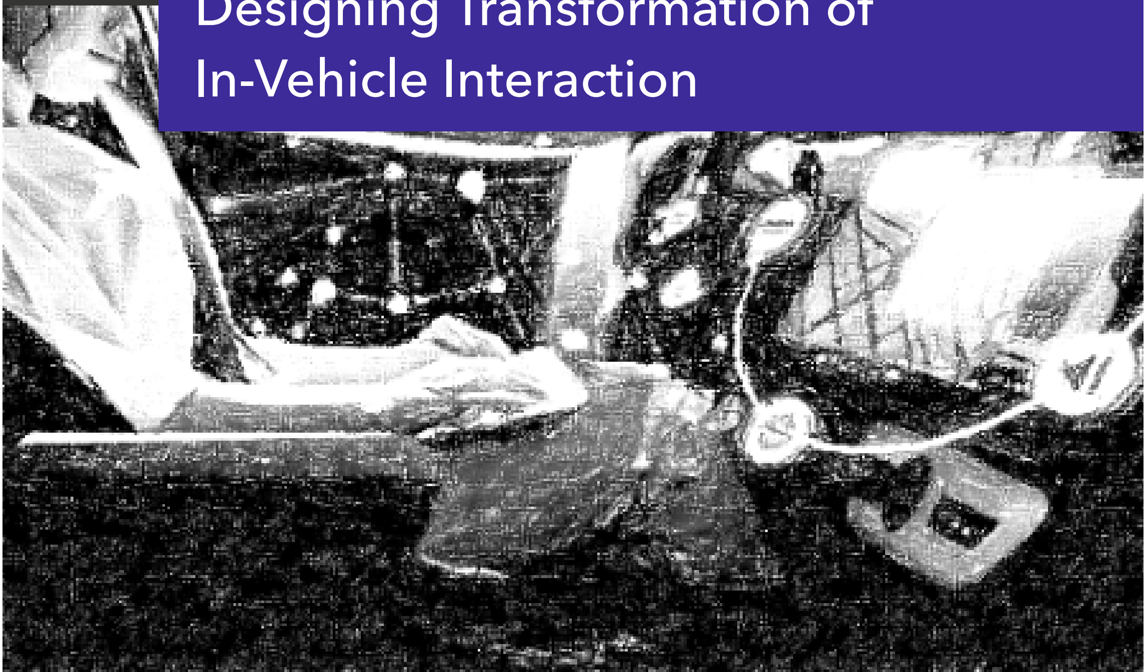
HUMAN-COMPUTER INTERACTION

Henrik Detjen

Towards Autonomous Mobility: Designing Transformation of In-Vehicle Interaction



Towards Autonomous Mobility: Designing Transformation of In-Vehicle Interaction

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Henrik Detjen
aus
Bremen

1. Gutachter: Prof. Dr. Stefan Schneegass
2. Gutachter: Prof. Dr. Stefan Geisler
3. Gutachter: Prof. Dr. Alexander Meschtscherajakov

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ABSTRACT

With constantly growing automation capabilities in vehicles, the way we interact with them has already begun to change. Whereas automotive design has been based on technical considerations (speed, handling, etc.) for a long time, the non-involvement of the human in the driving task, creates new requirements while being mobile. Not only will drivers become passengers, but the classical journey, e.g., visiting a friend in the next town, might start by foot and E-Bike, continue per train, and end with ordering an autonomous Robotaxi for the last mile. Given the service orientation of future mobility, the *journey experience* will be what users care for, and in that sense, the experience that fits their needs best.

In this thesis, we provide answers to the question of how users' needs and goals will change in future autonomous mobility services compared to today's individual transport. Thereby, we focus on in-vehicle interaction between users and vehicle automation. Further, we look at how to improve the users' safety and overall experience during automated and autonomous driving modes. In particular, we aim to bridge the gulfs of evaluation and execution of automated driving. We design and evaluate interfaces that are based on user needs and goals and provide them with maneuver-based control to intervene in the driving process and augmented reality interfaces that help understand and predict the vehicle's driving process. From these design studies, we derive lessons learned and design recommendations for future automated vehicles.

This thesis contributes to the understanding of user needs and goals for future automated vehicles and corresponding design requirements, and, thus, helps to shape the transformation towards autonomous mobility.

Zusammenfassung

Mit den ständig wachsenden Automatisierungsmöglichkeiten in Fahrzeugen hat die Art und Weise, wie wir mit ihnen interagieren, bereits begonnen, sich zu verändern. Während das Fahrzeugdesign lange Zeit auf technischen Erwägungen (Geschwindigkeit, Fahrverhalten usw.) beruhte, entstehen durch die Nichtbeteiligung des Menschen an der Fahraufgabe neue Anforderungen an die Mobilität. Nicht nur der Fahrer wird zum Passagier, auch die klassische Reise, z.B. der Besuch bei einem Freund in der nächsten Stadt, könnte zu Fuß und mit dem E-Bike beginnen, per Bahn fortgesetzt werden und mit der Bestellung eines autonomen Robotaxis für die letzte Meile enden. In Anbetracht der Dienstleistungsorientierung der zukünftigen Mobilität wird das *Reiseerlebnis* das sein, worauf die Nutzer Wert legen, und in diesem Sinne das Erlebnis, das ihren Bedürfnissen am besten entspricht.

In dieser Arbeit geben wir Antworten auf die Frage, wie sich die Bedürfnisse und Ziele der Nutzer bei zukünftigen autonomen Mobilitätsdienstleistungen im Vergleich zum heutigen Individualverkehr verändern werden. Dabei konzentrieren wir uns auf die Interaktion zwischen den Nutzern und der Fahrzeugautomatisierung. Darüber hinaus untersuchen wir, wie die Sicherheit und das Gesamterlebnis der Nutzer beim automatisierten und autonomen Fahren verbessert werden können. Insbesondere versuchen wir, die Kluft der Bewertung und der Ausführung des automatisierten Fahrens zu überbrücken. Wir entwerfen und evaluieren Schnittstellen, die sich an den Bedürfnissen und Zielen der Nutzer orientieren und ihnen eine manöverbasierte Steuerung bieten, um in den Fahrprozess einzugreifen, sowie Augmented-Reality-Schnittstellen, die helfen, den Fahrprozess des Fahrzeugs zu verstehen und vorherzusagen. Aus diesen Designstudien leiten wir Erkenntnisse und Designempfehlungen für zukünftige automatisierte Fahrzeuge ab.

Diese Arbeit trägt zum Verständnis der Nutzerbedürfnisse und -ziele für zukünftige automatisierte Fahrzeuge sowie der entsprechenden Designanforderungen bei und hilft so, den Wandel zur autonomen Mobilität zu gestalten.

Preface

This thesis presents the work I have done at the University of Applied Sciences Ruhr West in partnership with the University of Duisburg-Essen over the past six years. During this period, I collaborated with various researchers, practitioners, and students with diverse backgrounds. Out of these collaborations, several papers emerged that are integral to this thesis. Each chapter clearly states the contributing authors, who are co-authors of the respective papers, and at the end of the thesis, individual contributions are highlighted, too. Throughout this thesis, I use the scientific plural "we" to emphasize the illustrated joint efforts.

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Introduction & Background

Chapter 1

Introduction

For a long time, shifting gears has been an important part of car user interfaces, allowing the motor to transmit force to the crankshaft. However, automatic gear shifts have become a more affordable and comfortable alternative to manual shifting. Nowadays, automated gear shifts perform their duties more efficiently than most human drivers, which has led to increased use and acceptance of this technology and fewer cars that require a gear shift. Furthermore, classical gear shifts are becoming obsolete in electronically driven cars. This trend toward automation will likely continue for many other tasks that people currently have to do in their cars. As a result, user interface elements of cars designed for driving tasks will change accordingly. The industry aims to automate all human driving-related tasks in the car, promising comfort, safety, and a new era of mobility. Eventually, the human will become a passenger in a vehicle driven by an artificial chauffeur, much like a passenger driven by a taxi driver today. The user will simply tell the car where to go.

Nowadays, people often face this or similar visions of personal transportation, and interest in vehicle automation continues to increase. Some embrace the idea of autonomous driving, seeing it as an opportunity for unique experiences, such as using their car as a mobile office or living room or taking advantage of shared car services. Others are hesitant about the changes automation may bring, as they may not fully grasp the capabilities of such systems and are, therefore, reluctant to rely on them. As vehicle technology continues to evolve rapidly, it is crucial to keep users in mind, prioritize their needs, and develop systems that they find acceptable instead of driving innovation from a purely technical perspective. Consequently, we are focused on understanding the *human aspect* and its role in the development of technology in the automotive industry.

In this thesis, we explore the needs and goals of automated vehicle users and how these needs may differ from those of currently available vehicles. We focus on the potential possibilities and use cases for future autonomous mobility services where the system can take complete control, at least for a certain time. By providing insights from the users' perspective, we aim to inform design directions that enhance acceptance and improve the design of human-system cooperation.

Moreover, we address fundamental challenges in the transformation of human-system cooperation. Firstly, we investigate how the current driving task, which involves controlling and supervising the vehicle, will change in future cars. We anticipate that the driving task will primarily become a configuration task. After setting up a specific driving configuration, users may still want to take control from time to time. However, constant vehicle control on a fine-grained level will not be necessary for highly automated vehicles, as the system will be able to drive safely while users are engaged in other non-driving-related tasks. The user will only need to set directions and adapt situation-wise. This fundamental shift in the driving task requires new interaction paradigms. We demonstrate how future vehicle control based on simple maneuver commands can be designed and show its feasibility in different interaction scenarios. On the other hand, while not concerned with driving, the users might still wish to know how the system handles the driving task in order to get acquired to the situation as a passenger, or, if they are needed as a fallback for the machine, to safely retake the driving responsibility. We provide insights into improving the design of aspects of the automation's driving task performance, such as increasing the system's transparency with augmented reality applications so that the users can better understand and predict the automation capabilities to handle a specific driving scenario.

1.1 Research Questions

	#	Research Question	Chapter
	PART II: UNDERSTANDING USER NEEDS & GOALS IN TRANSITION TO AUTONOMOUS MOBILITY		
Goal-centered	**RQ_II**	**How to will user needs and goals change in autonomous mobility services?**	
	RQ_II-1	How is a real-world experience changing needs and goals?	Chapter 3
	RQ_II-2	How to assess diverging patterns of needs and goals?	Chapter 4
	RQ_II-3	How to include users with special needs and goals?	Chapter 5
	PART III: BRIDGING THE GULF OF EXECUTION IN AUTOMATED DRIVING		
Cooperation-centered	**RQ_III**	**How to bridge the gulf of execution in automated driving?**	
	RQ_III-1	How would users express maneuvers via voice or mid-air gestures?	Chapter 6
	RQ_III-2	Which direct input modality is most feasible for expressing driving maneuvers?	Chapter 7
	PART IV: BRIDGING THE GULF OF EVALUATION IN AUTOMATED DRIVING		
	RQ_IV	**How to bridge the gulf of evaluation in automated driving?**	
	RQ_IV-1	Can augmented reality benefit vehicle automation User Onboarding processes?	Chapter 8
	RQ_IV-2	How to communicate the system's motion intents on the virtual windshield?	Chapter 9
	RQ_IV-3	Should the system repeatedly warn about potential hazards on the virtual windshield?	Chapter 10

Table 1.1: Summary of primary (in bold) and secondary research questions addressed in this thesis regarding the changing interaction with vehicle automation.

On the way from modern vehicles with assistant systems that allow for assisted and partly automated driving to future, entirely autonomous mobility, technological challenges arise and challenges from the human perspective. This thesis tackles challenges for future mobility users in three fundamental areas. First, from the interaction perspective, we address *goal-centered* challenges (*RQII*, part of the thesis labeled as *Understanding User Needs & Goals in Transition to Autonomous Mobility*). Here, we seek to understand how automation changes individuals' mobility behaviors and perceptions. Based on this user and context analysis, we then address *cooperation-centered* challenges. We investigate how driving-related interaction design should look like to enable and keep a highly comfortable, safe, and acceptable form of communicating intentions from human to the car (*RQIII*, thesis part labeled as *Bridging the Gulf of Execution in Automated Driving*) and vice versa (*RQIV*, thesis part labeled as *Bridging the Gulf of Evaluation in Automated Driving*). Table 1.1

shows the main categories with the research questions addressed in each part and chapter.

Vehicle automation shifts the human driver's role from actively involved in the driving task to being a task-free passenger during the autonomous driving phases. Suppose the system can handle the driving task in all situations. In that case, the passenger can be continuously involved in non-driving-related activities. Thus, the first question focuses on eliciting a realistic prediction about automated cars' use and perception (*RQII-1*). We see that these perceptions can vary; consequently, it is crucial to handle diverging user needs (*RQII-2*). Commonly, technology design founds on the needs and requirements of the average potential user. Especially marginalized societal groups, such as persons with physical or mental limitations, are typically not considered average. Thus, we are interested in integrating their views to get a whole picture of the potential autonomous mobility brings (*RQII-3*).

After understanding user-related challenges for future mobility will define the goals and context of interaction with automated vehicles, we dive deeper into interaction-related challenges during autonomous driving. We focus on the changing driving task that will mostly remain with the car. However, from time to time, the human might want to or sometimes even have to intervene in the driving process and adjust or take over the task – depending on the automation's capabilities to handle the driving situation. For quick and comfortable interventions in the driving process, traditional car interfaces (steering wheel and pedals) might not be the best option. Instead, alternative concepts of cooperative control are required for humans to express their intentions to control the driving task. Consequently, we investigate how to design control interventions for widely- and well-known interaction modalities, namely voice, touch, and mid-air gestures, from a user perspective (*RQIII-1*) and compare their feasibility for interaction (*RQIII-2*).

After exploring comfortable ways the system's driving for humans to execute the driving task temporarily, the last part deals with the meantime when the system performs the driving task. A system must be transparent to be an accepted and trustworthy cooperation partner. Thus, this category's first question is about building a precise mental model of the system's capabilities and responsibilities before the driving task is performed (*RQIV-1*). During a ride, the system should communicate its intentions to be predictable and transparent. Consequently, we are interested in strategies that enhance communication system intentions (*RQIV-2*) to get a better understanding of 1) what the car is about to do and strategies that help efficiently warn about potentially critical situations while 2) maintaining the user experience (*RQIV-3*).

1.2 Research Method

Different design paradigms influence our research approach. This section describes the most influential paradigms before integrating them into a common perspective.

1.2.1 Users, Activities and Interaction

As usual in the field of Human-Computer Interaction (HCI), and contrasting to many technological-driven engineering fields, our approach relies on integrating human needs in technological progress and design from the beginning. We utilize the *User Centered Design* process as described by Norman and Draper [ND86] in his famous book "The design of everyday things" and later standardized in ISO DIN 9241-210 [Int19]. After the initial system idea development, the User-Centered Design (UCD) process includes four main phases to meet the users' requirements: 1) Context of Use (identifying product stakeholders and tasks), 2) Requirements, 3) Prototyping, and 4) Evaluation. The procedure ensures that the design of cars not only focuses on the technological solution but also considers the future user with all needs and requirements. Therefore, it catalyzes individual acceptance of technology or, the other way around, prevents designs that are likely to be rejected. However, in 2005, the same Norman, was one of the UCD pioneers, published an article called "Human-centered design considered harmful". In this article, he questions the focus on the end user for innovative product designs. He pleads for integrating designers' and domain experts' views into product development. Users, in our case, vehicle users, are neither design nor domain experts. Instead, they use transportation services and are good at describing experienced problems with them. However, designers probably know the right tools for solving these problems or creating new experiences. Mobility experts can contribute to a deep understanding of the system beyond using a product or service. Thus, it is beneficial to integrate these complementary perspectives in the design process, e.g., combining literature reviews, expert workshops, and user opinions in the analysis phase. In a later version of the book “The design of everyday things”[Nor13], Norman acknowledged this circumstance and added a chapter to extend the UCD perspective with a broader view on the whole activity that a product supports and *could* support. *Activity Centered Design* (cf. [Nor05; Nor13; Nar96]) bases on the Activity Theory [KKB95; BB03] which defines activities as a set of goal-directed actions influenced by co-workers, tools, communities, or rules. The *Seven Stages of Action* model by Norman [Nor05] provides a fine-grained explanation of actions that form activities. The model describes the process steps involved in interacting with a system, emphasizing the underlying goal execution and evaluation. We use the previously described design and interaction models to approach the design for interaction with future automated vehicles.

1.2.2 Our Research Approach

Activity-Centered Design (ACD) inspires the research approach of this thesis. Nevertheless, we focus on the users’ perspective, which gives our approach certain proximity to UCD. However, to better understand the users’ perspective on changing in-car activities, we use the *Seven Stages of Action Model* [Nor05] by Norman (cf. Figure 1.1). Norman’s model describes the process from goals to concrete actions. Actions or tasks consist of atomic operations and are concrete behaviors that contribute to an overarching activity. For instance, a “turn left” with the car consists of multiple steering and brake/acceleration pedal adjustments and contributes to reaching the desired destination. We are interested in the overarching journey activity – to the workplace, the supermarket, or a friend in the next town. With automation, the journey’s predominant driving-related sub-activities become less relevant. In contrast, new sub-activities become more relevant or even possible. This shift towards

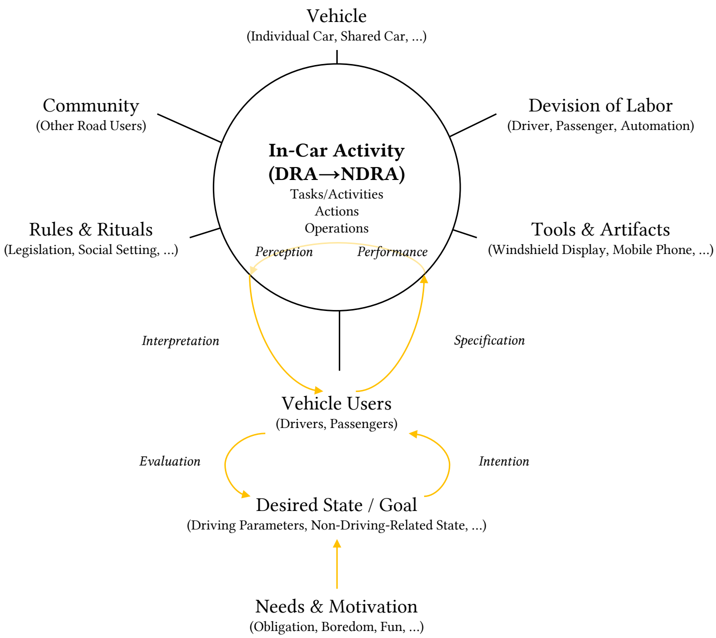


Figure 1.1: The Activity-Centered Design inspired approach to design future driving-interaction in the transition from driving- (DRA) to non-driving-related activities (NDRA) – integrated with Norman's seven stages of action model and underlying human needs.

being a passenger in the future car changes the activities and the activity context in multiple ways as described in ACD (upper circle in Figure 1.1):

- The *Division of Labor* changes: The automation can or is even required to (e.g., emergency braking) take control over the driving task. Human drivers and passengers might also conduct the car or configure their driving style preferences.
- The road's *Community* changes: The more the automation is in charge

of the driving activities, the more these artificial drivers have to communicate with other (human) road users.

- The technology evolves, and vehicle technologies, too. Thus in-car *Tools & Artifacts* change: Future cars will likely include windshield displays and open up the possibility to use personal devices.
- *Rules & Rituals* change: regulations will be (and are already) adapted to automated driving, and one can spend free time with others.
- The *Vehicle* used for a journey will change: Shared car concepts will become more effective, and the interior will adapt to the changing activities.
- The *Vehicle User*'s roles will change. Accordingly, their needs and requirements will adapt to the new roles and the changing overall journey context.

These descriptions of the main perspectives on the journey activity include just a few examples of the change dynamics but already illustrate the design space complexity. The lower part of Figure 1.1 shows the detailed users' perspective on the activity by utilizing the seven stages of action model. The model describes how human actions are formed and evaluated against a specific goal. Human needs influence the motivation to reach a certain goal (cf. Maslow [Mas43] or Herzberg's Two-Factor Theory [ASM17]). Consequently, our approach starts with an extra step/stage of understanding the user goal's underlying *Needs & Goals*. Transferring a goal into a task consists of forming the intention, specifying required actions and operations, and performing them, e.g., calculating the required steering angle and braking behavior for a turn left. The perception of the changing position, its interpretation as an intended outcome, and evaluation within the turn left context to decide over the outcome's success which again influences the next desired state. The design of the system support for the activity and outcome should bridge the "gulfs of execution and evaluation" [Nor05] (users know how to reach / when they have reached the goal). Figure 1.2 shows the gulfs in the context of automated driving.

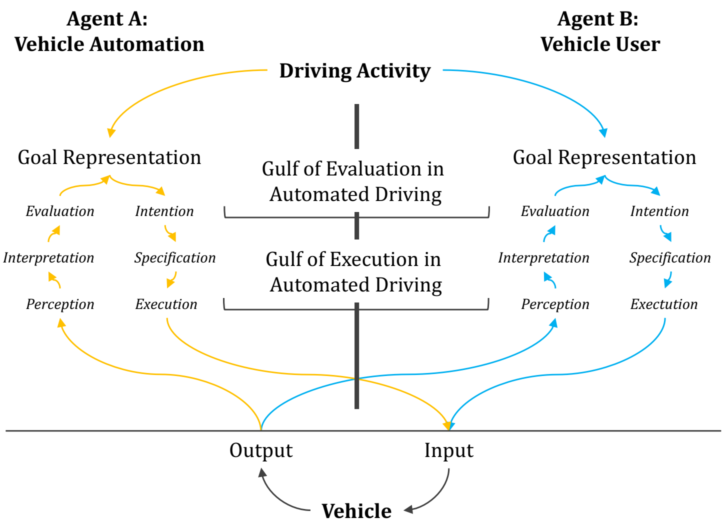


Figure 1.2: The Interaction Gulfs of Automated Driving – Extension of Norman's seven stages of action model for a dual agent setting (simplified), i.e., vehicle automation and user.

The driving task in distributed between the two agents, human and the automated system from which both can execute varying parts of the driving task, depending on the concrete automation capability and cooperation mode. From the human perspective, in the context of growing automation in vehicles, the gulfs of execution and evaluation become broader, as they need a deep understanding of the automation's activity boundaries (evaluation) and need to know how to control the system (execution).

To sum it up, in our research approach, we start with an examination of the users' needs and motivation during a journey and how automation will affect these needs and related sub-activities in the future. Then, we look into the specific driving activity, i.e., how current driving-related activities' execution and evaluation will change in future vehicles.

1.3 Research Contributions

This thesis makes multiple contributions to the field of First, an understanding of future automated vehicle (AV) users' needs and goals for the driverless transportation context. Second, an exploration and first evaluation of direct modalities for intervention in the otherwise autonomously driving system during a journey. Third, a series of investigations and design recommendations on the communication of system behavior to increase predictability for the vehicles' users before and during a journey.

1.3.1 Research Context

The research for this thesis was carried out between the autumn of 2017 and the summer of 2022. Many interactions with different researchers and students occurred throughout the years, resulting in successful collaborations that influenced the work described in this thesis.

University of Duisburg-Essen & University of Applied Sciences Ruhr West

This thesis has been conducted in a tandem setting, i.e., in cooperation between the University of Duisburg-Essen (*HCI Group*, led by *Stefan Schneegass*) and the University of Applied Sciences Ruhr West (*UX Space*, led by *Stefan Geisler*). Starting at the *UX Space* at the University of Applied Sciences Ruhr West, the first idea for this thesis was presented at the *AutoUI* doctoral colloquium in the summer 2017. Within the next year, in autumn 2018, a collaboration with *HCI Group* in Essen was set up. In this setting, the research efforts that led to this thesis were primarily done in practical teaching projects since I was mainly working as a lecturer in that period.

In my work as a lecturer at the University of Applied Sciences Ruhr West, I supervised student projects, i.e., practical courses, seminars, project groups, and bachelor/master theses – most of them in cooperation with the respective lab in Bottrop or Essen. The interaction with the students and research labs was a great source of motivation and a place for the sparring of ideas that turned out to be very fruitful in the progress of this thesis. *Maurizio Salini*'s master thesis, for example, is particularly noteworthy because it lead to the publication of Visualizing Motion Intentions of AVs [Det20], which was eventually awarded the Best Paper Award at the MobileHCI'21 conference.

Competence Center for Automated Mobility Starting in autumn 2019 till spring 2022, I partly worked in the project *Competence Center for Automated Mobility North Rhine-Westphalia*[1], a research transfer project that aimed at connecting local municipalities with industry and research partners. Fur that purpose, we developed information, qualification, and consulting services. Some of the later research projects in this thesis were promoted over this platform and the inclusive mobility project was part of this efforts, too.

Further Collaborations

Over the course of this thesis, collaborations beyond the labs of Duisburg-Essen and Bottrop took place. In 2019, we started to work with *Bastian Pfleging*, an expert in ubiquitous computing and future mobility, who was at the *Technical University of Eindhoven* at that time. Together, we investigated the challenges for the implementation of AVs and studied use and perception in real-world settings leading to publication in the IJHCI [Det+21b] and at the AutoUI 2020 conference [DPS20]. Further, we co-organized an automotive HMI workshop at the MuC conference with *Andreas Riener* from the *Technical University of Applied Sciences Ingolstadt* for several years [Rie+18; Rie+19b; Rie+21]. In 2021, we worked with *Shadan Sadeghian* from the *University of Siegen* on a project that helped to understand how take-over requests (TORs) in AVs can be supported through AR windshields, leading to a publication at AutoUI 2022 [Det+22a]. In 2021, we started to work with the *University of New Hampshire* on the topic of inclusive future mobility. With *Andrew Kun* from the engineering department and *Vidya Sundar* from the occupational therapy department, we organized a workshop [Det+21c] at AutoUI 2021 and published a design framework for inclusive design [Det+22b] at AutoUI 2022. These activities became part of a larger research movement towards inclusive HCI in mobility.

[1] `https://www.camo.nrw/`

Category	Description
Empirical	Discovery-driven knowledge-generation (science) through observation and data-gathering (field studies, experiments, interviews, sensors, ...)
Artifact	Design-driven activities (invention) that generate new possibilities (systems, hardware toolkits, input technique, envisionment, ...)
Methodological	Informs knowledge about the way we work, improving research or practice (method applications, new measures, new instruments, ...)
Theoretical	Consist of new or improved concepts, definitions, or models that describe and/or predict a phenomena (thought framework, design space, conceptual model, ...)
Dataset	Provide a new and useful corpus for research purposes (test corpus, benchmark tasks, repository, ...)
Survey	Synthesize work done in a research area (technology, domain, emerging topic, ...)
Opinion	Essay or argument that aim for discussion and debate (prioritization, application, vision, definition, ...)

Table 1.2: Categorization of research contributions in HCI after [WK16]

1.3.2 Summary of Research Contributions

The contributions of this thesis are towards the field of future mobility and user experiences with automated vehicles, mainly from the user perspective. We first elicit needs and goals for future mobility services and provide contextual understanding about the use and about perception of future vehicles, contributing to a better understanding of the future traveling context, focusing on capturing the shift from manual to autonomous driving. Then, we provide develop and evaluate interaction concepts in highly or fully automated vehicles that help to comfortably cooperate with the automated driving system, considering the shifting role of the driver – with lessons learned from these studies, we provide a set of design recommendations for future vehicles. Overall, the Part II of this thesis is more discovery-oriented, whereas Part III and Part IV are more invention-oriented, often a mix of both. To further specify the contributions, we refer to the taxonomy of Wobbrock and Kientz [WK16] which consists of seven contribution types for HCI (see Table 1.2). Table 1.3 shows a brief description of every chapter's research goal and contribution.

1.4 Thesis Outline

This thesis presents five parts with a total of twelve chapters (see Figure 1.3). The first part (Introduction & Background) introduces the topic and sets up

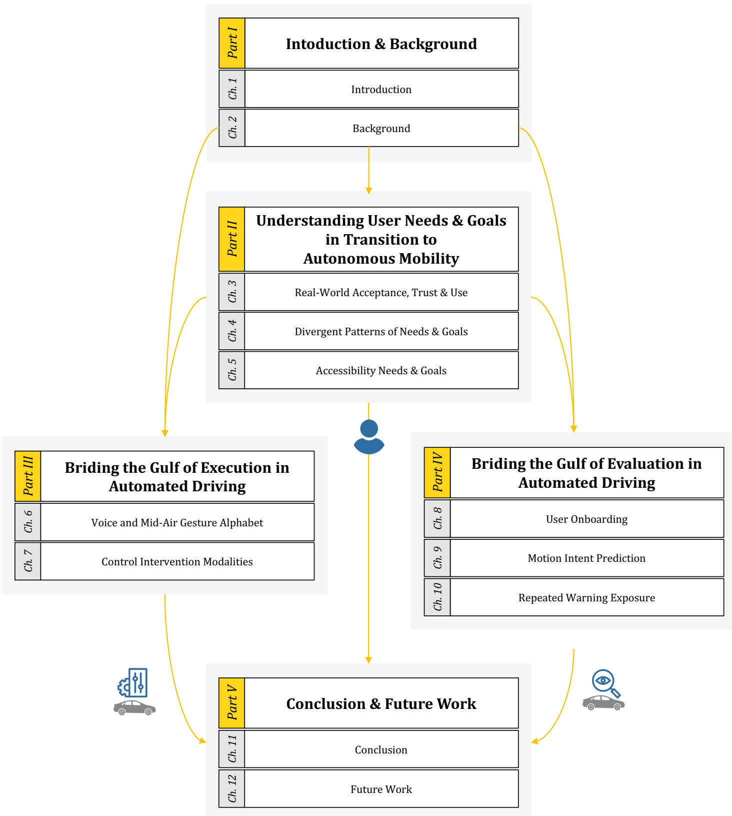


Figure 1.3: Overview over the parts and chapters of this thesis.

the background and motivation for the following parts. Our interaction design approach (cf. Section 4.1) structures the following three main parts of the thesis. The second part (Understanding User Needs & Goals in Transition to Autonomous Mobility) starts with examining the context of automated driving and provides an understanding of what users expect to be a satisfying interaction. The part aims to understand the users' needs and goals that influence the context of interaction with autonomous vehicles and, vice versa, are influenced through interactive experiences. The third and fourth parts are about the interaction experiences with autonomous vehicles and how we can bridge the gulfs of execution and evaluation, i.e., how to make interactions with AVs cover underlying needs and goals. Part three (Bridging the Gulf of Execution in Automated Driving) looks into the execution part of interaction during autonomous driving. Here, we present new concepts and modalities of steering the vehicle to bridge the gulf of execution. Part four (Bridging the Gulf of Evaluation in Automated Driving) looks into the evaluation part of interaction during automated driving. Here, we propose augmented reality applications to bridge the gulf of evaluation. The last part (Conclusion & Future Work) contains the summary and outlook of this thesis. In the following, we describe each part in more detail by describing the parts' content chapters.

Part I: Introduction & Background

Chapter 1 - Introduction This introductory chapter presents our vision of future mobility and the role of HCI research in future mobility. From there, we derive research questions that will be addressed in the course of this thesis and describe our corresponding activity-centered research methodology. Last, we summarize this thesis's outcomes and research contributions and briefly overview the thesis outline.

Chapter 2 - Background The second chapter contains the grounding theories, concepts, and taxonomies that we use in this thesis concerning the changing driving activity. In more detail, we present driving activity aspects such system automation, takeovers, and cooperation with the car. Further, we look at relevant psychological aspects like attention, situational awareness, UX, automation trust, basic needs, and acceptability of automated and autonomous mobility. We close the chapter by reflecting on design aspects. This includes a short survey on how related work has already tackled major design challenges, how to make AVs inclusive by design, and discuss methodological challenges when investigating autonomous driving.

Part II: Understanding User Needs & Goals in Transition to Autonomous Mobility

Chapter 3 - Real-World Acceptance, Trust & Use To better understand the changing driving activity, we first look into the changing needs and requirements and how that might affect the other activity aspects like vehicle design or task distribution. To this end, we simulate a high or complete automation level to get perceptions of the future activity that can help inform the most viable design directions from the users' perspective. We start with a Wizard of Oz (WoZ) automated vehicle study that allows us to gain real-world informed insights into the use and perception of a future mobility service. Services used for daily activities like commuting to work or going to the next shopping mall. We compare our observations regarding trust, acceptance, and vehicle use results from online surveys.

Chapter 4 - Divergent Patterns of Needs & Goals To further understand the context of future autonomous mobility services, we look into shared transport settings, i.e., the public transport domain, and investigate attitudes toward driverless transportation. We investigate the influence of missing human bus or tram drivers with the help of a Q-sort online study. People judged and prioritized statements concerning perceived safety, trust, or acceptance in this study. From the sorting, in contrast to the factorial analysis of acceptance models, we cluster different user types that allow for a hands-on view of the underlying attitudes.

Chapter 5 - Accessibility Needs & Goals The last chapter in this part is about the potential and hurdles that the changing driving activity brings for those with impairments or disabilities. In the future autonomous mobility services, individual and shared transport driving licenses will not be required. In consequence, these services have the potential to be more inclusive. We present a design framework based on a literature review, expert interviews, and discussions. The design framework helps mobility designers to be aware of essential parameters and aspects for inclusiveness.

Part III: Bridging the Gulf of Execution in Automated Driving

Chapter 6 - Voice and Mid-Air Gesture Alphabet Right after the context and user properties for the changing driving activity, we dive into the distribution of responsibility, i.e., the control of automatically driving vehicles. In this thesis, we look into the more abstract form of maneuver-based control, e.g., “turn left”). Fine-grained control with the steering wheel and pedals is not required in the future. We start with investigating how users would perform such maneuvers with established hands-free communication means, i.e., with voice and gesture commands. We present driving maneuvers to which participants reacted with a fitting command and cluster their responses into a voice and gesture command alphabet.

Chapter 7 - Control Intervention Modalities Intervening with simple maneuvers in the driving process of the system requires, depending on the user input modality, more or less effort. In order to investigate the amount of effort that comes with the most common and direct input modalities (voice, touch, mid-air gestures), we conduct two driving simulator experiments. In the first experiment, we compare the modalities in terms of general usability, workload, and acceptance in a distraction-free setting. In the second experiment, we prepare multitasking settings that are likely to occur, e.g., listening to music while trying to intervene with voice control and observe which modalities are when preferred. We discuss the pros and cons of each interaction modality for its applicability in future automated vehicles’ intervention user interfaces.

Part IV: Bridging the Gulf of Evaluation in Automated Driving

Chapter 8 - User Onboarding After elaborating on how to control future vehicles, which is more on the execution side in the seven stages of action model, we have a look at the other side, the evaluation side. The increasingly automated driving activity poses new challenges in understanding and predicting system behavior which is required to build trust and acceptance.

As a first step, we present an online survey with modern car owners and look into the discrepancy between understanding and trust within different advanced driver assistance system (ADAS). We pick automated parking as a function with a high discrepancy and evaluate the utility of an augmented reality (AR) User Onboarding app to close this gap.

Chapter 9 - Motions Intent Prediction During automated driving, the evaluation of the system behavior can be improved through the communication of upcoming vehicle maneuvers on the HUD. This chapter compares different visualization approaches, i.e., planar and 3D-based displays. We conduct two studies to assess their impact on safety in lower automation levels where a handover is required and UX in higher automation levels where the car predominantly drives on its own. From the results, we derive design guidelines for HUDs that inform future automated vehicles' design and help users to predict the system's intentions.

Chapter 10 - Repeated Warning Exposure The system requires human fallback for the driving activity until it is possible to handle every situation through the machine. Visualizing potentially relevant information on the HUD for a quick handover requires user monitoring. This attentional demand can distract the user from other non-driving-related activities and make the information less salient through overexposure. In this chapter, we conduct a driving simulator study that systematically varies the required attention for the HUD. We reduce the demand by changing the warning presence (absent vs. constant vs. TOR-only) and implementing a gaze-adaptivity mechanism that removes the warnings from the HUD (with vs. without). Our results help to understand the line between HUD warning exposure and overexposure.

Part V: Conclusion & Future Work

Chapter 11 - Conclusion & Future Work In this chapter, we answer our initial research questions and reflect our contributions. From that, we derive and present design recommendations for future in-vehicle design. We show what next steps one could take to improve further the transition of the driving activity, i.e., collaboration between human and machine. Finally, we conclude by embedding this thesis in the scope of future mobility.

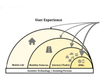
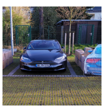
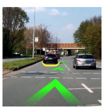
	Short Description of Method and Contribution	Main Contr.*	Chapter
	We used a road-legal *Wizard of Oz Automated Vehicle* (M) to generate insights into the real-world use and perception (E) when traveling with future car services. The car was operated by a "safety driver" (cover story told to participants), which operated the car the whole time.	E	Chapter 3
	We used a *Q-Sort Online Tool* to do a remote card sorting study to gather insights into user attitudes towards autonomous public transportation (E). We showcase how to handle diverging attitudes by classifying them through clustering methods.	E	Chapter 4
	We combine insights from interviews with caregivers and disability representatives and discussions in workshops with automotive HMI experts (E), with a literature survey (S) to create a *design framework for inclusive future mobility* (T).	T	Chapter 5
	We used a real car and projector setup with a predefined route where users had to react with commands on the vehicles' driving behavior (E). The empirically gathered commands were clustered to a set of *user-defined voice and gesture commands* for automated car maneuvering (A).	A	Chapter 6
	To compare *direct interaction modalities* (touch, voice, gesture), we used a driving simulator lab setup with WoZ interaction to simulate and compare the feasibility of intervention modalities in automated driving processes while performing other activities (E).	E	Chapter 7
	We present an online survey that shows the understanding of users of current automated cars' automation features (E). Further, we design an AR app that helps with *Onboarding* of automated parking novices and evaluate it in a real car (E).	E	Chapter 8
	We approach the display of current and future *vehicle motion intentions* in AVs with two head-up display (HUD) concepts. We compare the AR and the icon-based concept in terms of User Experience (UX) in a video-based driving simulator in a real car and safety (E) in a traditional driving simulator setup.	E	Chapter 9
	We use a VR driving simulator to *constantly display critical situations* on the road that eventually lead to a takeover request. We investigate the effect of gaze-adaptivity and the warnings' presence on UX and safety (E).	E	Chapter 10

Table 1.3: Chapter-wise short description of applied methods and main research contributions; * E = Empirical, A = Artifact, T = Theoretical (cf. Table 1.2)

Chapter 2

Background

This chapter is based on the following publications:

Henrik Detjen, Sarah Faltaous, Bastian Pfleging, Stefan Geisler, and Stefan Schneegass. "How to Increase Automated Vehicles' Acceptance through In-Vehicle Interaction Design: A Review". In: *International Journal of Human–Computer Interaction* (2021), pp. 1–23. DOI: 10.1080/10447318.2020.1860517

In the following chapter, we describe the evolution of driving activity towards cooperative driving, relevant human factors, and design considerations. We start with the driving task's terms, models, and taxonomies (Section 2.1). Then, we look into a prominent research problem, the so-called take-over paradigm (Section 2.2), and look at the next level of automated driving, i.e., cooperative driving (Section 2.3). After the activity-centered view, we take the user-centered view and deep-dive into related human factors (Section 2.4). Finally, we end the design perspective and point out current challenges for future mobility service design (Section 2.5).

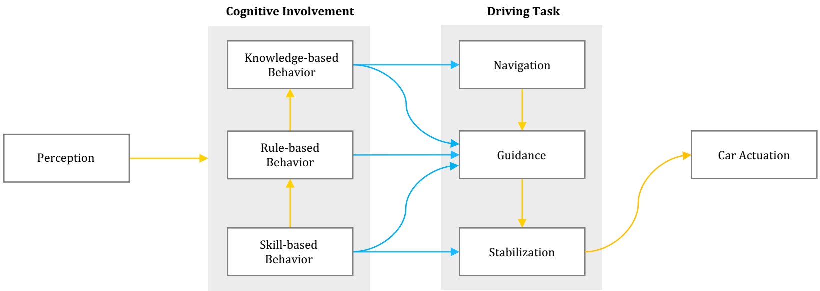


Figure 2.1: The perception of the driving scene leads to different levels of cognitive involvement after Rasmussen [Ras83]. The involvement is linked to the driving task complexity after Donges [Don82]. With experience, drivers need fewer cognitive resources for the driving task.

2.1 From Manual to Autonomous Driving

A foundation of new mobility is automation. In this thesis, we look particularly at the automation of the driving task and briefly introduce established models, terms, and taxonomies in this context. Models of the driving task originate from traffic psychology and human factors engineering but are also applicable to an automated system or virtual driver. They help to describe which parts of the task are performed by the human and which parts are performed by automation. Further, they help understand the concrete benefits and pitfalls of driving task automation. After summarizing the most commonly used models for the description of the *driving task* and a definition of what we consider *not as driving* (cf. Section 2.1.1). Then, we look at the shift towards *non-driving-related activities* (cf. Section 2.1.2), and at the interplay between human and system driving and where we provide definitions and taxonomies of *driving task automation* (cf. Section 2.1.3).

2.1.1 Driving Task

When it comes to driving, the framework proposed by Rasmussen [Ras83] is useful in estimating how much cognitive effort is required for goal-directed behavior. This type of behavior involves monitoring and controlling actions, as well as learning from them, in response to either the current situation or patterns of sensorimotor information. The framework divides behavioral responses into three levels, each requiring more cognitive effort than the previous one – as shown in the left side of Figure 2.1.

- *Knowledge-based behavior*: unknown situation without matching rule, a new behavior heuristic is entirely created from scratch for future responses, high cognitive demand.
- *Rule-based behavior*: an unknown situation with a matching behavior heuristic, e.g., when starting the TV for the first time, the start procedure from comparable devices like radio will be applied, medium cognitive demand.
- *Skill-based behavior*: automatic response, e.g., catching a ball, low cognitive demand.

Donges [Don82] divides the driving task into three hierarchical levels – as shown in Figure 2.1, right:

- *Navigation* (route planning and estimation of time requirements, not applicable for known routes)
- *Guidance* (anticipatory adaptation of perceived actual variables to reasonable target/guidance variables, e.g., determining a suitable speed to drive around a curve; open-loop control)
- *Stabilization* (corrective interventions, e.g., accelerating/braking to reach the target speed; closed-loop control)

As suggested by Frank Ole Flemisch et al. [Fra+14], it can be helpful to differentiate between two types of guidance on a higher level: *maneuver guidance* and *trajectory guidance*. Maneuver guidance refers to vehicle behavior described as abstract maneuvers, such as "change lane to the left". On the other hand, trajectory guidance provides detailed vehicle behavior through specific trajectories, indicating the exact vehicle position for each point during a certain period of time.

Donges [Don09] compares the previously described driving task models and their relation to task involvement. As depicted in Figure 2.1 with blue arrows, the navigation task aligns with knowledge-based behavior, while stabilization aligns with skill-based behavior. The driver's experience determines vehicle guidance, with initial guidance in unfamiliar situations relying on knowledge-based behavior, such as during our first driving school parking attempt. Repeated exposure to a specific driving situation leads to a heuristic behavior, which can be easily applied to similar surroundings, like parking in a similar spot. This behavior may become automatic with time, like when we drive home from work. Generally, the more experience a driver has, the less cognitive resources they need to perform the driving task. Vehicle automation likewise reduces the cognitive demand of the driver by partly substituting the execution of the driving task.

2.1.2 Non-Driving Related Activities

According to Bubb [Bub03], there are three types of driving tasks in a traditional car. The first type, known as the *primary* tasks, includes all necessary actions to reach a particular destination. The second type, known as *secondary* tasks, supports the primary task but isn't essential to reaching the destination (such as using the turn signal). Finally, *tertiary* tasks have nothing to do with transportation but rather with infotainment control. As automation increases, the role of the human in the car changes from being the driver to being the passenger.

In this situation, the former primary and secondary driving tasks fade away, swapping importance with the former tertiary tasks. To avoid confusion when using these established terms, we follow the terminology of Pfleging and Schmidt [PS15] who propose to use the terms of *Driving-Related Activities or Tasks*, which include the former primary and secondary tasks, and *Non-Driving-Related Activities*, which include the former tertiary tasks. Expected non-driving related activities (NDRAs) are, for example [PRB16; Det20; HDB20; Hec+20]: Watching out of the window, talking to other passengers, using the smartphone, eating, listening to music/radio, taking a nap, knitting, or doing office work. These activities require different physical and cognitive resources and influence the human vehicle user's multitasking capabilities and travel preferences.

2.1.3 Automation Taxonomies

Organizations such as the American Society of Automotive Engineers (SAE), National Highway Traffic Safety Administration (NHTSA), or the German Bundesanstalt für Straßenwesen (BASt) have established vehicle automation levels to standardize the assessment of a system's ability to handle driving tasks. The SAE definition J3016C [SAE21] has become the de-facto standard in scientific publications on vehicle automation.

The SAE classification outlines the conditions and extent to which a driving task is automatically performed by a system. It defines six levels, ranging from 0 to 5, which represent increasing levels of automation capabilities (see Figure 2.2). In the first two levels of vehicle automation, the driver is responsible for monitoring the environment while the system handles steering through, e.g., a lane keeping assistant (LKA), and accelerating and braking through, e.g., an adaptive cruise control (ACC), in certain driving situations. In level three and above, the system takes over monitoring the environment but still requires the driver as a backup in unsafe or critical situations until level four, where human backup is no longer necessary. Level five represents full autonomous driving, but its implementation faces technical, ethical, and legal challenges, making it uncertain when it will become widely available. However, the lower levels of automation are already becoming standard. Currently, a *transitional phase* exists where manually operated, partially autonomous vehicles like the

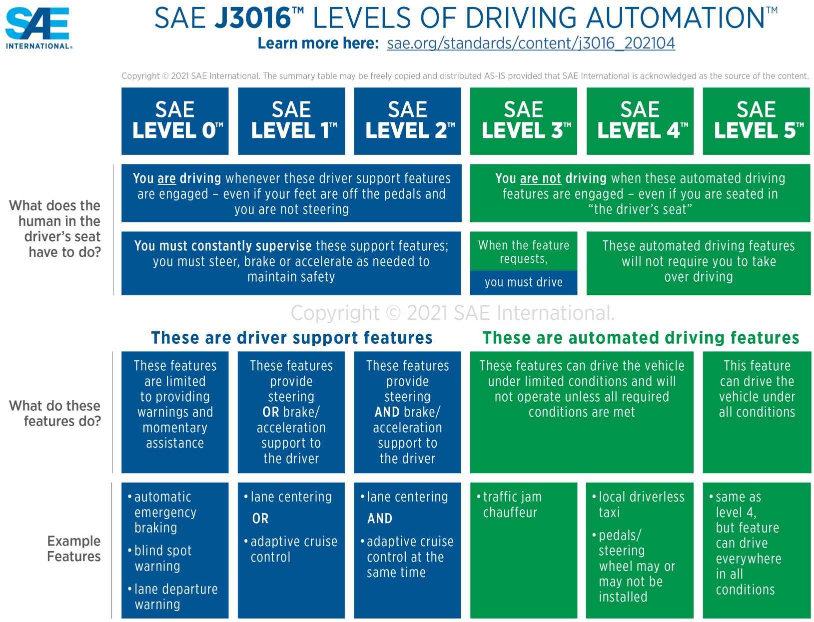


Figure 2.2: SAE J3016 definition of driving automation levels [SAE21].

Mercedes S-Class and Audi A8 coexist with fully autonomous vehicles like the Google Driverless Car on German roads.

The SAE taxonomy has different levels of automation which involve the same human behavior in the vehicle. The difference lies in the technical capacity of the vehicle to handle specific road situations. However, from a human-centered viewpoint, the SAE definition may not be ideal since it uses more levels than necessary to explain human behavior in the car. Furthermore, the requirements for mandatory or optional behavior dictate how one interacts inside the vehicle. In essence, a single level can cover many human *operating modes*. As a result, the Allgemeiner Deutscher Automobil-Club (ADAC) from Germany contends that it is more practical to differentiate based on the car's operating modes rather than the system capabilities. The simplified ADAC classification only has three levels of car operating modes:

1. *Assisted driving*: The driver is always and at all times responsible for driving. The driver may perform permissible secondary activities but is always in control of the car. The driver must keep an eye on the traffic. As far as possible, the vehicle keeps in lane, brakes, and accelerates. Nevertheless, feedback is not mandatory, and a sudden stop is always possible.
2. *Automated driving*: The vehicle only drives itself in the application specified by the manufacturer (e.g., stop-and-go in a traffic jam. The driver may temporarily turn away from the driving task and the traffic situation. Outside employment is possible. The driver must take over at short notice when requested by the system.
3. *Autonomous driving*: The driver can completely relinquish control of the vehicle and become a passenger. Operation without occupants is also conceivable. The autonomous mode can be limited to defined routes. The system itself handles critical driving situations. An operator (not the driver) must constantly monitor the vehicle to respond to operational problems (e.g., flat tires). A "flying switch" to manual mode may remain possible (e.g., after the highway).

Table 2.1 compares the driving modes classification with the system-centered SAE classification.

So far, we have introduced two different perspectives for automation taxonomies, SAE better describing the system's capabilities and the human involvement in the driving task. Researchers from different communities and backgrounds often misunderstand each other when using the term "autonomous vehicle" or "autonomous driving". To be clear: We use both perspectives on automation throughout this thesis. We will mainly stick to the SAE classification when speaking of vehicles, e.g., fully automated vehicles (system perspective). However, when speaking of the driving task, we also use the ADAC classification, e.g., speaking of an *autonomously driving vehicle*

Task-Centered Taxonomy (ADAC)		System-Centered Taxonomy (SAE)	
Name	*Level*	*Level*	*Name*
Autonomous Driving	3	5 4	Full Automation High Automation
Automated Driving	2	3	Conditional Automation
Assisted Driving	1	2 1	Partial Automation Driver Assistance
-	-	0	No Automation

Table 2.1: SAE J3016B 6-step vehicle automation taxonomy and the ADAC automated driving mode taxonomy used in this thesis. Important notice: The comparison is cumulative for the ADAC levels, meaning that in SAE level 3 includes both ADAC operating levels 1 and 2; and in SAE level 5 all three ADAC operating levels are possible.

(task-perspective) – corresponding to the operating mode level 3 (ADAC) in level 4 or level 5 automated vehicles (SAE).

Automation in cars will revolutionize the way we use our time and space, leading to significant changes in system designs such as integrated interiors, technology, and services. Different levels of automation will support various use cases, with higher levels allowing passengers to request entertainment or relaxation activities like watching movies or taking a nap. As system designers, we must be aware of these levels of automation and the shift from driving-centered interactions to *activity-centered* interactions. To create richer user experiences and obtain user acceptance, we need to explore new concepts and possibilities, as proposed in *possibility-driven design* [DH12]. In this article, we will outline the possibilities for current and future human-vehicle cooperation.

2.2 Take-Over Paradigm

It is crucial to stay focused on driving to ensure safety on the road. Various personal and environmental factors can cause distractions, such as lack of trust, tiredness, emotional stress, disruptive noises, or challenging traffic situations. While vehicles at SAE level 5 can handle all situations independently, drivers may need to take control in levels 4 and 3. To enhance safety when driving manually, driver assistant systems like night-vision enhancements [Cha+11; BB08], turn-left assistants [Ort+17], or blind spot warnings [Pla+09] can be useful. However, transitioning from autonomous driving to manual driving in safety-critical situations can be challenging for level 3. For a complete taxonomy of control transitions between automation and human drivers, we refer to [LW15], [McC+16], and [Mir+17]. The driver must be alert and ready to take over control from automation to avoid accidents. Additionally, as drivers become less active in future cars, their driving skills may decline in the future.

Paradox of Automation for Safety

Automation presents a new challenge immediately after handover. With less time spent on manual driving and more on automation, future drivers may lack the skills compared to today's drivers. While experienced drivers may not forget how to drive, novice drivers require adequate *training* to take over manual driving from automation when necessary [Trö+16]. Manual driving becomes less frequent but more critical. This phenomenon is also known as the *Paradox of Automation for Safety* [Kab19]. This skilling and deskilling issue is a familiar problem in aviation, where pilots must regularly prove their manual flight time through tests [Trö+17]. As AV drivers are not professional pilots, other mechanisms must be employed to prepare them for situations like heavy rain [Trö+17], which may require a takeover.

Automation Drop-Out: Take-Over Request

The driver can initiate automation by pressing a button or using voice commands. However, when automation needs to transfer control to the driver, the situation becomes more complex. Vehicles at SAE level 3 require the driver to intervene in critical situations, so the transition to manual driving mode should be as quick as possible to prevent accidents. According to current literature, the transition time may take up to 15 seconds, depending on the driving situation's complexity [Wal+15; Nat+14; DB12; Gol+13]. A meta-study of Eriksson and Stanton [ES17] found variances between 1s and 23s. The driver's mental state affects how quickly they can resume driving. If the driver is aware of the surroundings and traffic, (s)he can respond more efficiently. Usability metrics and driving performance metrics are often used to determine driving performance (cf. [For+18]).

If a driver is not attentive to the driving context and suddenly needs to focus on capturing a critical road situation, there is a potential for slower transitions and danger. Studies have shown that as automation levels increase, drivers become drowsier [Kun+18a], more distracted, and less focused on the road [Rei+16]. In consequence, it is essential for drivers in level 3 automation to have adequate situational awareness (see Section 2.4.2) at any point of the journey.

According to a study by Gold et al. [Gol+13], automation effects can lead to a decrease in driving quality, such as missing mirror checks, even after seven seconds. Lu, Coster, and Winter [LCW17] found that it takes drivers at least 20 seconds to correctly perceive the speed of surrounding cars, even though they can detect them after seven seconds. Gold et al. [Gol+16] discovered that traffic complexity can negatively impact the performance of TORs. Ultimately, driving performance is affected by both the environment and the driver's abilities.

Various methods can be used to immediately alert drivers to the TOR, such as vibrotactile feedback through the steering wheel [Bor+17] or seat [SJK16; Seb+17], warning sounds [PBP15; Wal+15], ambient lights [Bor+16], jumping light-emitting diode (LED) blocks [Trö+18], and even scents [Qiu+20] or proprioceptive cues [Fal+19]. Changing the hue is the most effective way to alert drivers through the visual channel, while an increasing alarm sound is best for the auditory channel. However, auditory TOR signals were slower than other types of signals. Combining warning modalities, seat vibration, and sounds can improve performance. On the visual channel, changing hue

[Kun+18c] works best. For the auditory channel, an increasing alarm sound [Lah+18; vIJ17] leads to better TOR performance. In contrast, [Won19] found auditory TOR signals to be slower than visual, haptic, or multimodal signals. For example, a combination of warning modalities, seat vibration, and sounds [Seb+17] leads to better performances.

Typically, drivers use the steering wheel to control the car. However, when they need to avoid obstacles, consumer devices can assist with lateral control. This eliminates the need to switch between interfaces and improves the TOR performance in terms of time [SRW18]. Whether the car is moving or not does not affect the driver's ability to switch tasks [vKJ16]. Monitoring the driver's activities makes it possible to request a takeover at the most opportune moment, such as during a typing pause in a text message conversation [Win+18].

To sum it up, using driving assistance systems can enhance driving safety. However, transitioning from automatic to manual driving mode can be challenging. In critical situations, time is of the essence, and therefore, Human-Machine Interfaces (HMIs) are mainly evaluated based on practical performance measures, such as error rate and time. A driver's mental model of the surrounding objects and their future state is crucial in preventing errors. To increase takeover time, it is necessary to implement strategies that effectively draw the driver's attention back to the road. Although current research focuses on these situations, they are relatively infrequent, and some car vendors even skip level 3 automation due to safety concerns.

Volvo's CEO Samuelsson, in [Ibs17]: "In this mode, the car is in charge of the driving, yet the driver must still be prepared to take over in case of emergency, which could be a matter of a few seconds. Volvo considers this Level 3 driving mode unsafe and will thus skip this level of autonomous driving."

Higher automation levels also pose the issue of deskilling, thus requiring more research on systems and concepts that maintain driving skills. Cooperative control concepts could also improve safety and performance, such as allowing the car to execute emergency braking while the driver controls the steering wheel. The following section will explore cooperative strategies for handling automated rides in less critical situations.

2.3 Human-Vehicle Cooperation

In this section, we cover the foundations of cooperative driving (Section 2.3.1), maneuver-based interventions (Section 2.3.2), a specific form of cooperation, and possible interaction modalities (Section 2.3.3).

2.3.1 Cooperative Driving

One might ask why to take over control of an automated vehicle in a non-critical situation, where the car can handle all aspects of the driving task. We look at *why*, we show *when* and *how* the human might intervene in the automated driving process and how both agents might benefit from each other.

Need for Cooperation

There are multiple reasons for having (different) control options during automated driving. First, from a functional perspective, there is a need for control in many automated driving scenarios, including [TP20]: Influencing the route taken, influencing the acceleration for takeover maneuvers, or violating the speed limit (e.g., to take your pregnant wife to the hospital). Second, also from a functional perspective, automated vehicles always require a specific destination. If the user cannot name a destination, e.g., (s)he only remembers a track visually, (s)he consequently has to perform the control part herself/himself. Third, from a psychological perspective, the pure presence of control interfaces has been shown to a) increase driving pleasure and attractiveness compared to autonomous driving [Fri+17] and b) to increase acceptance of the system [Hew+19; Röd+14]. Beyond these three reasons to override automation, there are certainly more, and we see that putting all kinds of automation and vehicle cooperation into a specific taxonomy (as seen in a previous section, Section 2.1.3) that is traversed upwards or downwards is, in fact, not that simple. It is more likely that we see cars with different control mechanisms per vehicle type, user, situation on the road, and so forth. In line with that, [Wal+17] recommend a broader view of automated driving for research, as the driver may need the most support exactly when automation reaches its limits. The solution to overcoming uncertainties and risks on both sides could be *cooperative user interfaces*: an integrative concept in which humans and machines (agents) work together as a team, with one part compensating for the weaknesses of the other. They define four fundamental requirements for such interfaces: 1) Mutual Predictability, 2) Directability, 3) Shared Situation Awareness (cf. Section 2.4.2), and 4) Calibrated Trust in Automation (cf. Section 2.4.3). These requirements are interwoven, e.g., providing system predictability may increase user trust. We have a deeper look at Predictability and Directability from the users' perspective in the following.

Predicability: Strategies to Describe an Automated Vehicle's Action Intention

Transparency of a vehicle system can increase the interaction quality due to better predictability: Concrete and measurable effects can be a) higher trust in the system and b) increased situation awareness. These constructs have been proven viable in the context of automation [PSW08] and context of automated cars: Being transparent about the system's state and communicating the system's reliability [Fal+18] improves driver-vehicle cooperation behavior in terms of take-over performance [Kun+19] and trust [JMM13].

To predict the intentions of the vehicle, the amount of information should not overload the user and, at the same time, also guarantee a sufficient level of detail [End01]. To describe the level of detail, we use established models of the human driving task, which also apply to a system (virtual driver) that executes the driving task (cf. Section 2.1.1). The complete driving task is typically divided into three levels: navigation, guidance (maneuver/trajectory), and control. Maneuver guidance describes vehicle behavior in the form of abstract maneuvers (e.g., "change lane to the left"). Regarding a sufficient level of detail: People describe vehicle behavior on the guidance level [MMR09; Ben14]. Therefore, we aim to communicate vehicle intentions on the guidance level throughout this thesis.

Directability: Granularity, Frequency, and Comfort

To better understand how people could intervene in automated driving processes from a conceptual point of view, we look at the driving task structure and existing task-sharing strategies. As previously mentioned, the driving task is typically divided into three levels: navigation, guidance (maneuver/trajectory), and control. Through human-machine cooperation, automated driving allows us to steer the car at the guidance level instead of the control level. At the guidance level, there are two branches: (1) *Maneuver guidance* is more abstract and provides discrete control (e.g., "turn left"), whereas (2) *trajectory guidance* offers continuous control of the vehicle trajectory (e.g., through a joystick [Lar+17]).

Regarding *trajectory guidance*, a popular control concept is H(orse)-Mode [Fle+03], which proposes cooperative automation modes based on a rider-horse relation. When driving, the level of control over the vehicle can be adjusted by using either a tight or loose rein, much like riding a horse. According to a study by Kienle et al. [Kie+09], the H-Mode concept, which involves using a sidestick to alternate between trajectories, was found to provide similar or even better control compared to traditional interfaces like a steering wheel and pedals. Another example is the haptic interface "scribble" offers a new way of vehicle control by drawing the future vehicle trajectory [Ros+18]. It allows one to pass other vehicles and obstacles quickly and comfortably.

Regarding discrete *maneuver guidance*, in the Conduct-by-wire project [WH06], [M S+10] developed a maneuver control set that allows drivers to handle their cars in common situations on highways and rural roads. These atomic maneuvers can be used to create more complicated maneuvers, such as overtaking a car. The conduct-by-wire principle, also known as maneuver-based driving, was designed to keep the driver in control while increasing comfort and situational awareness. Drivers continuously select maneuvers (SAE levels 2 and 3 [SAE18b]). In autonomous driving cars (SAE levels 4 and 5), where the human does not need to take over quickly in potentially safety-critical situations and controls the car infrequently, these concepts are referred to as Trajectory-based Interventions and Maneuver-based Interventions. Maneuver-based Interventions can increase user comfort because the car remains in control of the driving task. They can also complement traditional car control and meet user needs and requirements [DSG19]. We have a closer look at maneuver-based intervention (MBI) in the next section.

2.3.2 Maneuver-based Interventions

The MBI approach is based on the maneuver-based driving concept by Winner and Hakuli [WH06]. Maneuver-based driving involves certain maneuvers that can be picked by the driver to make decisions on a guidance level, e.g., lane change to the left. Instead of the driver entirely overtaking control from the automation for an intervention, the car still handles the execution of these maneuvers on an operational level. For example, choosing the exact speed and steering angle for a maneuver remains within the car's responsibility.

The prerequisite of a maneuver interface is a set of maneuvers, a so-called maneuver catalog, through which the driver makes guidance-level decisions. Schreiber [Sch12] developed a driver-centered maneuver catalog with the goal of high expectancy compliance, short input times, and few input errors: *Start*, *Turn Right*, *Turn Left*, *Lane Change Right*, *Lane Change Left*, *Straight*, *Hold at Stop-Line*, *Hold on Side-Strip* and *Parking*. This basic set of maneuvers allows a complete driving mission on country roads and highways. Complex maneuvers, "Overtaking" for instance, can be realized through a combination of the base maneuvers: *Lane Change Left*, speed adjustment (parameter), *Lane Change Right*.

Maneuver-based driving was initially developed for SAE level 2 and 3, to maintain driver regulation and control. However, for higher automation levels (SAE 4 and 5), MBI is used when the driver is not always involved in the driving task. This allows for the *possibility* of control. Studies, like the one conducted on the Hotzenplotz system [Fri+17], indicate that users perceive MBI as more positive, attractive, and less boring than pure automation. Additionally, users feel more competent and autonomous when using MBI. However, such interventions require a new type of in-vehicle control, as traditional automotive user interfaces are not designed for such maneuvers.

The traditional user interfaces in cars were not designed to control the vehicle based on maneuvers. A new type of interface is needed for this purpose.

One example of such an interface was developed by Kauer, Schreiber, and Bruder [KSB10], which is a touchscreen mounted on the steering wheel allowing the user to select maneuvers by tapping on a static list. Another example was developed by Franz et al. [Fra+12], which is a touch board mounted on the armrest that displays maneuver options in a circular menu on a head-up display, and the user selects an action by swiping in the desired direction on the armrest. Although touch interfaces are the most usable for constant interaction, there are other interface options that could be useful in some scenarios, such as voice and touch interfaces that allow for contact-less interaction in situations where the user's hands are busy. These options could be useful when the user is engaged in non-driving-related activities that bind their hands to a particular location, such as typing on a smartphone, or when the design of future vehicles makes a touch interface hard to reach because the seats are moved back.

To sum it up, although automated driving makes it unnecessary for drivers to control their cars from a technical standpoint, there is still a strong argument for providing optional control interfaces to meet the human need for competence and autonomy. Depending on the situation, it may not be necessary to rely solely on manual control. Interventions can occur at different levels, including tactical, maneuver, and operational. While traditional controls like the steering wheel and pedals will remain in cars for some time and cover operational control, there is a need for new interfaces that allow for maneuver control. More research should focus on developing such cooperative control mechanisms. Next, we outline possibilities for current and future in-car interactions.

2.3.3 Interaction Modalities

When creating in-vehicle HMI, the way that people interact with the vehicle's technology and interior must be considered, along with their senses and actions. Many modern vehicles include advanced technologies such as touch panels, microphones, cameras, Global Positioning System (GPS) sensors, light sensors, and algorithms that analyze the driver's steering behavior. As technology continues to advance, future vehicles will offer even more options for interaction. For guidance on best practices for sensing and feedback, we refer to Riener et al. [Rie+17].

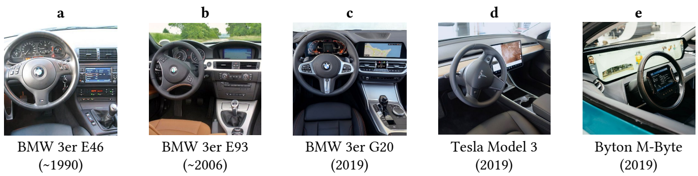


Figure 2.3: Cockpit Design Evolution.
Sources: a [Wit11], b [Doe09], c [Wag19], d [Jur17], e [Ver19].

Figure 2.3 displays the development of cockpits in BMW 3 series cars over the past three decades. The images in Figure 2.3.a–c show designs from the past, whereas Figure 2.3.c–e depict current designs. These designs are intended for lower automation levels (SAE 0-2) and do not account for automation cooperation or fully autonomous driving. The current designs feature touch and haptic interfaces with visual or vibrotactile feedback. Today, some designers believe that certain human senses and actions, such as human brain interfaces, are impractical as they require additional effort. However, technology is advancing rapidly, and ideas that seem unfeasible today may become feasible in the future. As the importance of the primary driving task decreases, other control mechanisms may become more relevant.

Therefore, we do not limit our design options for interaction to established interface best practices but explore various interaction methods from design studies, research, and other areas. The following summary provides a reference to determine suitable technological requirements and future applications. When interacting with highly automated vehicles (HAVs), we differentiate between input modalities (related to human senses) and output modalities (related to human actions) of the system.

Input Modalities

When using autonomous vehicles, users may engage in various activities and not always face forward. Therefore, it is important to have input options that do not require physical controls in a specific part of the vehicle. Generally, there are two ways to interact with autonomous vehicles: *explicit* and *implicit*. Explicit interaction is when the user intentionally interacts with the system, such as through direct touch on the infotainment system. Implicit interaction is when the system utilizes unintentional user interactions, such as a drowsiness alarm system triggered when the driver's eyes begin to close slower than usual. Input options for interaction can range from implicit to explicit:

- *Physiological Properties*: An AV system can use physiological properties to recognize a person and adjust its behavior accordingly. Biometric methods use characteristics like fingerprints, facial features, or weight distribution [RF08] to identify the driver. This allows for individualization of AVs in terms of interior and functionality, leading to more positive travel experiences. For example, the driver's weight and height can be used to increase seat comfort.

- *Emotions*: When it comes to emotional interaction, it often involves detecting physiological properties and facial expressions. However, objectively measuring emotions can be difficult because physiological arousal can be caused by other factors, such as high cognitive workload [RFA09]. Despite this challenge, detecting a driver's emotions can help the system adjust its actions to the user's state of mind. For example, it can change the lighting, entertainment experience (such as music playlists or VR applications), or driving style.

- *Thinking*: It is possible to use brain interfaces to predict drivers' intentions, such as emergency braking [Hau+11], detecting drowsiness [COL14], or measuring cognitive load [Pal+10]. While it is generally possible to control actions through active thought, the patterns of brain activation can vary between individuals. One limitation is that EEG technology is typically used to predict these patterns, which requires the driver to wear additional devices.

- *Eye Gaze*: It is possible to utilize gaze tracking to monitor the driver's focus or even for hands-free control, such as when fixating on a specific area for an extended period of time [Ker+10].

- *Position*: The driver's position in the car, head movements, and body posture can help identify the driver and anticipate upcoming actions, such as changing lanes [GHB19].
- *Mid-Air Gestures*: Interacting through mid-air gestures can feel natural and intuitive. When done correctly, using familiar symbols and gestures, mid-air gestures can be an effective way to control a limited set of commands or choose from a few options [Ahm+18]. Unlike surface gestures, mid-air gestures are not limited to a specific position in the car [Rie12b]. However, there is a possibility that future cars may have touch-sensitive interiors, such as steering wheels or seats [Dör+11], which could eliminate this limitation.
- *Speech*: When driving, using speech control is a comfortable way for the driver to communicate because it is the primary way we interact with others, supported by secondary cues like gestures, facial expressions, and tone of voice. As a result, it can create a feeling of connectedness, as people communicate with voice assistants as they would with other people [Lar+17]. In the car, speech interaction is hands-free, so it is not restricted to a specific interaction location. However, voice interaction can be affected by noise from other passengers or vehicle vibrations. Nevertheless, with the increasing popularity of home assistants, speech control is becoming more prevalent.
- *Haptic*: The controls in vehicles are typically haptic, as seen in Figure 2.3. These include the steering wheel, pedals, gearshift, and rotary knobs. Haptic controls are securely fixed in place and quite durable. While they are less adaptable than touch interfaces and have lower resolution, they can be operated without visual guidance and provide an immediate response.
- *Touch*: The current design of car interiors typically features hard buttons for frequently used functions and touch panels for less frequently used functions. However, there is a recent trend towards using large touch screens in cockpits (as seen in Figure 2.3.d–e) which allow for a more dynamic configuration of elements and are replacing the traditional center console. It is important to note that this trend also has

its drawbacks as a touch interface can be more visually demanding than a haptic interface, increasing the risk of accidents, especially when driving manually.

Output Modalities

According to Shneiderman [Shn97], effective communication of the system's current state and feedback on user actions can improve the quality of interaction. However, the output modalities of the system are limited by human senses.

- *Visual*: Visual feedback is our primary sense, and it is quick and lasting. However, interpreting a shape takes longer than motion, and our field of view is restricted and changes with attention. The use of technologies like AR [GFK14; Rie+19a; Wie+19a] and virtual reality (VR) in AVs is becoming widespread, such as on virtual windshields [HPA16], which provide a broad range of potential applications.
- *Somatosensory*: Fast confirmation of driver actions or announcement of system actions can be achieved through somatosensory feedback. This tactile feedback can be experienced through haptic controls, in the driver's seat, or even in the air using ultrasound technology [Har+18].
- *Auditory*: When it comes to warning drivers, auditory feedback is not limited to their visual or physical focus. Therefore, alerts are often provided through the auditory channel to grab the driver's attention. However, speech feedback can be time-consuming. To speed up the process, efficient auditory design methods, such as earcons and spearcons, can be utilized to convey information more quickly [WNL06].
- *Olfactoric*: Car technology usually doesn't incorporate smells as a form of feedback. It is difficult to come up with accurate scent-based metaphors and physically distribute them throughout the car's interior. However, it is possible to use scents to discreetly alert drivers to changes in the vehicle or driving conditions.

- *Gustatory*: Implementing gustatory feedback through technology is challenging, similar to olfactory feedback. However, at higher levels of automation, it could enhance user experiences and support various forms of interaction.
- *Vestibular*: Feeling movement relies on receiving vestibular feedback. This feedback can be experienced when adjusting speed, such as when driving a car. While the speed can be seen on the tachometer, it can also be felt through the car's movements, including acceleration, deceleration, and lateral movements. However, this type of feedback can cause nausea.

After this brief overview of possible interaction modalities, answering *how* people can interact with AVs, we briefly introduce the natural user interface paradigm.

Natural User Interfaces

One definition of a Natural User Interface takes a back seat, stands behind the content, and usually uses a direct manipulation style such as touch, gestures, or voice commands [FPT12]. Norman [Nor10] offers an important critique of Natural User Interfaces (NUIs). He describes the direct manipulation style of *natural interaction* as not necessarily natural because it too must be learned. Gesture systems, for example, are not fundamentally different from other interaction systems. They, too, would need clear forms of expression and a clear conceptual model of how to interact with the system, its consequences, and means of error handling. As a consequence, feedback, instructions, and hints on possible actions would always be needed. As a condition for useful interfaces, he sees above all the prior standardization of the same - even if this is not necessarily the optimal (most natural) version (e.g., qwerty keyboard layout). The criticism aims at the understanding of NUIs through higher naturalness to automatically gain higher intuitiveness. In addition to the aspect of direct manipulation and non-negligible standardization, NUIs in this thesis, without the assumption of higher intuitiveness, are to be understood primarily in terms of their naturalness in the sense of exploiting given human abilities, i.e., by exploiting touch, sight, movement, and higher cognitive functions such as expression, perception, and memory. Hence, we stick with Liu's [Liu] understanding of NUIs when using the term "natural" throughout this thesis: in a NUI, humans exploit abilities acquired through traditional physical interaction. Next, we look into the psychological aspects of automated driving, i.e., the user's states and traits.

2.4 Psychological Aspects

In this section, we deep-dive into the psychological concepts and theories related to automated and autonomous driving. This includes safety-relevant concepts like the (split) attention in multitasking settings (Section 2.4.1) and the situational awareness of the driving scene (Section 2.4.2). Further, more experience-relevant concepts like trust (Section 2.4.3), user experience (Section 2.4.4), and basic needs (Section 2.4.5). We end with AV acceptance which leads to adoption and, in consequence, a fast and successful introduction of the technology (Section 2.4.6).

2.4.1 Attention and Multitasking

Attention can be formed in two ways, either through *goal-directed capture* or *stimulus-driven capture* [Yan93]. Goal-directed capture is when the driver intentionally focuses their attention on specific objects in the environment, such as street signs for navigation, while stimulus-driven capture is when objects automatically and unintentionally capture attention, such as a traffic sign changing colors. Even if the driver is not actively looking for it, a sudden change in color will often catch their attention. Research suggests that under certain conditions, stimulus-driven capture is more effective than goal-directed capture (cf. [YJ96]), such as when new stimuli appear or move in the environment (cf. [YJ96; Mer+18]).

During times when vehicles are traveling autonomously, the occupants may engage in NDRAs. When doing so, they expend physical and mental resources on that task. For example, reading a book requires physical effort to hold the book and mental effort to decode and understand the written letters. This task demands the focus of the eyes and hands, as well as attention. In-car interactions may use the same resources and therefore interfere with the NDRA. According to Christopher D. Wickens [Chr08], there are four dimensions of resource sharing in multitasking settings: perception, cognition, response, codes of processing (spatial vs. verbal), modality (auditory vs. visual perception), and visual channels (focal vs. ambient). The less a multitasking procedure occupies the same dimensions, the better the later performance. This means, e.g., for warning signals about potential hazards, that goal-directed capture may be more difficult, especially in level 3 AV: Constant visual warnings about pedestrians and bicycles can interfere with important behaviors like potential *NDRA* or scene parsing during a *TOR* (cf. Endsley: *SA Demon 5 - Misplaced Salience*; Endsley defined phenomena that hinder the process of gaining correct situational awareness, see next subsection, Section 2.4.2). In response, users may start to ignore the warnings, a phenomenon known as attention tunneling (cf. Endsley: *SA Demon 1 - Attention Tunneling*).

According to a study by Roider et al. [Roi+19], switching between interaction modalities for side tasks during driving can improve efficiency compared to using only one modality. Surprisingly, this switching does not increase the overall time it takes to complete tasks. The study also found that distractions from the main task are determined by the modality used for the side task, rather than the transition process. Therefore, when the distraction from the main task is no longer a primary concern, it is beneficial to switch between modalities to take advantage of each modality's efficiency and suitability for a specific task. For instance, during a non-driving related activity, like listening to music, voice control may not be the best option, and using touch may not be ideal while using a smartphone.

Overall, attention is more of a general resource required for all cognitive processes, including situational awareness, during (non-)driving-related activities. Next, we look at how users for a precise picture of the driving scene.

2.4.2 Situational Awareness

To accurately anticipate and navigate traffic, it is crucial to have a clear understanding of the current situation [EG00]. This applies to both human drivers and automated vehicle agents, who both engage in a process of situation awareness to plan their next moves, such as changing lanes or stopping at traffic lights. By clearly communicating their intentions, autonomous vehicles can enhance *mutual situation awareness*, helping drivers better anticipate and respond to the vehicle's actions. This can ultimately lead to greater cooperation between humans and machines in the context of driving [Wal+17].

According to Endsley [End16], there are three levels of situational awareness: (1) *perceiving* the environment, (2) *understanding* the objects in the scene, and (3) *predicting* their future position. In the context of automated driving, Endsley also identifies a relevant situational awareness demon, specifically relevant for automated driving: *SA Demon 8 - Out-of-the-loop syndrome*. This occurs when a driver is not fully engaged in driving, and suddenly needs to re-engage and quickly assess the scene. The challenge becomes even greater when the driver is mentally engaged in another task, as described by Recarte and Nunes [RN03] and by Endsley as *SA Demon 2 - Requisite Memory Trap*). Overall, the risk of making a perceptual error (level 1 situational awareness) during a TOR increases.

There are multiple ways to make the driver aware of the current situation depending on the step being enhanced in the situational awareness (SA) process. For instance, while driving automated, improving the perception of surroundings can be achieved through various methods such as playing AR games [SS16], highlighting the presence of other road users through ambient lights [vKT17], or mapping their position with tactile in-seat [Tel+15] or auditory feedback [Gan+18]. Additionally, to enhance the prediction of surroundings, one can project the real-world traffic situation onto a miniature AR twin scene on the head-up-display [Wie+18]. Correct prediction of changes involves predicting the car's behavior, which includes the user's mental model and mode awareness. *Mode-awareness* can be improved by announcing vehicle operations through movement patterns [SJ19; CSB17], explanatory auditory messages [Koo+15], or a steering wheel that changes its shape when entering a different driving mode, for example, from a round to a rectangular form [PLK15].

Overall, supporting the correct perception, understanding, and prediction of the traffic scene, including the autonomously driving car's actions, can help improve situational awareness. The correct understanding of the scene is a requirement for an adequate level of trust which we look into next.

2.4.3 Trust

Trust is crucial for users to rely on automated systems like AVs, especially in uncertain situations [RV97]. If the system is unreliable, people will avoid using it, leading to a drop in their intention to use it. We will explore trust in automated systems, including vehicles, and how mistrust and overtrust can impact interaction with AVs. Trust in automation is fragile: "Once lost, trust in automation, like interpersonal trust, can be hard to reestablish" [Hof+13].

Trust in Automation

According to Kevin Anthony Hoff and Masooda Bashir [KM15], trust is formed through exposure to new information, either consciously or unconsciously. This trust can be categorized into three levels: (1) *dispositional* trust, (2) *situational* trust, and (3) *learned* trust.

Dispositional trust pertains to the variance of trust between individuals in a system. It is influenced by culture, age, gender, and personality traits, which determine an individual's propensity to trust an automated system.

Situational trust, on the other hand, explains the variance of trust in a system in different situations. Every situation is characterized by both objective situation factors (external factors) and individual factors (internal factors), which create a unique situation experience. Internal factors include self-confidence, subject matter, mood, and attentional capacity. External factors include the system type, its complexity, task difficulty, task framing, workload, perceived risks, perceived benefits, and organizational setting.

Lastly, *learned trust* explains the variance of trust in a person in a similar situation at two points in time. It is the result of all evaluated interactions a person has had with automated systems. Learned trust can be established before (*preknowledge*) or during an interaction with a system (*experience*), either initially or dynamically. Concerning preknowledge, ease of learning, and self-rated knowledge increase perceived trust [DB17]. E.g.,Nathan L. Tenhundfeld et al. found that a sounder understanding of the Tesla "Autopark"-assistant leads to higher levels of trust [Nat+20]. Further, providing transparent information about the automation can prevent a reduction in trust [Joh+20; MJ13]. Concerning *experience* with a system over time, Dikmen and Burns [DB17] found in a survey with Tesla drivers that the assistants' (Autopilot and Summon) trust increased over time – regardless of the actual experience – even in face of automation failures. Johannes Kraus et al. [Joh+20] also demonstrate that trust declines after experiencing system failures whereas it is reestablished after a period without errors.

Mismatched Trust in Automation

It is crucial for individuals to trust autonomous vehicles based on their actual abilities. Many users of such systems do not fully understand their capabilities and limitations. This is partly due to the fact that autonomous vehicles are not included in driving school curricula, and manufacturers fail to provide adequate education to their customers. There are two potential issues with trusting automation. First, if people underestimate a system's capability and mistrust it (*undertrust*), they may opt not to use it [RV97], leading to discomfort for the user. Second, overestimating a system's capability can compromise safety, leading to errors or accidents due to *overtrust* and using the system in inappropriate situations.

When drivers trust their vehicles too much, they may become less vigilant. This can lead to a problem known as the out-of-the-loop issue (cf. [Mer+19; End16]), which can negatively impact their ability to take control of the vehicle in critical or uncertain situations. As a result, the risk of accidents increases because drivers may not be aware of the situation and may not react quickly enough [II13; Ito12; Nil96]. In a recent experiment, Körber, Baseler, and Bengler [KBB18] found that providing more trustful information to drivers raised engagement in non-driving-related activities and negatively impacted takeover performance.

In some cases, the consequences of not paying attention while operating autonomous vehicles can be fatal. This was evident in 2018 when Elaine Herzberg lost her life due to the negligence of an autonomous Uber car driver [Dai18]. However, autonomous vehicles have the potential to increase road safety because they are not prone to fatigue or distraction. Unfortunately, many people still perceive AVs as unsafe since they lack experience with them. This lack of trust poses a significant obstacle to the transition to higher levels of automation. Reports of accidents involving AVs in the press and media only reinforce these doubts. To increase trust in AVs again, designers must focus on making them more trustworthy. For example, [Boy+15] [Boy+15] found that providing transparent information is an effective way to calibrate trust in autonomous robotic agents. In another study, [Hel+13] [Hel+13] discovered that displaying continuous support system uncertainty during automated driving better prepares drivers for take-over situations and enhances trust calibration. Additionally, [Fal+18] [Fal+18] have provided design guidelines on how to improve communication to enhance reliance on automated vehicles.

In situations where vehicle sensors malfunction, causing a drop in the car's capabilities, the driver may become overly reliant on the system, e.g., in snowy conditions. To ensure safety, it is crucial that the system communicates its reliability and current capabilities to the driver. This information can help the driver calibrate their trust and maintain situational awareness in critical situations, ultimately improving takeover performance [Hel+13; Wie+19b]. To visualize uncertainty, hue is the most effective parameter [Kun+18b], and design metaphors such as bars, graphs, percent values, or pictograms can be used [Noa+17]. Other methods of improving communication reliability include LED stripes [Fal+18], vibrotactile in-seat feedback [Kun+18d], or olfactory cues [Win+19]. Further, visually augmenting traffic and indicating the safety of performing a takeover for oncoming cars can be helpful [Win+17].

Overall, trust in automation is not the same as trust between humans. Trust in automation is based more on how well it performs. It is easy to overestimate or underestimate these qualities, which can lead to mistakes when using a system or not using it at all. Hence, calibrating trust to an adequate level is still a challenge. Next, we will examine the overall user experience with AVs of which trust is an important factor.

2.4.4 User Experience

In HCI, the tool-oriented view on products (usability) has already been extended by a more experience-oriented view (cf. [HT06]), and is commonly called the UX. We look at how UX is changing through increasing vehicle automation and how this perspective could even be broadened with the frame of Positive Computing.

Changing User Experiences in the Vehicle

Research has shown that individuals have reservations about using automated vehicles, as they may not find it enjoyable (e.g., [Röd+14]). Furthermore, when driving in an automated manner, users may become bored after a certain amount of time [vTE18]. Even presently, journeys can be stressful for both drivers and passengers. Therefore, it is vital to ensure that individuals are entertained and feel at ease in the confined space of a vehicle. The precondition is that users trust the system and feel safe (see next section, Section 2.4.5). In the future, driving and traveling should be associated with positive experiences, whether through entertainment or making efficient use of travel time.

Designers should adopt an experience-oriented approach to automotive HMIs when creating positive experiences in AVs [Fri+19a]. With the help of technologies such as ambient intelligence and augmented and virtual reality, there are several visions for creating positive in-car experiences. These experiences could transform future automated vehicles into mobile offices [Jan+19], spaces for conversations, mental recreation, play, or self-extension [Wu+18]. It is vital to gather user feedback to design these experiences positively. To achieve this, public AV prototyping [Bra+18], probing [Gär+14; PJ17], trip experience sampling [Mes+12], field experiments, contextual inquiries, scale scenarios, and Wizard-of-Oz [PJ17] could be valuable supplements to existing design and evaluation suits.

Examples for new UX design in AVs include playful interactions for drivers [Die+13; Ste+17]. An example is using a playful anti-stress ball interface [Ter+13]. This can change the car's mood theme to create a relaxing atmosphere when driving home after work. Additionally, drivers and passengers can enjoy playing a cooperative music quiz [Bro+11]. To ensure a seamless experience switching from task to task, interruption management techniques can be applied [NWS17; TFM19; Sem+19]. These new types of user experiences provide customer value for future cars.

Beyond UX: Positive Computing

The term "Positive Psychology" was coined by Seligman and Csikszentmihalyi [SC14] in psychology. It advocates for psychological research to focus on investigating conditions that promote human potential and *well-being* rather than solely on human deficits. Positive Computing, Positive Technology, and Positive Design aim to remove technology barriers and develop products that support individual flourishing and well-being. The Positive Design framework proposed by Desmet and Pohlmeyer [DP13] includes three components: Design for *virtue* (being morally right), design for *pleasure* (experiencing positive affect), and design for personal *significance* (pursuing personal goals). The design should be balanced and tailored to individual needs. Additionally, it should be driven by *creating possibilities* rather than reducing the lack of something. Positive Technology is classified by Riva et al. [Riv+12] by the type of user experience: *hedonic* experiences, *eudaimonic* experiences, and *social* experiences. Calvo and Peters [CP14] classifies Positive Technology by the type of involved emotions: *self-related* emotions, *social* emotions, and *transcendental* emotions. *Positive Computing* is a similar framework that bases on basic human needs – we cover these in the next section (Section 2.4.5).

Today's vendors often promote vehicle characteristics as a unique selling point, but future autonomous vehicles may not have noticeable differences between brands in that terms; thus, hedonic experience qualities with the vehicle use become more important (cf. Figure 2.4). This means the overall *experience* with an autonomous vehicle will likely become an important factor when choosing a brand. To improve the hedonic qualities of autonomous vehicle systems, researchers and designers must develop and apply new methods for design and evaluation based on activities. Next, we look into basic human needs that influence the users' goals and, hence, their experience.

2.4.5 Basic Needs

According to the American Psychological Association (APA) dictionary [Ass23], a need is a tension that results from deprivation of "something required for survival, well-being, or personal fulfillment", whereas a goal is "the end state [... of] striving" and motivation the effort that one puts in to reach a goal. Throughout this thesis, we often use the terms together (*user needs & goals*) to include both user states a) the absence of something (need) and b) the presence of something (goal). These states form the users' expectations and shape their interaction experience.

In psychology, there is a long history of examining basic human needs. One of the most popular frameworks is the Self-Determination Theory (SDT) [DR00]. SDT is widely acknowledged for its ability to explain human motivation and well-being. According to this theory, there are three fundamental human needs: 1) *autonomy*, 2) *competence*, and 3) *relatedness*. Depriving someone

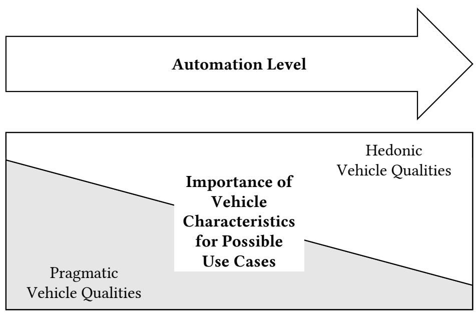


Figure 2.4: With increasing automation, in-vehicle experiences shift towards hedonic qualities, and user needs will adapt accordingly, shaping the future activities in the car.

of a basic need has adverse effects on their health and overall well-being [DR00]. Recently, the field has been applied to technology design. Hassenzahl, Diefenbach, and Göritz [HDG10] was one of the first to link human needs with a design approach and showed the relevance of need satisfaction for UX. In addition to the SDT basic needs, he identified the following needs as design-relevant: competence, relatedness, stimulation, popularity, security, and meaning. The Positive Computing framework [CP14; Paw+15] calls these design-relevant needs "well-being determinants" and provides a similar base as an anchor for user-centered design. Later, in an automotive-specific framework (DAUX: A Need-Centered Development Approach for User Experience in Driving Automation), Frison and Riener [FR22] highlights the importance of the following needs for UX: *security/safety*, meaning, relatedness, *stimulation*, *competence*, *autonomy*, popularity. We explain these needs in more detail in the following. However, we leave out the need for relatedness, popularity, and meaning since this thesis does not focus on social settings and value alignment.

Safety & Security

Safety & Security are, in the context of automated vehicles, especially relevant: the need to feel safe and secure [She+01]. In contrast to other domains, one has to trust the autopilot system in potentially safety-critical situations, where errors due to system failure or a hacker attack can lead to fatal accidents. We consider this need to be a "hygenic" factor [Her17], i.e., further needs will not become relevant without fulfillment of basic safety requirements. Hence, AVs have to offer this safety and security so that people consider using them.

Stimulation

Stimulation refers to the need for satisfying activities [She+01; Joh+12; Csi97]. Boredom causes a lack of stimulation: "In a nutshell, it boiled down to boredom being the unfulfilled desire for satisfying activity" [Joh+12]. Thus, for AVs, in-car user interfaces should aim to find a substitution for the driving task, which was the primary cause of stimulation in manual cars – entertainment features and games can be a way to achieve that. A study of van Huysduynen, Terken, and Eggen [vTE18] found reasons that motivated people to deactivate the autopilot: overtaking of other vehicles (cf. needs for competence and autonomy), *boredom*, *sleepiness*, lacking trust (cf. need for safety/security), and *joy of manual driving*.

Competence

Competence refers to the desire to make a positive impact on significant factors in a particular situation and its outcome. People with a strong desire to drive are less likely to trust autopilot. They believe they drive better than others, and surveys show this bias. Even in more automated systems, people want some control and to feel competent. One of the reasons why people hesitate to hand over control to a machine is because they believe they perform better than others. In a survey conducted by Ola Svenson [Ola81], drivers from Sweden and the US were asked to compare their driving skills to those of others. In the US, 93% ranked themselves in the top 50%, while in Sweden, 69% did so. This survey demonstrates that people are often biased; they tend to overestimate their abilities and underestimate the abilities of others, particularly in ego-centric, individualistic cultures. As a result, individuals may have more faith in their driving skills than in automation and be hesitant to give up control (and trust). Therefore, even in higher levels of automation, it is beneficial to provide people with some sense of control and avoid undermining their competence.

Autonomy

Autonomy refers to the need for individuals to have control over their experiences and align their actions with their intrinsic motivation and their “integrated mission" [Rya13] – free from social controls, evaluative pressures, rewards, and punishments. Autonomy is about personal control, not just task proficiency. Automation could enhance autonomy for some individuals (e.g., those with disabilities). Personal autonomy also involves the freedom to choose how to spend free time, so autonomous cars should not impose activities on users.

Overall, every potential AV user has a more or less pronounced profile of the needs for *security/safety*, *stimulation*, *competence*, and *autonomy*. Beyond influencing the user experience, we argue that basic needs also influence the acceptance process, which we cover in the following.

2.4.6 Acceptance

We examine technology acceptance processes and factors to answer *why* people would interact with AVs, or *why not* respectively.

Basic Needs Driving Adoption

In order to understand the role of human needs in adoption processes and why people choose to adopt vehicles, we utilize a Stimulus-Organism-Response (SOR) model (see Figure 2.5). This model involves the vehicle having certain qualities that are perceived by the user as a stimulus. However, this perception is not solely influenced by the vehicle itself, as personal emotions and opinions of others can also play a role. The user, or organism, then compares their perception of the vehicle with their personal needs. These needs are dependent on how the user imagines using the vehicle. If the perceived characteristics match up well with the needs of that particular use case, it will form a positive attitude towards the vehicle. A significant match of perceived and offered need satisfaction, or the match of a particular use case (goal) may lead to acceptance of the vehicle. Therefore, product designers should consider these needs (cf. previous subsection, Section 2.4.5) in order to create vehicle designs that are empathetic and intuitive.

Technology Acceptance

The concept of technology acceptance refers to a person's willingness to use a particular system, which then leads to its adoption. Various models exist to explain this behavior, with factors that influence intentions and evolve based on different theoretical contexts. In the following, we will discuss the development of selected models used for vehicle acceptance. For a more detailed history of technology adoption models, we refer to Sharma and Mishra [SM14].

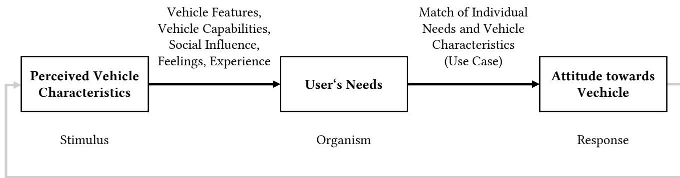


Figure 2.5: The role of human needs in acceptance processes – A match of (perceived) vehicle characteristics and user needs leads to a positive attitude towards the vehicle.

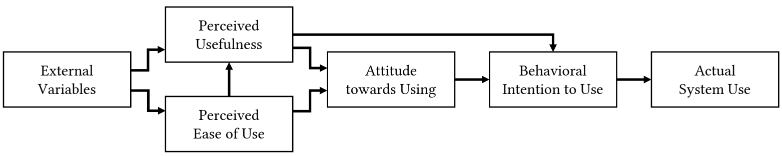


Figure 2.6: Technology Acceptance Model by Davis [Dav85].

Traditionally, when evaluating information technology acceptance, the Technology Acceptance Model (TAM) by Davis [Dav85] (cf. Figure 2.6) and its successor, the Unified Theory of Acceptance and Use of Technology (UTAUT) by Venkatesh et al. [Ven+03], are very popular across different domains. The primary benefit of the TAM/UTAUT is that they split behavioral intention to use technology (technology acceptance) from actual usage behavior. The TAM explains technology acceptance through a combination of one's general attitude towards technology and the perceived usefulness and ease of use this technology offers to perform a particular task, e.g., to file an income tax return.

The UTAUT combines eight previous acceptance models, including the TAM, which adds social influence, the gain or loss of social status through technology, as another critical aspect of technology acceptance. It also adds the factor facilitating conditions, which does not influence behavioral intention, but directly the usage behavior. A person has to have the resources to use

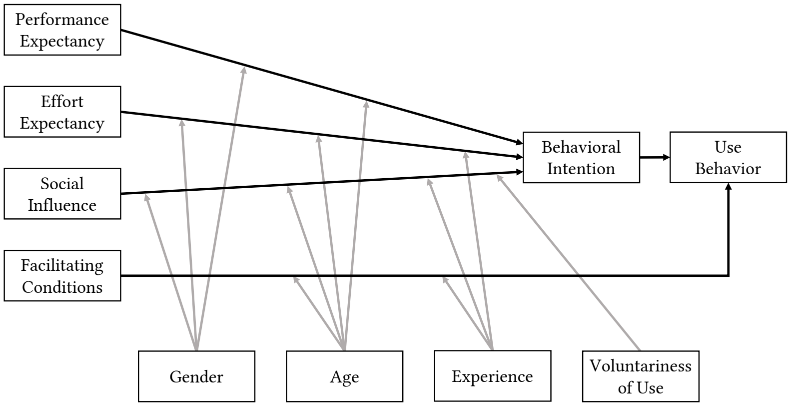


Figure 2.7: Unified Theory of Acceptance and Use of Technology by Venkatesh et al. [Ven+03].

technology, e.g., time or money. Further, the personal factors age, gender, experience, and the voluntariness of use moderate the proposed relation. It makes a difference if one designs technology for expert or occasional users if users have to use a system for their work or use a particular system by choosing and installing it on their home computers. The authors evaluated the UTAUT model in the context of information technology, where it shows an explanatory power of behavioral intention to use a system of up to 70%. The UTAUT2 [VTX12] extends the original model by the factors habit, price value, and hedonic motivation. In 2019, in a meta-analysis of the UTAUT model, Dwivedi et al. [Dwi+19] found that attitude towards a system mediates the influence that performance expectancy, effort expectancy, social influence, and facilitating conditions have on behavioral intention. Moreover, attitude toward a system directly affects both behavioral intention and use behavior. Thus, it is vital to understand *user attitudes* towards technology to predict acceptance.

To sum it up, with TAM and UTAUT, two robust and straightforward theories have become most famous for predicting technology acceptance, and for a good reason: their explanatory power is high in diverse application contexts. When required, one can extend both models to the needs of a specific application area. In the automotive community, researchers already made an effort to capture the adoption of AVs using these models.

Automated Vehicle Acceptance

The acceptance of driver support systems was measured by Adell [Ade10], whileMadigan et al. [Mad+16] measured the acceptance of automated road transport systems. However, the explanatory power of behavioral intention in their adaptations of the UTAUT model only reached around 20%, compared to the original UTAUT model which had a power of 70%. The authors argue that other factors, such as onboard comfort [DFG11], travel distance [DFG11], and the users' hedonic motivation, which is critical in consumer contexts [VTX12], as well as perceived safety [Mad+16], are essential determinants for the adoption of automotive technology. These factors are not included in the original UTAUT model, making it necessary to incorporate vehicle-specific and comfort-oriented factors to achieve a better prediction of user acceptance.

The Car Technology Acceptance Model (CTAM) by Osswald et al. [Oss+12] expands upon the UTAUT model by including factors such as perceived safety, anxiety, task-related self-efficacy, and general attitude towards technology for car adoption. However, it was created specifically for manual cars and therefore Hewitt et al. [Hew+19] refined the model in their Autonomous Vehicle Acceptance Model (AVAM) study with the aim of standardizing acceptance research in the AV domain. They adopted the factors used in CTAM and tested the AVAM using use-case scenarios containing all SAE levels of automation, comparing their results with a previous study by Rödel et al. [Röd+14]. Both results indicate that people's intention to use AVs decreases as automation levels increase. In contrast to AVAM, Rödel et al. used factors such as ease of use, attitude towards using, behavioral control, and UX-factors trust and fun to assess behavioral intention. It is worth noting that the variance of nearly all factors also increases with automation level, indicating that other factors may be important for those with highly automated or autonomous driving preferences. For example, Payre, Cestac, and Delhomme [PCD14] found that attitudes, contextual acceptability, and interest in being driven while impaired were predictors of acceptance for fully autonomous vehicles. A comparison of factors used to predict acceptance in different studies is shown in Table 2.2.

A first step towards a more process-oriented model is presented by Nordhoff et al. [Nor+19]: They describe the process of autonomous vehicle acceptance and relate factors to different phases of the adoption process. They claim that people form autonomous vehicle acceptance in a four-step process: 1) Exposure to autonomous vehicles, 2) Forming of positive or negative attitudes, 3) Deciding to accept or reject AVs, and 4) Implementation of AVs into practice.

	Surveys on Technology and Automated Vehicle Acceptance					
	General		*Automotive Specific (Targeted SAE Level)*			
	TAM Davis	UTAUT Venkatesh et al.	CTAM Osswald et al. (~0-2)	Rödel et al. (0-2,4-5)	AVAM Hewitt et al. (0-5)	Payre, Cestac, and Delhomme (5)
Explaining Factors						
Usefulness	x	x	x		x	
Ease of Use	x	x	x	x	x	
Attitude: Using	x		x	x	x	x
Behavioral Control				x		
Self-Efficacy			x		x	
Anxiety			x		x	
Trust				x		
Safety			x		x	
Impaired Driving						x
Fun				x		
Social Influence		x	x		x	
Context						x

Table 2.2: Factors used by popular papers to explain general technology and automotive technology acceptance.

To summarize, the acceptance of technology relies on the individual, the technology itself, and the context in which it is used. The TAM and UTAUT models have proven to be very effective in various domains and provide a strong foundation for future studies on the acceptance of automated vehicles. However, there are two significant issues with current research on the subject. Firstly, the models used have low [Ade10; Mad+16] or unclear [Oss+12; Röd+14; Hew+19; Nor+19] predictive power when it comes to behavioral intention to use a vehicle system, which affects acceptance. Secondly, with higher levels of automation and reduced driving responsibilities, new use cases in vehicles become possible, and people's needs change accordingly. This means that new factors may arise in acceptance research, such as comfort and entertainment-oriented needs, which may not have been as relevant in lower automation levels. Furthermore, the increasing variance with higher automation levels shows that people value such acceptance factors differently, suggesting that there might be different "acceptance personalities". Next, we discuss general aspects when designing for AVs.

2.5 Design Aspects

In this section, we first present a design space (problem domain x interaction modalities) to get an overview of previous work (Section 2.5.1). Then, we discuss the potential of inclusive design (Section 2.5.3) and end with a discussion of methodological challenges for research on AVs (Section 2.5.2).

2.5.1 Design Challenges and Literature Taxonomy

In the following, we classify existing literature by the challenges for design (problem space) and the kind of interface modalities they use. We constructed the problem space as follows: From our analysis in Section 2.4.5 and Section 2.4.6 and based on research challenges by A. L. Kun, S. Boll, and A. Schmidt [ASA16], we formed four major challenges categories for AVs design: Trust & Transparency, Safety & Performance, Competence & Control, and Positive Experiences. There are more challenges for automated driving design, such as Security & Privacy or public perception of autonomous vehicles. However, we are focusing on the challenges that can be addressed through in-vehicle interaction design and challenges that are influenced by basic UX needs. In Table 2.3, we describe these challenges and provide examples of research topics related to each category, along with their relevance to human needs and user acceptance. These categories are not mutually exclusive and should be continuously expanded upon.

After spanning the problem space, we thoroughly reviewed the literature in the automotive domain to explore how user interface research contributes to higher levels of automation. Specifically, we aimed to understand how a

Challenge Category	Description	Needs	Acceptance Factors
Trust & Transparency	Design for trustworthiness and reliability. This category focuses on systems which reduce use barriers and generate proper trust. Topics covered in this category are found commonly for all SAE levels. Examples: calibrated trust, overtrust, undertrust, reliance communication, anthropomorphic design, transparent design	safety & security	trust, anxiety, attitude, behavioral control, safety, ease of use
Safety & Performance	Design for safe and efficient traveling. This category focuses on technology for safety-critical situations in context with other road users and increased driving performance. Topics covered in this category are found commonly for SAE levels 3 and 4. Examples: driving performance enhancement, re-engagement in the driving task, safety assistants, performance of takeover requests, increasing situation awareness, skilling the driver	safety & security	usefulness, safety, ease of use, anxiety, trust, behavioral control
Competence & Control	Design for future driving and interaction with the car. It focuses on controlling the vehicle movement. Topics covered in this category are found commonly for SAE levels 3, 4, and 5. Examples: abstraction of control, cooperative driving, maneuver-based driving, control interventions	competence, autonomy	self-Efficacy, usefulness, ease of use, behavioral control
Positive Experiences	Design for positive travel experiences and interaction inside the car. It focuses on hedonic qualities like fun, excitement, beauty, positive emotions, and well-being. Topics covered in this category are found commonly for all, but mostly higher SAE levels. Examples: comfort, relaxation, entertainment, mobile office, personalization, playful interaction, creativity	stimulation, meaning, autonomy	attitude, fun, usefulness, self-efficacy, social influence

Table 2.3: Challenges for AV design – Categories used for the literature review.

	Challenge Category			
	Trust & Transparency $n = 23$	*Safety & Performance* $n = 48$	*Competence & Control* $n = 19$	*Positive Experiences* $n = 6$
Input Modalities				
implicit				
Physiological Prop.				
Emotions				
Thinking				
Gaze				
Position				
Speech	[Wal+16; Tsc+17; OS17; PSS12; Lar+19]	[Lar+16]	[Hia+13; Det+19]	
Mid-Air Gestures			[Tsc+17; Det+19; PSS12]	
Tactile	[Gha+16; PLK15]	[Ter+13; Lar+17; Fri+17; Ros+18; GY19; Zim+14; Kie+09; Gha+16]	[Fri+17; Kro+15; Kro+17]	
Touch	[SRW18]	[Wal+16; Tsc+17; SRW18; KSB10; Ben+12; Wal+19]		
explicit				
Output Modalities				
Visual	[SS16; Win+17; MDT16; LTB17; Zih+16; Kun+18b; Fal+18; Noa+17; Kra+15; GJK14; Hel+13; Wie+19b]	[Won19; Kun+18c; Hel+13; Wal+15; PBP15; Noa+17; vKT17; Bor+16; FNN16; Wie+18]	[Trö+18; Wal+16; Ben+12; Zim+14; Sch+18; Wal+19]	[ST15; LIU17; Ter+13]
Somatosensory		[Fal+19; Won19; Seb+17; PSA18; Bor+17; PBP15; Tel+15; SWS17; SJK16]	[Kie+09; Lv+20]	
Auditory	[Lar+19; Hoc+16]	[Won19; Wal+15; vIJ17; Seb+17; Koo+15; PBP15; Gan+18; Lah+18; Hoc+16; Ort+17]	[Mau+18; Wal+16; Zim+14]	[Kro+17; Ter+13; Hia+13]
Olfactory	[Win+19]	[Qiu+20]		
Gustatory				
Vestibular		[SJ19; CSB17; S C+17]		

Table 2.4: Literature review - Design challenge by solutions used modalities.

contribution can enhance user acceptance and which modalities the system or concept utilizes. This review is not exhaustive but covers a significant amount of literature on automotive HMI. The reviewed papers introduced a system or idea that falls under one of the categories for acceptance challenges (refer to Table Design Goals). Additionally, we concentrated on research and projects that were related to driving in higher levels of automation (SAE levels 3, 4, and 5) by searching for variations of the search terms *(automated OR autonomous) vehicle**, *(automated OR autonomous) driving*.

We conducted a thorough review of literature from various sources. Firstly, we explored the proceedings of the "AutoUI"-conference, a specialized event for automotive user interfaces in the HCI field. We also examined the CHI conference, which covers a wide range of HCI topics, totaling 5496 papers. We reviewed 76 relevant papers and expanded our scope by scanning the reference lists and authors' Google-Scholar-Profiles, including conferences and journals (e.g., "ACM ICMI", "ACM IUI", "IEEE IV", "IEEE ITSC"). Table 2.4 provides a comprehensive taxonomy, including 67 papers. We categorized the design solutions' interactions into input and output modalities. Input modalities are sorted from explicit to implicit. This literature classification provides an overview of work done for a (1) particular interaction modality in a (2) specific problem area. We describe both points in the following.

Regarding the first point, with our taxonomy, we provide a comprehensive overview of interaction modalities (see also Section 2.3.3). The less critical the primary driving task becomes, the higher the potential that other interaction mechanisms might become more useful for input. On the output side, we have already described that additional modalities, like elements on a virtual windshield, can improve, e.g., trust during automated driving (see Section 2.4.3). Overall, there is a need to explore interfaces beyond the traditional instrument cluster, steering wheel, and pedals.

Regarding the second point, the problem domain, we see that there is a lot of work done in the *Safety & Performance* category, less work in the category of *Positive Experiences*, yet the categories that help to bridge the gulfs of execution (*Competence & Control*) and evaluation (*Trust & Transparency*) are underrepresented. Thus, we see a need to examine these problem areas further. After concentrating on the need-based design challenges, we look at the ability-based or inclusive design approach in the following.

2.5.2 Inclusive Design

Autonomous driving bears the potential to provide life-long individual mobility for people with impairments or mobility restrictions (e.g., elderly people with physical impairments or children) that would be excluded from using traditional cars and, thus, enable personal autonomy. However, this potential has to be considered from the beginning. Retrofitting accessibility features into vehicles can be complicated and expensive.

In this thesis, we are using the definitions of the World Health Organization (WHO) [WHO18] for the terms *impairment* and *disability*. According to WHO, an *impairment* is “any loss or abnormality of a psychological, physiological, or anatomical structure or function.” Impairments could be temporary or permanent. On the other hand, a *disability* is “any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being.” Such limitations could be due to environmental barriers of a cultural, social, or physical nature. These barriers can cause disadvantages or *exclusion* in terms of social life or occupation, also called *handicaps*. As technology designers and researchers, we need to consider potential barriers that users may encounter and find ways to resolve them. This will ensure equity and participation in mobility for all, also known as *inclusion*. *Assistive technology* is designed to help individuals overcome barriers and gain *access* to mobility services. For example, a ticketing app equipped with a screen reader can provide those with vision impairments access to mobility services. Assistive technology aims to promote independence by bridging the access gap between individuals with impairments and the environment designed for the non-impaired [BBB18].

To create mobility services that are accessible and inclusive for all users, designers can apply Universal Design (UD) principles (see Figure 2.8). The UD framework aims at the “design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design. Characteristics of any UD product or environment are that

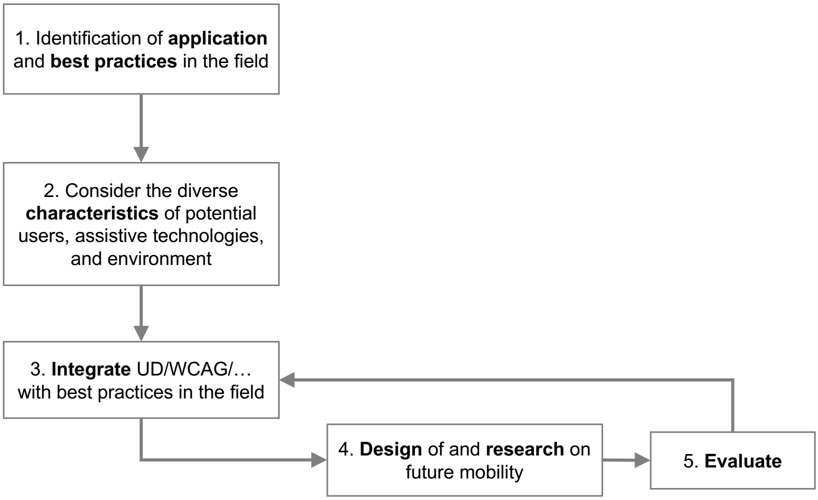


Figure 2.8: Universal Design process by Burgstahler [Bur21] – Adopted for inclusive design of future mobility services.

it is accessible, usable, and inclusive." [Bur21]. Ability-based Wobbrock et al. [Wob+11] and user-sensitive design by Newell and Gregor [NG00] share a similar philosophy. While it may not be possible to address every user's needs (cf., [Duv21]), finding synergies between different abilities can be beneficial. For example, an aural interface designed for users with low-vision can also benefit non-impaired users.

One example of an application of the UD framework is the Web Content Accessibility Guideliness (WCAGs) [Wor21]. WCAG requires websites to be visible, operable, intelligible, and resilient, with many of these guidelines applicable to mobility. However, it is important to consider mobility-specific UD as WCAG rules do not cover non-digital elements such as trip settings, movement, or social scenarios during a ride. To better understand the specific adaptions, it is necessary to get a better overview of potential vehicle users and vehicle design possibilities – we cover this topic in Chapter 5. Overall, the user experience and acceptability of automated vehicles are strongly influenced by the user types, and many users may bring ability-specific needs that designers should consider.

2.5.3 Methodological Challenges

The following will discuss different research approaches to examine user perceptions and behaviors concerning future automated vehicles. We focus on research on NDRAs because these activities require a high level of automation and thus present a high gap between current and future user experiences, whereas, e.g., safety measures will stay comparable to today's cars. Through non-exhaustive literature research, we have determined four key methodological approaches for studying non-driving related activities in AVs (see Table 2.5). These approaches are, of course, applicable to studying other phenomena, such as situational awareness or trust in automation as well. Next, we briefly describe the four major categories.

The different approaches to studying passenger behavior can be categorized generally into *observation-based* and *self-report-based* methods. The latter category involves *thought experiments* [Sor98], where participants are presented with hypothetical scenarios of autonomous mobility services and asked to provide their opinions on the situation. This can be done through, e.g., co-design sessions [Ste+19a], interviews [PCD14], or online questionnaires [CFL15; PRB16; Pat19b]. However, these studies heavily rely on the participants' sensitivity and understanding of the situation. One issue with these approaches is the *Chicken-and-Egg Problem* of autonomous driving [YFB20]. As there are no publicly available autonomous mobility services yet, participants may find it challenging to imagine a future usage scenario. The *task-artifact cycle* [CKR91] suggests that technology is developed to fulfill existing human needs and preferences. For autonomous vehicles, these needs could include autonomy, competence, safety/security, or stimulation (cf., Section 2.4.5). However, the availability of technology can also influence and change users' needs and preferences, leading to a continuous cycle. Therefore, findings from thought experiments can provide an initial snapshot of user needs and preferences for the development of autonomous vehicles. However,

Method	Study Example
Self-Reported	
Thought Experiment Experience	
Questionnaires	Questionnaire about NDRA preferences [CFL15; PRB16; Pat19a]
Interviews & Focus Groups	Interviews about motivation to use HAD [PCD14]
Design Fiction	Co-Creation Session to build a future vehicle [Ste+19b]
Observation	
Simulator Experience	
Traditional Driving Simulator	Observing NDRAs on a highway ride [Hec+20]
VR Driving Simulator	Rear-seat mobile office [Li+21]
Video-based Driving Simulator	Video-based driving simulators [GSV19] for UX research
Comparable Experience	
Train, Tram, Cable Car	Observation protocol of passenger behavior [Rus+11; PRB16]
Bus	Observation protocol of passenger behavior [Rus+11]
Taxi-like	Interviewing passengers during their daily commute [Per+16]
In-situ Experience	
Vehicle Prototype with simulated Environment	Self-driving, pod-like vehicle in a arena with video-walls [Lar+19]
Wizard of Oz Automated Vehicle	WoZ Car to study fatique [Oli+19] or TORs during NDRAs [Fre+19]

Table 2.5: Taxonomy of methods used to study NDRAs – Similarly, other phenomena of interest, such as automation trust, can be studied.

these may only represent a starting point, as user needs and preferences can evolve over time with the introduction of new technology.

The second group of methods focuses on analyzing phenomena through a *driving simulator experience*. This includes traditional setups (e.g., [Hec+20]), video-based driving simulators [GSV19], or virtual reality simulations [Li+21]. These lab settings are easy to replicate and set up while proving a sufficient degree of realism to the user. The downside is that these experiments provide a safe setting where the driving experience may differ from real-world conditions (e.g., causing motion sickness). Factors such as the perception of safety are likely to influence users' choices regarding NDRAs or their perceptions regarding automation trust.

The third category of studies involves observing *experiences in other contexts*, such as using trains [Rus+11; PRB16], buses [Rus+11], or taxis [Per+16]. While these findings can be useful in investigating NDRAs or for eliciting, e.g., driverless transport, one disadvantage is less privacy in these environments. This could affect passenger behavior and activities as users may avoid certain activities in public spaces or choose different activities altogether. Perceptions of trust and safety might differ through the different kinds of transport services – a train is likely to be considered safer as an autonomous vehicle that navigates through dense traffic.

The final group of studies involves real-world or *in-situ experience*. However, conducting experiments with actual AV poses significant risks for drivers, passengers, and other road users, as highlighted in previous research [BL17]. To mitigate these risks, researchers can regulate and control either the *system* or the *environment*. There are several options for creating a safer testing *environment*, such as (1) using a real autonomous vehicle in a simulated environment, (2) using a simulated autonomous vehicle in a real environment, or (3) a combination of both. Regarding the first point, one possible solution is to use VR driving simulators in real cars [Goe+18; Hoc+17]. This approach offers a fully controlled environment but requires users to wear a head-mounted display that restricts their real-world physical activities. Regarding the second point, windshield augmentations [Ben+19] or video projection walls [Lar+19] can create a virtual and controlled environment while allowing passengers to perform real-world behaviors in the car. However, the user experience, such as driving speed or traffic, may be limited. To control the study on *system-side*, *Wizard of Oz* Vehicles are a viable approach [Wan+17; Bal+15; Oli+19; WMB19; Fre+19]. This method provides a realistic driving environment in a real car while giving users the illusion of interacting with a fully automated car. The system is operated by a human operator known as the "wizard". This approach can offer a rich user experience for studying future autonomous vehicles if the illusion is maintained. A downside of this approach is that it requires high effort, and participants, after being debriefed or noticing a deception, are no longer available for follow-up studies. Further, the replicability of the traffic conditions is not possible.

Overall, when designing user interfaces for future automated vehicles, we encounter a challenge known as the chicken-and-egg problem [YFB20; PRB16]. Because fully automated vehicles are not yet available, it is difficult for users to imagine what driving in them (such as when asked in surveys) would be like. Currently, prospective users of AVs have limited to no experience with driving automation in real-world situations. The more immersed users are in the technology scenario, the more accurately we can determine future needs and requirements. Consequently, researchers employ various methods and combine their findings to comprehensively understand the technology [Ste+19b].

II

Understanding User Needs & Goals in Transition to Autonomous Mobility

OUTLINE

The following part of this thesis deals with the user needs and goals in changing context of autonomous mobility services (cf. *RQII* – How to will user needs and goals change in autonomous mobility services?). Understanding user goals is essential to capturing what motivates them to use or reject autonomous mobility services and what they expect to be a satisfying journey experience. However, a journey experience also influences future users' needs and goals. Carroll and Long [CL91] formulated this phenomenon as the "task-artifact-cycle": Tasks/activities inform the future use of an artifact (cf. Figure 2.9). Since autonomous mobility services have yet to be available, we confront users with scenarios of autonomous mobility. We present them with the changed task/activity context and collect feedback about the new possibilities or potential use constraints in three chapters. This feedback can help inform the design requirements of such services. First, we conducted a real-world driving study (Chapter 3) to help users to imagine the new possibilities of autonomous mobility services and collect their feedback regarding their trust, acceptance, and practical use of the vehicle. Second, we rolled out an online survey that collects users' diverging needs and goals toward an autonomous mobility service in public transport and demonstrates how to detect underlying patterns of attitudes (Chapter 4). We close the part by looking deeper into needs and goals beyond the average user, e.g., those with disabilities. For that, we collect requirements and use cases from experts in the inclusion field and from the literature and integrate these insights into a comprehensive design framework for inclusive autonomous mobility services (Chapter 5).

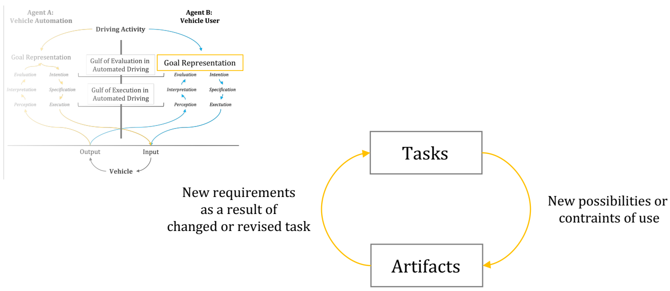


Figure 2.9: Task-artifact-cycle by Carroll and Long [CL91] – The evolving nature of artifacts used for a specific task also influences how one performs the task. Comparably, the increasing automation technology used in cars changes the nature of the driving task and offers new possibilities, e.g., NDRAs. New possibilities in the car require new kinds of technical support, e.g., handover warning systems.

Chapter 3

Real-World Acceptance, Trust & Use

This chapter is based on the following publications:

Henrik Detjen, Bastian Pfleging, and Stefan Schneegass. “A Wizard of Oz Field Study to Understand Non-Driving-Related Activities, Trust, and Acceptance of Automated Vehicles”. In: *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. New York, NY, USA: ACM, 2020, pp. 19–29. ISBN: 9781450380652. DOI: 10.1145/3409120.3410662

In this chapter, we present a real-world driving study to provide users with a firsthand experience of autonomous mobility services and gather their feedback on trust, acceptance, and practical use of the vehicle. The study aimed to help users envision the new possibilities offered by autonomous mobility services and understand their perspectives on these advancements (cf. *RQII_1* – How is a real-world experience changing needs and goals?).

Understanding user needs and behavior in automated vehicles is crucial for designing effective in-vehicle interfaces and services in the future. The existing literature indicates the potential for people to utilize their travel time more efficiently (e.g., [Ste+19a]). However, without proper support from vehicle and service design, the travel experience in automated vehicles may not differ significantly from being a co-driver in traditional, non-autonomous cars. This could result in missed opportunities to leverage the potential benefits of autonomous mobility fully [Pat19a]. Therefore, it is essential to thoroughly analyze and support the design of future vehicles from a user perspective, ensuring that the travel experience is optimized and aligned with user needs and goals.

As shown in the discussion of research methods in Section 2.5.3: The current understanding of AV use and perception is primarily based on observations in other transportation modes, interviews, surveys, and hypothetical scenarios. Research on the behavior of passengers in AVs has predominantly focused on non-road modes of transportation, such as trains or subways (e.g., [PS15]). Additionally, studies often rely on potential users imagining and providing feedback on their experiences in interviews, surveys, or ideation sessions (e.g., [Ste+19a]). There is a significant gap in the current research regarding the actual behavior of users in autonomous vehicles, which is crucial for understanding how people utilize their travel time and adapting user interfaces to meet passenger needs and activities [ASA16]. This understanding is particularly important because tasks and artifacts in the context of autonomous vehicles continuously co-evolve (cf. Figure 2.9). Therefore, our objective is to move beyond previous studies that primarily focused on investigating user needs and preferences in the absence of an actual product. In this chapter, we address this gap by providing real-world insights into attitudes towards autonomous mobility services and the utilization of free time for non-driving-related activities.

In addition, we test models to investigate automation acceptance and trust. A common drawback of most studies in this domain is, as described above, that they are based on thought experiments. As we plan to expose participants to a real-world scenario, we also take this as an opportunity to validate results from existing models with real-world data from our experiment, i.e., acceptance (see Section 2.4.6) and trust models (see Section 2.4.3).

In the following investigation, to study NDRAs, automation trust, and acceptance, we utilized an in-situ experience involving a WoZ automated car. This vehicle closely resembled the features of an actual automated car. In addition to the WoZ rides, we conducted interviews and administered self-report questionnaires to gather further insights. The study consisted of a multi-exposure design, with each participant experiencing six rides over multiple days. By repeatedly exposing participants to the vehicle and its automation features, we aimed to observe any changes in their activities and perceptions over time. This approach allowed us to capture how users gradually acclimated themselves to the vehicle and the impact it had on their behavior and perceptions.

3.1 User Study

The central component of our study involves observing users in a real-world setting using a WoZ vehicle. Each participant takes part in six consecutive rides over multiple days, and these rides are accompanied by semi-structured interviews and questionnaires. We ensured that our study adhered to the current reporting guidelines for WoZ experiments [Rie12a]. Furthermore, we implemented the advisory recommendations provided by the departmental ethics committee in Eindhoven.

3.1.1 Participants

Twelve participants participated in the investigation ($N = 12$). Six identified as females and six as males. They were between the ages of 24 and 33 (M =28.67, $SD = 3.08$) and recruited through personal networks and local distribution lists. We chose participants from a variety of origins in order to obtain a broader spectrum of opinions (see Table 3.1).

We used the ATI scale [TCD19] (9 items on a 6-point Likert scale) to measure participants' affinity for technology. The affinity was rather high ($M = 3.87$, $SD = 1.24$, $MIN = 2.00$, $MAX = 5.67$). Participants had short- to medium-length daily commutes/travel times (M=19.63 min, $SD = 10.49$ min,

#	Pseudonym	Gender	Age	Occupation	Believed Cover Story?
1	Emma	f	20-35	Media Designer	Yes
2	Elias	m	31-35	Freelance Programmer	Yes
3	Isabella	f	20-25	Waitress / Student	Yes
4	Sophia	f	26-30	Barkeeper	No
5	Charlotte	f	26-30	Job-Seeking	Yes
6	James	m	26-30	Student	Yes
7	Lucas	m	31-35	Freelance Musician / Student	No
8	Mia	f	26-30	Teacher	Yes
9	Alexander	m	31-35	Service Engineer	No
10	Jacob	m	26-30	Research Assistant	No
11	Olivia	f	26-30	Financial Consultant	Yes
12	Benjamin	m	20-25	Material Tester	Yes

Table 3.1: List of participants with identified gender, age, occupation, and if they believed the cover story or not.

$MIN = 5.6\,\text{min}$, $MAX = 50.28\,\text{min}$) which we anticipate to be the most prevalent for the use of AVs in daily life in Europe (e.g., commute to work or trip to the nearest shopping center). In Germany, we conducted the investigation in the urban areas of Bremen and Essen. As the participants received six complimentary rides/commutes during the experiment, they were not compensated monetarily further.

3.1.2 Wizard of Oz Vehicle Setup

We utilized the TU/e Mobility Lab [Kar+18], a Renault Espace van, and modified it similarly to the BRADS platform [Bal+15] to simulate an autonomous vehicle. The actual pilot of the vehicle is referred to as the “automation wizard” or “safety driver” (see cover story below). A partition separates the safety driver from the participant seated in one of the rear seats (see Figure 3.3, Figure 3.1, and Figure 3.4). Consequently, the partition divides the *safety driver space* from the *passenger space*.

The partition wall mounted a Sony KD43XF7596 4K 43″ display connected to a GoPro Hero 6 Black action camera placed at the inner upper center of the windshield. The display gives the passenger a 4K real-time view of the driving

Figure 3.1: We conduct a real-world driving experiment with a Wizard of Oz automated vehicle in order to address the evolving needs and goals of users during autonomous driving ($N = 12$). We study non-driving-related activities in the vehicle along with the acceptability, trust, and overall experience of the journeys.

Figure 3.2: View into the passenger cabin – the cabin TV projects the camera view from the windshield into the passenger cabin.

scene as if they were seated in the (co-)driver's location. To increase occupant comfort and situational awareness, LED bars behind the left and right screen edges indicate whether the vehicle is turning left or right. The passenger space consists of standard car seats, a wooden center armrest, and a central table on which commuters can place devices such as laptops and tablets, as well as other personal items and catering (see Figure 3.2). Participants could bring their own devices and use an in-car WiFi hotspot.

Participants could make use of an "emergency" button on the central table to

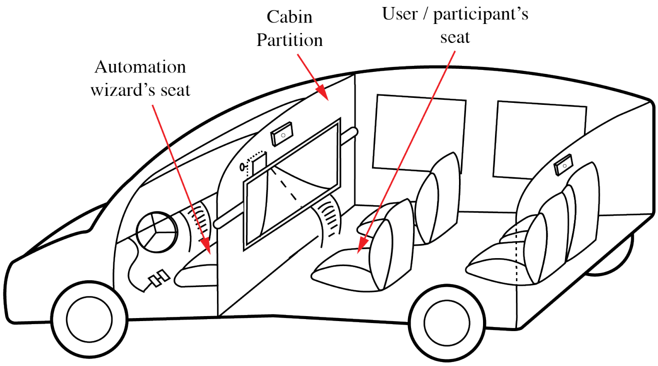


Figure 3.3: Overview of the Wizard of Oz AV setup – The automation wizard rests in the front row, a cabin wall isolates the wizard from the user, and a screen provides an unimpeded view of the road ahead.

signal distress and the need for intervention (e.g., stopping the vehicle). We utilized a laptop on the co-driver seat that was connected to an extra camera over the TV screen on the space's partition to allow us to observe and capture the passengers' activity (see Figure 3.4).

Automation Wizard

The author of the thesis (m, 32 years) was the automation wizard and was fully aware of the study's objectives. Before the experiment began, he rehearsed driving the vehicle for a week in order to become acclimated to it and cultivate an AV-like driving technique. To mitigate the risks during the journeys and maintain the facade of an autonomous vehicle, the wizard driver mimicked the defensive (e.g., adhering to speed limits and paying attention to other drivers) and forward-thinking behavior of an AV.

Cover Story

Since informing participants that we would be observing them during the experiment could influence how they behaved, we deceived them with a cover

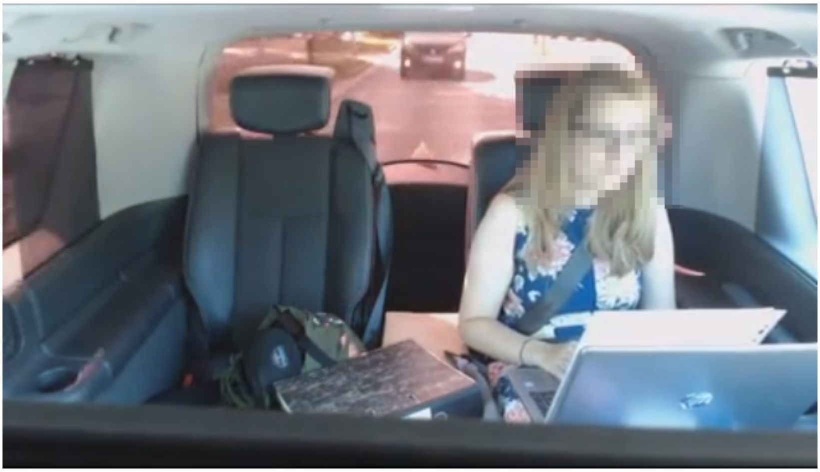


Figure 3.4: Passenger performing office duties as viewed by the passenger space camera. This might represent an example of the mobile office in the near future.

story. In order to measure trust in automation and acceptance of automation technology, we also pretended that the vehicle was being operated by a self-driving system.

We informed the participants that the aim of the study is to investigate the impact of various driving techniques of AVs on the comfort and preferences of their users. Following each journey, we asked the participants to evaluate their assigned driving style. We addressed possible discrepancies regarding the wizard's driving behavior by providing this information. We explained that we would use the interior video recordings to understand better the passenger's responses to the current driving behavior and that the safety driver would use the real-time video feed to respond to requests from the passenger. As the participants could see the automation wizard – who was also steering the car – before and after pickup and dropping off, we stated that the safety driver would a) constantly track the vehicle's actions and b) support the automation if needed especially while parking the car, i.e., along pickup and the drop-off.

Following the study's completion, we inquired the participants as to whether they believed in the cover story. Four individuals (33%) indicated that they had observed the deception (as indicated on the participant list). For all other participants ($n = 8$), the belief in the cover story endured throughout the entire study.

3.1.3 Procedure

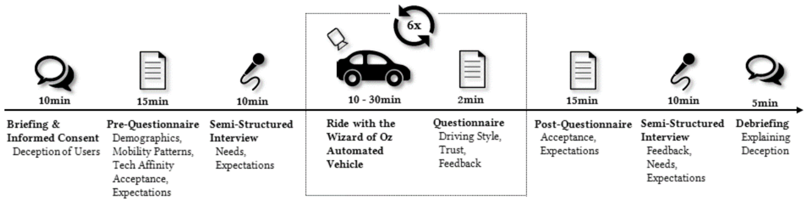


Figure 3.5: Study protocol.

Figure 3.5 depicts the protocol we went with for our study. During enrollment, we explained to participants that the study would consist of six freely selected journeys with our AV, as well as introductory (kick-off) and concluding interview sessions. The participants received a brochure with instructions on how they could book the six separate journeys.

Introductory Session

For the introductory session (25 min), we either visited the participants in their homes or invited them to a video call, depending on their inclination. Before deciding to participate, we motivated the participants to ask questions regarding their involvement as well as regarding the project's objective (at this point masked through the cover story). We ensured that they received comprehensible and sufficient responses. In accordance with GDPR [EUR16] guidelines, we requested permission to use their data, including for follow-up research (see Section VII for the entire consent form). Passengers in the WoZ vehicle may experience motion sickness while reading or operating mobile devices, for instance. Yet we did not anticipate this risk to be greater than riding in a taxicab. To prevent distress, we informed the participants that they might withdraw the consent at any time and asked the driver to halt the car.

After instructing the participants, we asked for their signatures on the consent form and gave them a duplicate of it. Next, they completed an initial survey that contained inquiries about demographics (age, gender, education, occupation), mobility patterns, and technology acceptance (which includes a scenario description and a picture of the WoZ car; measured with AVAM questionnaire [Hew+19], 26 items on a 7-point Likert scale), affinity for technology, and expectations concerning autonomous driving which include activities and car inventory. In addition, we did semi-structured interviews to determine attitudes regarding autonomous driving to understand their acceptance and expectations further.

Real-World Driving Study

The participants registered for their six individual trips by supplying the experimenter with the pick-up date and time, starting point, final destination, and expected duration of each ride. We collected up the participants at the designated time and transported them to their destination from the starting location. During the trips, we recorded the activities of the passengers in the vehicle. At the end of every drive, we prompted participants to complete a short survey regarding their automation trust (estimated with the Trust Scale questionnaire [JBD00], 12 items on a 7-point Likert scale) and, to reinforce the credibility of the cover story, about the driving parameters (style, comfort, safety, and overall satisfaction) – the whole set of questions can be found in Section VII.

Final Session

right after their sixth and final trip, participants completed the post-ride questionnaire in the vehicle (see also Section VII). Next, we did a second semi-structured interview to determine whether their attitudes had evolved since their initial interview. At this point of the interview process, we debriefed the participants, unveiled the cover story, and informed them of the study's genuine purpose. We gave all participants the option to either keep or withdraw their approval of the use of their data. Everyone involved kept his or her consent and agreed to the further use of the data for the study's actual objectives, i.e., observing anonymized activities and measuring trust/acceptance.

3.2 Results

The study's findings are tripartite. Firstly, we gathered information regarding users' expectations, the way they perceive the implications of self-driving cars, and their reasoning for adopting or rejecting them. Secondly, we show the user's view with regard to AV in the real-world setting, where trust in the vehicle's capabilities, safety while driving, and time use are important journey experience factors. Thirdly, we show our observations regarding the NDRAs in the WoZ automated vehicle. Since four of the participants (33 %) claimed to have noticed the cover story facade, we excluded their responses from the post-study interviews, trust and acceptance questionnaires, as well as the activity observation, in order to present solely the most immersive automation experiences.

3.2.1 Expected Impact of Autonomous Driving

From our interviews, we collected a multitude of impressions regarding the expected influence of autonomous driving. All interview responses from the pre- and post-interview were analyzed using a qualitative content analysis after Mayring [May10]. The author of this thesis inductively coded the material and connected similar codes and curated the codes into thematically coherent narratives (cf. thematic analysis [BL17]) that recollect the prevalent themes of the interview responses, i.e., *A better life?*, *Autonomy Through Automation*, and *The Car as a Social Place*.

A better life?

Concerning the introduction of self-driving vehicles into society, one participant expressed concern over the unknown situation (Olivia: “Of course you have some respect for that, you just don’t know that someone else is steering for you.”) and thinks that life may be increasingly digitized. Opposed, some participants believe they will have more leisure time due to being relieved of the driving obligation ($n = 2$, Mia: “Especially if you live in such a performance-oriented society, you can use the time to work more efficiently”) and better traffic regulation ($n = 4$, Benjamin: “There would hopefully be fewer traffic jams”). They consider this additional time to be comforting ($n = 2$) and assume that people will be calmer ($n = 1$). The traffic efficacy impacts the ecological aspects ($n = 3$) of mobility, which could result in greater energy efficiency, reduced CO_2 emissions, and less noise. In addition, safety could be enhanced ($n = 1$, Lucas: “There will be far fewer accidents”). In sum, a few participants predicted that autonomous driving would have no impact on their daily lives ($n = 3$), but the majority anticipated that their lives would become better($n = 9$).

Autonomy Through Automation

On an individual level, a few participants ($n = 2$, Benjamin: “I’ll have to try it first”) are undetermined, yet the majority ($n = 10$) are convinced AVs will increase autonomy. (Sophia: “That you can do something else in time, that’s already a plus of freedom”). When prompted about which activities they intend to do given their newfound autonomy, participants mention working ($n = 4$), reading ($n = 4$), eating and drinking ($n = 4$), and doing nothing or unwinding ($n = 4$) as their top choices. Whereas one participant brings up sleep as a routine, another cannot imagine sleeping in the vehicle (Mia: “Maybe that’s still a little scary somehow because I’m not quite in control at all”).

The Car as a Social Place

Concerning ridesharing or ridepooling, we asked participants how having the company of people they know would impact their behavior in an autonomous vehicle. The majority of participants ($n = 9$) expect they are going to have more conversations in the future (Sophia: “Because everyone can chat and the driver does not have to be excluded anymore”) or that they participate in other forms of socializing, such as engaging in a game together ($n = 1$). Also pointed out is the enhancement of social gatherings ($n = 2$) if guests are incapable to drive themselves or if the gathering’s venue is not well accessible by public transportation (Jacob: “I think the celebration culture is changing, you can drive home after some drinks. From everywhere. That’s awesome”). Occasionally, the latter excludes people from areas not served by public transportation. On top of that, one person states that sleeping in the company of other familiar people may be acceptable due to the division of responsibility (Mia: “I’ll be a little calmer”). If the other passengers in the vehicle are unknown, respondents predict the same experience as if they were traveling alone ($n = 2$) on a bus or train ($n = 1$). One participant said that it would be risky to sleep in the company of strangers ($n = 2$, Mia: “You have your valuables with you”).

3.2.2 Well-Being and Acceptance

Based on the interviews, we extracted the most important factors influencing well-being in the car and the adoption or rejection of autonomous vehicles.

Well-Being

The top named reason for well-being is *safety* – the feeling that a) the vehicle performs safely ($n = 4$, Benjamin: “A safe and controlled journey”) and b) it employs robust technology ($n = 2$, Charlotte: “Flawless technology”). Moreover, the system needs to be *understandable* ($n = 1$, Emma: “If you know how this works, then maybe I could relax too”). Well-being is linked to the *driving style* ($n = 2$). In our experiment, the defensive driving strategy was deemed to be pleasant (Benjamin: “Because it started relaxed and drove at a moderate speed, I found that very pleasant”). The *vehicle interior* ($n = 3$) like a music system, Internet access, or massage seats, and *vehicle characteristics* like a silent engine ($n = 1$) are further well-being aids. Lastly, the increasing *experience* with the system is assumed to increase well-being and comfort, too

($n = 3$, Mia: “I’m a little skeptical. That might settle over time”). Mia confirms this in the post-interview (“I have become [...] a little more open-minded and less skeptical”).

Key Potentials and Barriers for Acceptance

When asked for the single most significant reason for using AVs, many participants name adequate safety. ($n = 6$, Elias: “The feeling that the car is driving safely”). Moreover, the increase in autonomy ($n = 1$) and the removal of the driving task were named as potentials ($n = 1$, Charlotte: “I don’t have to focus on traffic all the time”). While some participants view the absence of driving as a relief, others prefer to maintain control of the vehicle (Mia: “If I still have some way to intervene, I’d use it”). Moreover, environmental considerations ($n = 1$) and impaired driving ($n = 1$) contribute to use intentions. Ultimately, using AVs services must be comparable expensive to using conventional vehicles ($n = 2$, Isabella: “That it is not disproportionately expensive”).

Participants pinpoint a number of reasons why they would reject AVs, which are sometimes inversely to acceptance reasons. If the vehicle is considered to be unsafe ($n = 4$), as a result of news reports for instance (Isabella: “If there had been news about accidents”) or if too expensive ($n = 1$). Moreover, if one is unable to control the vehicle or the driving style, some fear a reduction of autonomy (Mia: “If I now sit in front of the steering wheel and cannot intervene then I would probably not use it”) or a reduction of driving pleasure (Benjamin: “It is still a matter of one’s own whether one can accelerate, brake oneself, drive around curves – or if the car does it for one”). Ethical concerns ($n = 1$, Mia: “value conflicts”) about the system can also influence the likelihood of usage.

Pre-/Post Study Acceptance

Figure 3.6 illustrates the acceptance factors assessed using the AVAM questionnaire prior to and following the study. Overall, participants rank performance expectations, attitudes toward automation, self-efficacy, and facilitating conditions as rather high. Social influence and perceived safety are rated as neutral, whereas anxiety is rated as rather low. As a result, the proportion of behavioral intent to use AVs in our sample is relatively high. Using dependent paired Wilcoxon signed rank exact tests, we found no statistically significant distinctions between the results prior to and following the study.

3.2.3 Trust in Automation

When prompted about who they would trust more as a driver, a human, or an automated system, opinions diverge. Some people favor a human chauffeur ($n = 7$, Elias: “An ultra-complex system always has a weakness”), whereas others favor automation ($n = 4$, Charlotte: ”Because I hope that human mistakes do not happen, e.g., when being tired”). One person was ambivalent (Isabella: “Depends on the driver, I also feel uncomfortable in some lifts [...], and if they are super programmed, I would probably rather trust the machine than any person”).

One’s trust in automation is expected to grow with ongoing interaction (cf. [KM15]; Sophia: “Human. But only because I am accustomed to it”). After each trip, participants evaluated their degree of trust to document their feelings. The assessed mean trust rating is rather high ($M = 5.41$, $SD = .87$) and grows marginally after the sixth trip (see Figure 3.7). In addition, we discovered significant correlations between the trust rating of the trips and both social influence ($r(8) = .75, p.05$) and the acceptance ($r(8) = .71, p.05$) from the post-questionnaire.

In the surveys, we also checked whether the participants evaluated the safety driver, the automation without human assistance, or both. As an outcome, we can further divide the eight participants who believed the cover story into two subgroups: those who rated the automation without human assistance ($n = 4$, abbreviated: A) and those who rated the automation plus the presence of the safety driver ($n = 4$, abbreviated: S). The S-subgroup ($M = 5.97$, $SD = .57$) shows higher trust scores than the A-subgroup ($M = 4.85$, $SD = .79$); nevertheless, checked with a Wilcoxon rank sum exact test, these disparities are not significant ($W = 14, p = .11$).

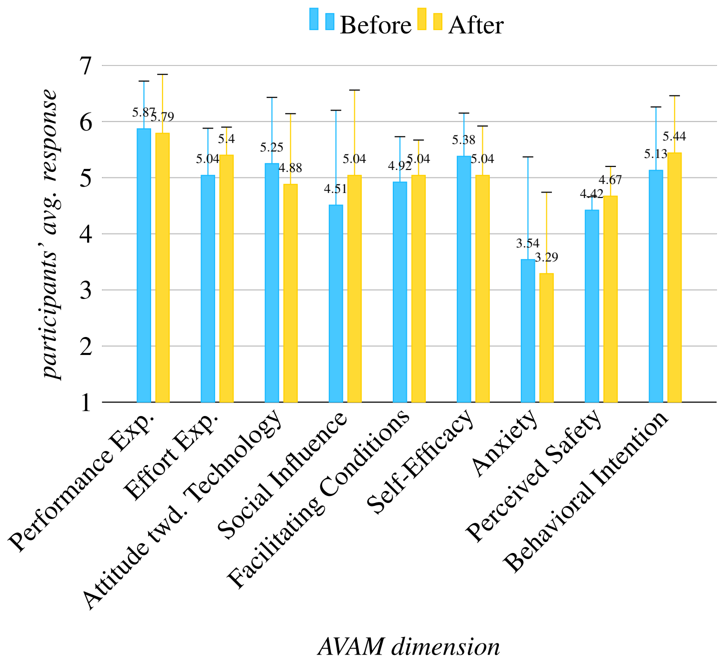


Figure 3.6: Acceptance factors (AVAM [Hew+19]) before and after the study ($n = 8$), error bars indicating standard deviation. Pre- and post-scores are comparable.

3.2.4 Non-Driving-Related Activities

To determine the activity habits of occupants in an autonomous ride, we examined footage of the participant's actions in the cabin space and also asked *what* (activities) they expected to perform *when* (use cases).

Non-Driving-Related Activities

As a supplement to our observations, we asked the participants prior to and following the study to name *five activities* they would probably engage in

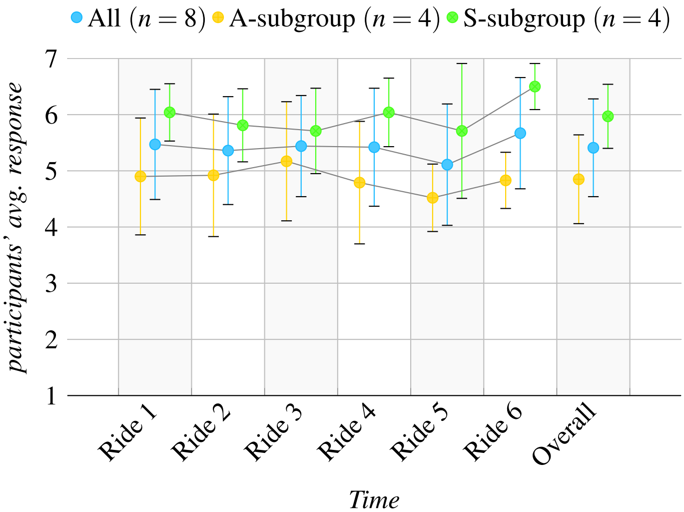


Figure 3.7: User's level of trust (Trust Scale [JBD00]) over the course of the trials – Participants who believed in the pretended system capabilities split by whether they rated the "automation without human assistance" (A, yellow) or the "system with safety driver" (S, green), error bars indicating standard deviation.

while using an AV. The ranking is as follows:

1. Using the smartphone (before: $n = 9$; after: $n = 9$)
2. Eating & drinking (before: $n = 7$; after: $n = 6$)
3. Reading (before: $n = 7$ after: $n = 5$)
4. Watching out of the window (before/after: $n = 4$)
5. Preparing for the job (before/after: $n = 3$)

Likewise, we asked for up to *five items they would place in an AV* before and after the investigation. The top five items are:

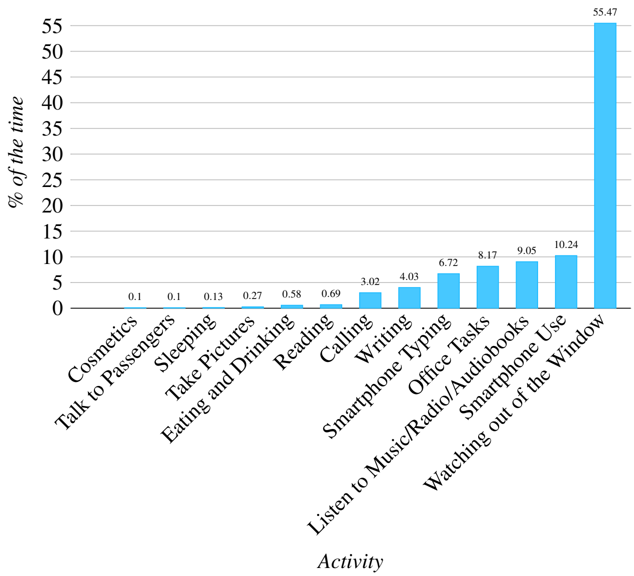


Figure 3.8: Observed activities' proportion of total time during the six journeys for all participants ($n = 8$). The three most prevalent activities were watching out of the window, smartphone use, and office tasks.

1. Laptop / PC / tablet / gaming console (before: $n = 6$; after: $n = 6$)
2. Pillow or blanket (before: $n = 6$; after: $n = 3$)
3. Foldable table (before/after: $n = 4$)
4. TV / computer screen (before: $n = 4$; after: $n = 2$)
5. USB / power charging station (before: $n = 1$; after: $n = 5$)

The preferred, predominant technological inventory fits the observed activities.

We accumulated more than 23 hours (1424 minutes) of video footage from the passenger cabin. In means of simplifying comparison, we make use of the categories from Pfleging, Rang, and Broy [PRB16] to classify our observed passenger activities. We added new categories for non-fitting activities we observed. To facilitate the analysis, we did not create a new category for simultaneous activities, such as listening to music while communicating, but instead counted each activity individually. In addition, we ignored distractions from the primary activity that lasted less than three seconds (e.g., a brief look out the window before returning to the smartphone). Figure 3.8 illustrates the breakdown of activity category shares for the passengers who believed the cover story ($n = 8$). The top five are (1) *Watching out of the Window* (55.47 %), (2) *Smartphone Use* (10.24 %), (3) *Listen to Music / Radio / Audiobooks* (9.05 %), (4) *Office Tasks* (8.17 %), and (5) *Smartphone Typing* (6.72 %).

Use Cases for Automated Rides

Generally, participants see advantages in utilizing AVs for more extended trips ($n = 5$) like cross-country journeys ($n = 1$), on the motorway ($n = 1$), or more specifically for holiday trips ($n = 2$) like going to the ocean with friends ($n = 1$). In addition, they would use it in situations requiring intense concentration, such as traffic jams ($n = 2$), and for routine trips such as the daily commute to the workplace ($n = 6$, Benjamin after the experiment: “I would take advantage of it, just driving to work in the morning was much more pleasant than driving myself. I arrive at work much more relaxed”), for shopping ($n = 2$), or to transport goods ($n = 1$). Using it in regulated and limited environments ($n = 1$, Benjamin: ”such as on a factory site”) is a potential use case that is already implemented. Innovative use cases found include: a) the transport of children via AVs ($n = 2$, Mia: “I’d find it handy if you had kids if they could drive in there alone”) and b) the vehicle use under short-term limitations such as illness or intoxication ($n = 3$, Jacob: “When you want to return home from a party, but are somewhere you can’t easily get home”) or under long-term limitations ($n = 1$, Sophia: “Physically or mentally limited people, that they can use the car and do not endanger traffic”).

Some people describe shorter trips ($n = 4$) and city scenarios ($n = 1$) as *anti-use cases* (Isabella: “For such short things as "I just drive to the bakery" it would be too exhausting for me always to enter the destination because I am faster when I drive myself”).

Influence of the Safety Driver

Following the investigation, we asked the participants if and how being aware of the safety driver affected their behavior. The main impact is that some people ($n = 4$) calmed down (Emma: “It felt more like a taxi ride; if you sit in the front and the steering wheel and pedals moved, it would be a completely different experience”). According to one user, the experimental setting was not always considered private and was therefore unsuitable for private communication (Jacob: “I would have communicated more with my buddies if I had known that no one was listening to me”).

3.3 Discussion

Our findings describe how users view AVs and the way they may utilize their free time in the car. Next, we discuss these findings, how they relate to previous research, and point out new research possibilities.

3.3.1 Non-Driving-Related Activities - Online Survey vs Real-World Study

In our real-world study, we find contrasts between the activities mentioned in a popular survey by Pfleging, Rang, and Broy [PRB16]. A direct comparison reveals similarities and contrasts. Figure 3.9 depicts a direct comparison between the activity assumptions derived from their survey and the activity frequencies observed in this study.

We discovered the following parallels: The third-ranked activity in their survey was *Watching Out the Window*, with 82% of respondents anticipating doing it (very) frequently. In our study, *Watching out the Window* occurred the majority of the time (55.5%) and on 95% of all journeys with marginal change over time. (The fear of) motion sickness may be one of the reasons why the participants in our study spent so much time looking out the window. We did not investigate the effect of motion nausea, so this is subject to future investigation. The survey by Pfleging, Rang, and Broy and our observation showed that smartphone usage is widespread. The respondents rated *Internet* (61%) and *Social Media* (48%) highly in their survey. We merged these categories because we could not see the participants' mobile devices. After that, we matched the survey category to our *Smartphone Use* category, which occupied 10.2% of the time and was performed on 67% of all journeys, making it the second-most popular activity. Nonetheless, given that this is one of the anticipated primary activities, a deeper examination of mobile device usage is required (cf. [Jac20]) and may be pursued in forthcoming studies.

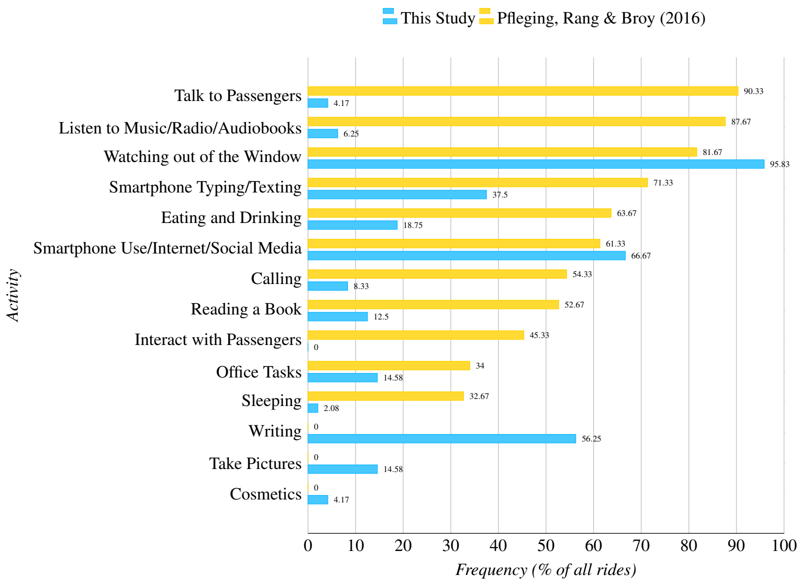


Figure 3.9: Contrast of the anticipated frequency of activities (very frequently + frequently) from the online poll by Pfleging, Rang, and Broy [PRB16] to the tracked frequency of activities in the present investigation (observed in n rides / all rides).

We found a couple of deviations from Pfleging, Rang, and Broy: The most anticipated activity, according to their survey, was *Music, Radio*, etc. (88%). In our investigation, the category *Listen to Music/Radio/Audiobooks* stood third in an overall timeshare but only occurred in 6.25% of all journeys. Similar distinctions exist for *Texting*, *Eating & Drinking*, *Calling*, *Reading a Book*, *Sleeping*, among others. Two potential explanations exist for the variances. The first is our study's substantially smaller number of participants. The second one is that the typical travel time in our investigation was approximately 20 minutes. As mentioned earlier, we anticipate that this is a typical trip from home to work or to a friend in a nearby town. Future work should incorporate these time factors for the purpose of a trip. We argue that during shorter to mid-range distance travels, certain behaviors, such as viewing a full movie or reading a lengthy text, are unlikely to be done, and that when people imagine autonomous driving, they primarily envision longer journeys. Current reports of anticipated non-driving-related activities are most likely associated with long-distance journeys. In the future, studies should consider the impact of travel time, e.g., by constructing different time-constrained scenarios.

3.3.2 Influence of Experience on Acceptance and Shaping of New Models

Before, as a hypothetical experience through the depiction of the vehicle, and after the study, when participants had the actual driving experience, we asked about various acceptance factors. Yet, we did not observe any changes through real-world experience. At least to some extent, the experience might not have a key part in the intention to use autonomous vehicles. Still, the attitudes may overlay the experience if the dissonance between both is small enough, e.g., when the car drove safely (often named in the interview as a key acceptance factor). As an example of this *attitude-experience dissonance boundary*, despite being aware of the system's mistakes, Tesla drivers continued to use their system as usual, according to a study of Dikmen and Burns [DB17]. Additionally, having the presence of a safety driver may have an effect on these assessments, particularly with regard to perceived safety and anxiety.

Known car acceptance models, such as the AVAM [Hew+19], facilitate capturing the general public's acceptance of autonomous vehicles. To contribute to the adoption AVs, we argue there needs to be a greater focus on extra advantages and needs of users that autonomous vehicles may offer. For instance, the safe use of a vehicle while either mentally or physically incapacitated, was identified as an essential use case because it was deemed to be of high significance by some interview participants. On the way home from work, one passenger consumed an alcoholic beverage in the vehicle. These findings align with those of Payre, Cestac, and Delhomme [PCD14], who identified an interest in impaired driving as a fundamental acceptability factor. We dig deeper into this specific question of user needs for people who are not able to drive in a later chapter (see Chapter 5).

These novel needs should be added to acceptability models, which still primarily attempt to map the use case of "driving and limited side-tasks" to autonomous driving requirements. Nevertheless, because autonomous driving is anticipated to facilitate entirely new use cases, such as a mobile office or sleeping, these opportunities must be considered, as these use cases generate completely novel needs that were not reasonable in manual driving scenarios. Looking at the observed NDRAs and personal responses provided in the questionnaires and interviews, we notice a challenge in accounting for the various autonomous driving scenarios and the users' intentions (e.g., entertainment vs work).

3.3.3 Building Trust

The findings show that confidence in the *system with the safety driver* is greater than confidence in the system without human backup. Further, trust is correlated to acceptance. Therefore, we can back up prior survey-based investigations in a real-world context, e.g., by Rödel et al. [Röd+14], who discovered in a web-based survey that user experience and trust as well as acceptance decrease as automation levels increase.

In addition, our study indicates that confidence in the vehicle's capabilities influences the anticipated activities. *Sleeping* is mentioned as necessitating a certain amount of trust in the vehicle's capabilities, likewise in the reliability of fellow passengers, i.e., their ability to control the situation. We assume that individuals just go into sleeping in a perceived safe and controllable setting; thus, sleep may be a useful indication for measuring trust in automation. On the opposite, this further suggests that when the amount of trust grows, non-driving-related activities can vary over time. In Emma's post-ride comments, we noticed an analogous perception. During the first rides, she noticed the defensive driving style as pleasant. However, this perception evolves with further rides and shifts in the opposite direction:

> "The vehicle starts smoothly, no bumping or anything, you are not pressed into the seat. Comfortable!" [Emma, Ride 3]

> "The car only starts when the traffic light is really green, not when it is already yellow. People start driving when the light turns yellow. The traffic lights could be used even more efficiently." [Emma, Ride 4]

> "It stresses me out a bit that the car starts so slowly and then continues to accelerate slowly. The other road users are a bit impatient." [Emma, Ride 5]

This example clearly indicates a *need for intervention* in the driving activity, a situational need for control, in this case, requiring the adaptation of the driving style. Further, this could mean that the dropping trust curve in higher automation levels might only be a *snapshot* of today's perception and that, after long-term exposure, AVs' trustworthiness could change positively which would be interesting to see in future work.

Moreover, this might indicate that the pattern of declining trust in higher levels of automation is merely a *snapshot* of current perceptions and that, over time, AV's trustworthiness might increase, which makes it a compelling topic for subsequent studies.

3.3.4 Limitations

When examining uses and perceptions of autonomous vehicles, field studies particularly encounter hurdles concerning the authenticity (ecological validity) on the *car side*, e.g., technical fidelity, or the *environment side*, e.g., test track. In our study, we prioritized environmental authenticity and, as a result, have selected the WoZ methodology. The automation wizard is an inherent limitation of our approach. If uncovered, the perception and behavior of the respective participants may be impacted, and their data may need to be excluded from the study, as we did. Additionally, user actions in an actual AV may differ due to varying driving styles.

Given the small size and youth of our study's sample, we interpret the observed behaviors as an early estimate of future behavior. Follow-up research on a larger scale needs to confirm how users trust and (intent to) use AVs. Nonetheless, our findings offer significant insights that will inform such projects. Using an WoZ vehicle to investigate qualitative aspects of autonomous vehicles is a helpful and effective method from a methodological standpoint.

3.4 Conclusion

In this chapter, we presented a repeated field investigation with six short to medium-duration trips resulting in approximately 1400 cumulative driving minutes. With the help of our field study, we give deep insight into the way people use autonomous mobility services. Thereby, we supplement previous research on user needs in the context of autonomous, road-bound services, which has primarily concentrated on studying people in other contexts (e.g., public transportation) or asking people to envision a self-driving scenario. In particular, we discovered:

- regarding trust, participants showed a higher level of *trust* when a safety driver is present, trust is correlated with acceptance, and some activities like sleeping need a higher level of initial trust than others

- regarding *acceptance* did not change through vehicle exposure and safety was highlighted as the primary acceptance factor in the interviews
- regarding NDRAs, the most popular *activities* are watching out of the window, smartphone use, and office task

Notably, all findings regarding trust, acceptance, and NDRAs were strongly influenced by participants' needs for safety and/or autonomy. Overall, we demonstrate that user needs and goals evolve as a result of repeated interaction (e.g., the defensive acceleration style was too slow for one participant after a while). With our study, we contribute to a better understanding of automated vehicle use and corresponding design implications, e.g., for in-car interiors and interfaces.

Chapter 4

Divergent Patterns of Needs & Goals

This chapter is based on the following publications:

Henrik Detjen, Irawan Nurhas, and Stefan Geisler. "Attitudes Towards Autonomous Public Transportation". In: *AutomotiveUI '21 Adjunct: 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. New York, NY, USA: ACM, 2021, pp. 62–66. ISBN: 9781450386418. DOI: 10.1145/3473682.3480265

In this chapter, we present an online study to gather opinions regarding an autonomous mobility service, i.e., driverless public transport. The study aims to understand participants' attitudes towards this driverless type of service and detect any underlying patterns of opinions that may influence their needs and goals (cf. *RQ_II-2* – How to assess diverging patterns of needs and goals?).

Because they are used to the presence of a human bus or cab driver, many people are skeptical about such driverless transport today (e.g., [VDI19]). Research on autonomous mobility acceptance has found many possible reasons for the tendency to adopt autonomous mobility services, e.g., perceived safety and trust (see also previous chapter, Chapter 3). Yet established technology acceptance models do not work well in the automotive domain (cf. Section 2.4.6). Hence, it is essential to understand the structure of individual factors for autonomous mobility services' acceptance.

The more factors that influence acceptance of driverless transportation services, the more complex the structure of how these factors lead to acceptance behavior becomes. Technology adoption models in the domain of automated driving (cf. Section 2.4.6), e.g., by Nordhoff et al. [Nor+19], already include and broad scope of possible domain-specific acceptance factors. However, the high number of relevant factors (> 30) leads to high complexity of autonomous vehicle or transportation acceptance models (30!). In addition, the factor *attitude* among them is one of the most significant [PCD14], mediator of many other factors [Dwi+19], and direct predictor of acceptance [Dwi+19]. Therefore, understanding the *relationship* between factors better is necessary to enhance structural modeling (if possible). We extend previous work by using the Q-Methodology [WS05; OWR13; MT13] for assessing users' subjective priority of different factors that lead to personal acceptance or rejection. Thus, we provide a perspective that assists in prioritizing the design requirements of autonomous mobility users and aids in communicating with the users' specific attitudes in mind.

In this chapter, we adapt the Q-methodology in an online study with 44 participants where they prioritize statements that represent typical factors of autonomous mobility acceptance, e.g., the perceived safety of the vehicle. We group the participants among their priorities into four prototypical attitude clusters, namely *technical enthusiasts*, *social skeptics*, *service-oriented non-enthusiasts*, and *technology-oriented non-enthusiasts*. We discuss how researchers can make use of these prototypical attitudes.

4.1 User Study

The social science-based Q-Method helps discover technology affordances and system requirements [OWR13; NGP19]. Figure 4.1 shows the Q-Method protocol.

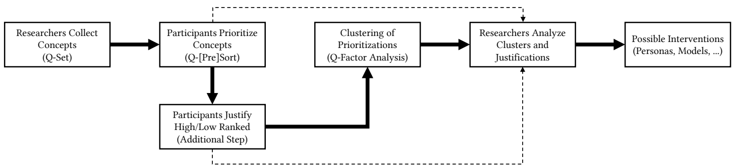


Figure 4.1: Study procedure – In addition to the usual Q-Method procedure, we let participants explain the reason for the highest and the lowest ranking of statements.

4.1.1 Q-Methodology

Q-methodology pattern analysis has three phases. First, researchers create a *Q-Set* of statements to offer to participants. Q-Set statements encompass a subject of interest from literature, interviews, or other sources [NGP19; WS05; WS12]. Second, participants contrast statements (*Q-Sort*). They score each assertion from low to neutral to high relevance or agreement. Research problems determine distribution shape. We used a normal distribution of statements, so participants may only give a few assertions of high or low importance while most are around a neutral center. This distribution produces a pyramid-shaped table of ranked statements (cf. Figure 4.3). Third, applied statistical factor analysis compares statement distributions from all participants. Before analyzing and discussing the data, we explain the three main phases.

4.1.2 Construction of the Q-Set

#	Concept	Statement
s1	Performance Expectancy	*I think driverless public transportation would be useful.*
s2	Effort Expectancy	*I think driverless public transportation would be complicated to use.*
s3	Social Influence	*I will likely use driverless public transportation options if they are recommended by people or institutions that I trust.*
s4	Hedonic Motivation	*I think that driverless public transportation would be fun to use.*
s5	Price Value	*I hope that driverless public transportation will be less expensive than modern public transportation.*
s6	Mobility Habits	*I think that public transportation works just fine already and should stay the way it is.*
s7	Attitude Toward Using	*I am eager to try driverless public transportation.*
s8	Attitude Toward Using	*I think that it is a good idea to introduce driverless public transportation.*
s9	Ethics	*I am afraid that driverless public transportation will be unethical.*
s10	Self-Efficacy	*I have the skills and knowledge necessary to use driverless public transportation systems.*
s11	Anxiety	*I would feel insecure using driverless public transportation (because of the potential for theft, sexual harassment, etc.).*
s12	Perceived Safety	*I am afraid that driverless public transportation would lead to more accidents.*
s13	Transparency	*The display of ride-related information (e.g., speed) would help me to feel safe in driverless public transport.*
s14	Empathy	*I believe that driverless public transportation has no tolerance for mistakes.*
s15	Social Control	*I worry that, without a human driver, public transportation units will become unclean.*
s16	Transparency	*I think that a driverless public transportation system should provide real-time information to passengers (e.g., route changes, connections, delays).*
s17	Autonomy	*I expect driverless public transportation to be more flexible.*
s18	System's Empathy / Trust	*I am afraid that, without a human driver, the vehicle could start moving before I sit down.*
s19	Social Control / Security	*I think that driverless public transportation will lead to more disturbing behavior among other passengers.*
s20	System's Empathy / Trust	*I think school-age children should be accompanied by adults when using driverless public transportation.*
s21	Privacy / Security	*I think that driverless public transportation units should have observation cameras.*
s22	Service Quality	*Without a driver, I think that I could still get the same information in an autonomous public transportation unit.*
s23	Connectedness	*The contact with a human driver is important to me.*
s24	Comfort	*Ordering driverless public transportation pick-ups through an app seems complicated.*

Table 4.1: The Q-Set – Statements used for investigating user attitudes were derived from technology acceptance models, user needs, and discussion.

We created a collection of statements for pattern analysis to differentiate user attitudes. Each statement is a concept, mostly acceptance factors. We considered mobility patterns, technological aberrations, and the absence of a driver in autonomous vehicles. Construction used three sources. First, we collected concepts from general technology acceptance models [Dav85; Ven+03; VTX12] and domain-dependent models [Hew+19; PCD14; Röd+14; Nor+19; Oss+12], e.g., "I think driverless public transportation would be useful." to reflect concept performance expectancy. Second, we examined the user's needs for competence, autonomy, and stimulation during autonomous driving. To test participants' autonomy, we created a statement that questions whether autonomous transportation increases or decreases flexibility. Third, we used the Positive Computing paradigm [CP14] to determine well-being (needs for competence, autonomy, positive emotions, meaning, engagement, and relatedness). All researchers discussed the previously collected concepts and added new ones, such as the possibility that older people may fear a decline in service quality due to automation because no driver will be available to help them find the right information during the journey. Table 4.1 shows the study's full Q-Set.

> "In the future, public transportation will not require human drivers. Buses, shuttles, cabs, and cable cars will operate autonomously. To take advantage of driverless public transportation and find the most suitable connections, passengers will need to type their desired destination into an app. Buses or cable cars will be implemented for highly frequented lines, while less-frequented lines will operate using smaller, on-demand vehicles. Every action that people need to perform today to get from one place to another—driving, buying tickets, providing information, will be done by or through a system."

Figure 4.2: Presented scenario that participants read prior to the Q-Sort.

4.1.3 Q-Sort Study

We performed the research online using a browser-based Q-sort software[2] (see Figure 4.3). Participants received a scenario narrative (see Figure 4.2). The study has three primary parts: 1) the statement presorting, whereby participants classified statements as neutral, positive, or negative; 2) the primary Q-Sort, a

[2] https://github.com/aproxima/htmlq

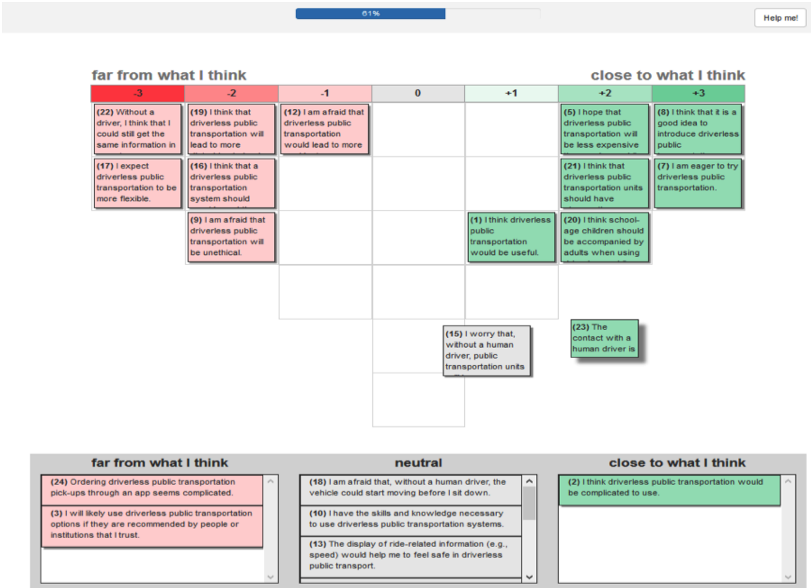


Figure 4.3: Web-based Q-Sort tool – Pyramid shape of statements resembles the normal distribution of positive and negative statements in user attitudes.

precise ranking of the statements along the Q-Pyramid (cf. Figure 4.3) from -3 to +3; and 3) the reflection phase, in which participants provided reasons for placing statements in the highest/lowest ranks (+3/-3). Finally, participants completed age and gender demographic questions. The process took around 15 minutes.

4.1.4 Q-Factor Analysis

Q-factor analysis identified clusters of participants' card placements (similarities and discrepancies in cart sorting). Thus, we eliminated covariance while maintaining a minimum of 60% explained variation across individuals [Hai+98]. Next, we utilized a centroid analysis to determine the starting number of clusters for statistical rotation, using a scree plot, Eigenvalue >= 1, and the lowest amount of explained variation [WS05]. The Z-score-based flagging mechanism allocated participants to a cluster [WS05]. The factor analysis shows four clusters with 64% cumulative explained variance. Only two people do not belong to a cluster, making the composite reliability of the four clusters >0.9. Table 4.2 exhibits factor analysis findings.

	Cluster			
	1	**2**	**3**	**4**
No. of participants	25	10	4	3
Avg. rel. coef.	0.80	0.80	0.80	0.80
Composite reliability	0.99	0.98	0.94	0.92
S.E. of Factor Z-scores	0.10	0.16	0.24	0.28
% Explained variance (EV)	35	13	9	7
Cumulative % EV	35	48	57	64
No. of confounded P-Set	2 (P-1, P-35)			
Cluster Correlations				
Cluster 1	1	-	-	-
Cluster 2	-0.06	1	-	-
Cluster 3	-0.01	0.52	1	-
Cluster 4	0.32	0.13	0.07	1

Table 4.2: Characteristics of the Factor Analysis.

4.1.5 Participants

We selected 44 participants (*m*=21,*f*=23) of different age groups (18-25: 9.09 %, 26-40: 47.72 %, 41-55: 34.09 %, >56: 9.09 %) from a technologically developed country (USA) via Amazon Mechanical Turk[3]. MTurk workers got

[3] https://www.mturk.com

compensated with 2$.

4.2 Results

Attitude #	Contrasting Statements	Rank
1	Technical Enthusiasts	
	I think driverless public transportation would be useful.	+3
	I think that it is a good idea to introduce driverless public transportation.	+2
	I think that public transportation works just fine already and should stay the way it is.	-2
	The contact with a human driver is important to me.	-2
2	Social Skeptics	
	I would feel insecure using driverless public transportation (because of the potentialfor theft, sexual harassment, etc.).	+2
	I believe that driverless public transportation has no tolerance for mistakes.	-2
	Ordering driverless public transportation pick-ups through an app seems complicated.	-3
3	Service-Oriented Non-Enthusiasts	
	I am afraid that, without a human driver, the vehicle could start moving before I sit down.	+2
	I expect driverless public transportation to be more flexible.	-2
	I will likely use driverless public transportation options if they are recommended by people or institutions that I trust.	-3
4	Technology-Oriented Non-Enthusiasts	
	The display of ride-related information (e.g., speed) would help me to feel safe in driverless public transport.	+2
	I expect driverless public transportation to be more flexible.	+2
	I think school-age children should be accompanied by adults when using driverless public transportation.	-2
	I worry that, without a human driver, public transportation units will become unclean.	-3
	I am afraid that, without a human driver, the vehicle could start moving before I sit down.	-3

Table 4.3: Attitudes and their distinguishing statements (strong opinions with Rank ≤ -2 or $\geq +2$ that are unique to that attitude). Ranks from -3 to $+3$.

Q-Sort factors include a cluster of individuals who sorted statements similarly. These aggregated perspectives are supra-individual opinions or attitudes. Distinguishing statements are the most essential relative rankings since they differentiate between attitude clusters (cf. Table 4.3).

We found four statistically significant clusters of Q-Sort ranks. These ranked *attitude prototypes* have distinct motivations to (not) use autonomous mobility services: The attitudes have distinct personal motivations: Attitude 1 participants are called *Technical Enthusiasts* because they are enthusiastic about new technologies, while Attitude 2 participants are called *Social Skeptics* because they concentrate on social consequences. In Attitude 3, *Service-Oriented Non-Enthusiasts* concentrate on public transit service, whereas in Attitude 4 *Technology-Oriented Non-Enthusiasts* focus on technological advantages.

4.2.1 Attitude 1: The Technical Enthusiast

"A system rather than a person will be more useful."

Participants with this attitude (accounting for 35 % of the explained variance) are technical enthusiasts who believe they have the skill to use the technology (+2), e.g., ordering a pick-up seems not complicated for them (−2). They believe that current public transportation should not stay the way it is (−2). Hence, they think driverless public transport would be useful (+3) and that it is a good idea to introduce it (+2): *"I think this is just a very useful thing that would be able to help everyone in all situations"*. Consequently, they are eager to try driverless public transport (+1), especially if it is recommended by people or institutions they trust (+1). A reason might be that they hope that driverless public transport will be cheaper than modern public transportation (+1). Generally, they would feel safe and secure in autonomous public transport because they would not feel insecure because of potential theft, etc. (−1) and do not fear an increase in accidents (−1). Also, they do not think that contact with a human driver is important (−2).

Overall, they value the technical progress and utility of autonomous public transport over the current public transportation state with a positive and enthusiastic attitude. They do not hesitate to use autonomous public transport due to ethical (−3) or social concerns like losing personal contact with the driver. It could be much more reliable, eliminating some human errors, reducing accidents, and being more efficient: *"Between lower accidents, more efficiency, and a system rather than a person showing information will all be more useful than the current way of things."*, *"I think having driverless options would eliminate some issues and possibly create more readily available public transportation"*.

4.2.2 Attitude 2: The Social Skeptic

"You cannot trust technology."

Participants with this attitude (accounting for 13 % of the explained variance) are social skeptics. They are not interested in the technical aspects of the transformation and do not think that ride-related information would help them feel safe (−1). However, this technological skepticism is neither related to their skills because they do not believe that ordering driverless public transportation through an app would be complicated (−3) nor to the technology's tolerance for mistakes (−2). The skepticism is instead a result of their beliefs about the social and technical consequences related to the safety and security of driverless public transportation: They think that current public transportation is okay and should stay the way it is (+2) and do not think that driverless public transportation would be a good idea (−3) or fun to use (−2) because they fear that the introduction of driverless technology will lead to more accidents (+3) and disturbing behavior among passengers (+2). Moreover, they value contact with the human driver (+1). Consequently, they would feel insecure in driverless public transportation units (+2) and think that children of school age should be accompanied by adults when using driverless public transport (+3): *"Children need to be watched because of untrustworthy people"*.

Overall, they see they focus on safety/security barriers and are skeptical about introducing driverless public transport. They do not trust the technology and instead depend on human authority like the driver: *"You cannot trust technology, and sometimes children get things wrong, and driverless transportation cannot help a child [...]"*.

4.2.3 Attitude 3: The Service-Oriented Non-Enthusiast

"I do not see the benefit from a service perspective of using a driverless system."

Participants with this attitude (accounting for 9 % of the explained variance) are service-oriented non-enthusiasts. In contrast, participants within this attitude cluster do not see benefits in driverless public transport and think that driverless public transportation leads to no-fault tolerance (+3), e.g., they believe that a driverless system could start moving before they sit down (+2). They do not think that the technology will be more flexible (−2) or fun to use (−2), and therefore they are not eager to try it (−3) - even if recommended by people or institutions they trust (−3): *"I do not see the benefit from a service perspective of using a driverless system"*. They are socially somewhat independent and think that they can get the same information as in current public transportation without a driver (+1). However, they also require autonomous public transportation to have observation cameras (+3): *"I mean everything has cameras nowadays why shouldn't driverless transportation"*.

Overall, they hesitate to try driverless public transport because of the, in their view, small benefits, leading to a non-enthusiastic but pragmatic attitude. They evaluate the consequences of new technology carefully: *"Since the driver is purposefully being replaced by an AI system, the transit operator becomes immediately liable for any accidents/injuries that result. There should be no additional incidents as a result of implementing an autonomous system"*.

4.2.4 Attitude 4: The Technology-Oriented Non-Enthusiast

"I believe that they might not be equipped to do what they are supposed to do."

Participants with this attitude (accounting for 7 % of the explained variance) are technology-oriented non-enthusiasts. They believe that driverless public transport would be less useful (−1) yet expect more flexibility (+2). Like Attitude 3, they also suggest that driverless public transport vehicles will have no fault tolerance (+3) and that driverless public transport vehicles should have observation cameras (+3). An observation camera is important to have evidence or analysis in case of an incident or when something happens: *"There are all kinds of rowdy behavior on public transportation, and I would want it recorded"*. Through the use of cameras, they would show trust in the technology because they do not fear that without human authority, public transportation would become unclean (−3), that there would be more disturbing behavior of others (−2), that the vehicle could start moving before they sit down (-3), or that school children should be accompanied (−2). They require the display of trip-related information to make people on driverless public transport feel safe (+2): *"That way everyone will know what is going on if the bus will be late or not"*.

Overall, even if they like to have personal contact with a driver is essential for them (+1), they would accept externalizing the human authority and functionality by implementing technical solutions: *"I believe that they might not be equipped to do what they are supposed to do and end up wrecking more problems than before"*.

4.3 Discussion

The Q-factor analysis might serve as input for two kinds of follow-up considerations. First, "Likert attitude scales could be structured around the factors revealed by a Q-sort study" [KVJ08] – we discuss this point in the context of modeling autonomous mobility acceptance (cf. Section 4.3.1). Second, the found patterns might serve as input for content-specific design and communication "since products, brands, and organizations are usually not expected to have one overall image, but multiple images in different stakeholder groups. A distinction of audience segments based on their own perspectives [...] may be an important step toward targeted interventions" [KVJ08] – we discuss this point in the context of addressing personas in design and communication (cf. Section 4.3.2).

4.3.1 Modeling Autonomous Mobility Acceptance: Aggregation vs. Segmentation

Researchers can understand user needs and goals via user attitude clusters. Some user needs and goals conflict. For instance, the statement "I am afraid that, without a human driver, the vehicle could start moving before I sit down." is significant (+2) for Service-Oriented Non-Enthusiasts (Attitude 3), yet irrelevant (-3) for Technology-Oriented Non-Enthusiasts (Attitude 4), and indifferent in all other attitudes (*1*: -1, *2*: 0). A technological acceptance model's typical goal is to unify these in our scenario above partly opposing opinions. Given the neutral ranking in the bigger clusters (1 and 2), a highly critical factor (rejectance reason for Attitude 3) might be excluded in such a model since it explains no considerable amount of overall variance. Conflicting attitudes limit generalization. In other words, the more contrasting opinions about driverless transport people have, the less precise a general model gets. As shown, a Q-method perspective can help explain some of these underlying issues. Further, one can use the structure of important and unimportant factors to build a Likert-Scale questionnaire around them and allow for a quick clustering into the different attitudes and corresponding personas/measures (cf. next subsection) or if there is a more homogeneous view to get a quick idea of the most relevant factors for a one-fits-all model.

4.3.2 Handling Divergent Autonomous Mobility Acceptance Patterns: Attitude-Specific Communication

Practitioners can order design requirements by user relevance using the attitude clusters. They may also create user personas [NPG19] for enhancing group-specific understanding and measures of autonomous public transit. For instance, marketing should emphasize performance-oriented advantages of autonomous public transport for *Technical Enthusiasts* (Attitude 1), such as improved timekeeping and efficient journey time use. Instead, for *Social Skeptics* (Attitude 2), communication should address the technology's limitations and provide evidence that driverless mobility services act safety and will not be compromised by the lack of human authority, e.g., through an offer to try the technology. In sum, using the Q-Method to identify attitude clusters assists in quickly recognizing divergent user attitudes and creating measures that aid in targeting their needs and goals.

4.3.3 Limitations

Our research only included people from a nation with advanced public transport. Thus, less developed nations should provide different outcomes. The same goes for participant age. They were 18–60 years old. Thus, findings for kids or 60+ users may vary.

4.4 Conclusion

This chapter introduced a modified Q-Method for autonomous mobility acceptance research. We examined factors that we would expect to change with autonomous public transport compared to today's transportation and asked users *what they would miss* and *what they would benefit from*. We found differences and clusters of characteristics that affect adoption processes inside a particular subgroup. We discovered four prototypical user types: technical enthusiasts, social skeptics, service-oriented non-enthusiasts, and technical-oriented non-enthusiasts. Our insights into the fragmentation of acceptability factors of autonomous mobility services help system designers to better empathize with users and address their needs and goals. Future work might develop user personas on these partially contrasting attitudes to drive the targeted design and communication and, thus, the acceptance of autonomous mobility services.

Chapter 5

Accessibility Needs & Goals

This chapter is based on the following publications:

Henrik Detjen et al. “An Emergent Design Framework for Accessible and Inclusive Future Mobility”. In: *Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Ed. by Yong Gu Ji and Myounghoon Jeon. Seoul, Republic of Korea, 2022. DOI: 10.1145/3543174.3546087

This chapter looks deeper into needs and goals beyond the average user, e.g., those with disabilities. We collect requirements from experts in the inclusion field use cases from the literature and integrate these insights into a comprehensive design framework for inclusive autonomous mobility services (cf. *RQII_3* – How to include users with special needs and goals?).

Autonomous mobility could grow its user base since non-drivers could utilize such services. This might help persons with cognitive or physical disabilities overcome mobility restrictions and better engage in social life, jobs, and education. Caregivers may also interact with their clients instead of driving.

These opportunities should be considered early in the design stages since upgrading existing systems is complicated. To make future transportation inclusive, designers should consider all possible user needs. Inclusion is not optional. The UN Convention on the Rights of Persons with Disabilities (CRPD) recognizes personal mobility as a fundamental human right [Uni06] and CRPD explicitly mentions the responsibility of producers/designers of mobility services:

> "Encouraging entities that produce mobility aids, devices and assistive technologies to take into account all aspects of mobility for persons with disabilities." [Uni06]

This raises the question of what designers and researchers can do to foster inclusive mobility.

The field of inclusive mobility research in HCI is just emerging and spans a broad range of users, services, and settings; as of 2021 until now (2023), *ACM AutomotiveUI* organizers designated *accessibility & variety of users* as a key topic for the conference. Recent studies examined the design needs of mobility services like shared rides from the perspectives of elderly people [Glu+20], women [SWR21], and those with impaired vision [BE20; CR20a]. A design framework or space for the inclusive design of future mobility services is currently lacking, despite its value in other contexts such as mobile computing [BGL18; Sch+16], AR-googles [Hir+19], external HMIs [CR20b], and automotive AR-displays [HPA16; Wie+19b]. To address this, we introduce a *design framework* that helps designers to take the perspective and think of the needs of non-average users.

With this framework, we help communicate about, understand, and construct autonomous mobility services for people with special needs and their caregivers. We provide (1) a list of possible use cases for inclusive future mobility, (2) a first design framework, and (3) a demonstration of the design framework. Since it targets a relatively new area of research that is still emerging, the design framework needs to be extended as the field advances.

5.1 Universal Design Approach

UD principles may help designers make mobility services accessible and inclusive. The UD framework aims for the "design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design. Characteristics of any UD product or environment are that it is accessible, usable, and inclusive." [Bur21]. Ability-based [Wob+11] and user-sensitive design [NG00] share a similar philosophy. However, addressing every user need is not goal-directed (cf. [Duv21]), but one can find synergies when thinking about different abilities. An aural interface for users with low vision could benefit non-impaired users, too.

A known application example of the UD framework is the WCAGs [Wor21]. WCAGs require websites to be visible, operable, intelligible, and resilient – many of them apply to mobility. The mobility-specific UD should be considered since the WCAG rules do not address non-digital elements like trip settings or social scenarios during a ride. For this, Burgstahler [Bur20] describes a five-stage UD method that may be applied to any domain – Figure 5.1 displays our future mobility service design modification. This chapter covers the first and second UD steps (see Figure 5.1): We gather experiences, applications, and use cases for inclusive future mobility, then apply design space analysis to construct a design frame for systematic assessment of non-average users' design needs.

To construct our design framework, we (1) reviewed the literature and (2) interviewed caregivers and disability representatives regarding existing and future mobility patterns and needs to *identify applications and best practices* (UD step 1; cf. Section 5.1.1). Design space analysis concurrently (3) identified and improved understanding of design characteristics for inclusive mobility (UD step 2; cf. Section 5.1.2). We explain each step below.

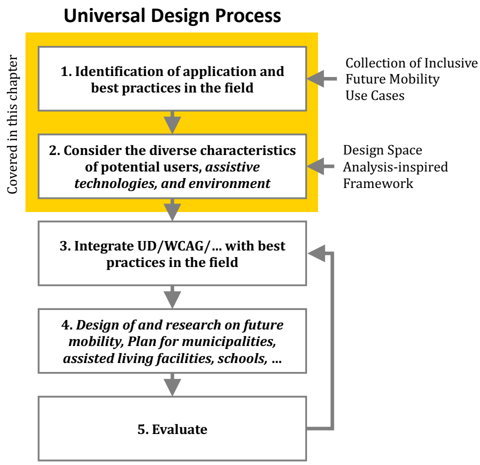


Figure 5.1: Universal Design process by Burgstahler – adapted (italic text) for future mobility services. Contributions of this chapter (yellow) are towards the identification of best practices and applications and the systematic consideration of user characteristics, as well as the users' vehicles, tools, and their (social) environment.

5.1.1 Applications and Best Practices

Review of Future Inclusive Mobility

We reviewed the literature on future mobility services that enable personal mobility. Regarding the review, we utilized the term *autonomous driving* and modifications with a variety of related inclusive mobility themes:

```
{
    { autonomous OR automated }
    AND
    {
      driving OR transport* OR ride* OR bus*
      OR mobility OR vehicle* OR car*
```

```
    }
}
AND
{
  inclusive OR assist* OR access* OR impair*
  OR disab* OR child*
}
```

* indicates word modifications, e.g., the term *vehicle** also includes the term *vehicles*. We searched Google Scholar and ScienceDirect. 153 papers were found. The papers required to demonstrate a use case for assistive technology, for example via prototypes, scenarios, or interviews. Considering machines be driving, we eliminated driving task assistance technology. We also checked each paper's references and Google Scholar profiles of the authors for missing works. We identified 33 inclusive future mobility use cases from 23 publications (cf. Table 5.2).

Expert Interviews

We further interviewed assisted living caregivers and community disability advocates (f=6, m=2, M=41.6yrs, SD=15.11yrs; reported as P1-P8, see Table 5.1). In this way, we want to study their mobility challenges and potential benefits through automation as well as the mobility needs and goals of their clients to learn about the possible effects and determine further use cases for inclusive autonomous mobility services (for the complete interview guide, see Section VII). These understandings provided practical portraits of literature use cases and contributed to collecting 49 additional use cases.

ID	Gender	Age *years*	Duration *min*	Facility	Background & Occupation	Experience *years*
P1	f	28	23.6	Sheltered workshop in a city	HCI background, working in research management (assisted workplace)	7
P2	f	47	18.2	Larger city	Social pedagogue, working as municipal disability and inclusion officer and	1
P3	f	62	18.0	Assisted living and work in a village	Occupational therapist, working as caregiver in a residential group	15
P4	m	35	17.5	Assisted living and work in a village	Social pedagogue, managing the social service in a residential area	10
P5	f	66	16.1	Larger city	Retired teacher, working in the municipal advisory board for inclusion	35
P6	f	35	15.6	Sheltered workshop in a city	Social pedagogue, working in the pedagogical management of caregivers	15
P7	m	33	21.6	School in a larger city	Special pedagogue, working as class teacher inclusive primary school	15
P8	f	27	30.4	School in a larger city	Special pedagogue, working as trainee teacher	4

Table 5.1: Expert Interviews – List of participants with identified gender, age, interview duration, and job/facility descriptions with respective experience.

5.1.2 Diverse Users, Technologies, and Environments

Review of Design Spaces

We began with a study of linked design spaces ($N = 6$; [Col+17; CR20b; KS09; HPA16; Wie+19b; Kim+21]) to identify useful classification aspects, with an emphasis on those that relate to automotive and accessible HCI. Further, we examined taxonomies ($N = 2$, cf. Section 5.2.1) regarding mobility services' users with special needs and goals [Hol+21; BB19].

Construction of the Design Framework

HCI design spaces are often built around a vast number of artifacts and use cases. Inclusive design solutions are scarce since highly connected and autonomous mobility is not broadly available. Moreover, vehicle designers and researchers lack expertise in developing these systems. Nonetheless, an inclusive design must be considered early on. Thus, we constructed a framework to enable researchers and designers to explore the design options of autonomous mobility services for non-average consumers.

Using the results of all prior efforts (literature analyses and interviews), we traversed every extracted user case and developed a structure to guide design for inclusive and accessible autonomous mobility. In this process, we added use cases, discussed linked design spaces, and added missing characteristics if necessary. In the following, we present the initial framework.

5.2 Design Framework

We ask mobility designers five leading questions to frame their work. These five questions assist consider users with accessibility needs and goals and begin a dialogue about inclusion. Next, we go over the questions (also referred to as *dimensions of the framework*) and potential response options (also referred to as *parameters of the framework*) that affect decisions about design. Figure 5.2 summarizes the framework.

5.2.1 Users

Each user has unique needs and goals, hence requirements and challenges happen in different spheres of the travel experience (cf. Figure 5.3). Designers should address users' special needs for access. Thus, designers' first question is: *What are the users' needs and capabilities?*

User Mode

A *single user* or *multiple users* may utilize a mobility service. For example, an inclusive school's excursion often involves the student and the assistant(s).

> "At our school, individual students have integration assistants with them. Either one-to-one support or two-to-one support. However,

> some students are cognitively and mobility-wise able to cope independently with our support." [P5]

Special User State/Trait

Mobility service users can have one or multiple distinguishable temporary (state) or permanent (trait) conditions that are access barriers. We utilized the LUDI [BB19] to describe these user conditions: *Intellectual Disorder*, *Hearing Impairment*, *Visual Impairment*, *Physical Impairment*, *Communication Disorder*, and *Autism Spectrum Disorder*. Cognitive, physical, or sensory (vision, hearing) impairments restrict consumers from using mobility services, e.g., dyslexic users require a text-free interface. In the vulnerable road users (VRUs) taxonomy [Hol+21] (layer 5, notably VRU), impairment subcategories (layer 6 and 7) are comparable to the LUDI classification. Yet they introduce includes age (children, elderly) as a road user's "vulnerability". Thus, we included *development state* as a further category. Depending on their developmental state, people diverge in their abilities and skills so that they are either still developing or have already surpassed full function, such as presbyopia and natural vision impairment in the elderly. Young children cannot read nor perceive speeds exceeding 20mph [Sci10]. They're prone to bad judgments, such as risky road crossings [GK21]. Consequently, internal and exterior HMI design should follow the *universal design guidelines*.

Accompaniment

Some impairments allow traveling *alone* under specific circumstances, such as a stable infrastructure present, while others need direct *on-site* or technology-mediated *remote support*. An example of a barrier for those who are physically impaired:

> "A physical impairment, for example, hemiplegia, and I can't get into this thing, into this bus, or into this self-driving car. That is, of course, another kind of hurdle that you have to consider, how is this means of transport designed so that I can simply get in and out. Because it is already sometimes with the buses with the entrances, there are indeed the low-floor buses, but for someone

> who is all alone with a gait problem and has no accompaniment, it is difficult perhaps." [P4]

When people get comfortable with a route, accompanying needs might shift. Assisted living institutions aim to move towards individual autonomy:

> "And the goal is not only to take over but, above all, to empower people so that they can actually do it themselves." [P4]

Needs & Goals

In addition to DAUX and SDT frameworks (see Section 2.4.5: autonomy, competence, relatedness, meaning. stimulation), autonomous mobility services are motivated by safety and control. Motivating not only passengers but a remote helping person in multi-user situations, such as caretakers connected to their clients or parents to their kids. However, restricting fundamental needs negatively impacts one's well-being and health [DR00]. As articulated in the Motivation, Engagement, Thriving in User Experience (METUX) framework [PCR18] (see Figure 5.3), assistive technology ought to fulfill these basic needs for better well-being.

5.2.2 Journey Context

Journey contexts are complex. Emotional context like prior experiences, the linked expectation, the route's development, or the traffic situation is important for users with special needs. When building autonomous mobility services, designers should consider these contextual variables, therefore our second framing question for designers is: *What is the journey's context?*

Travel Phases

A journey comprises five stages: 1) *Planning*, 2) *Ordering*, 3) *Onboarding*, 4) *Riding*, and 5) *Offboarding*. It is crucial to consider which phase a user requires what sort of help since requirements change: A journey must be *planned*, alone or with a caregiver. Assistive technology may help learn important route details (cf. route familiarity). If not owned, the ride must be *ordered*. The ride may be ordered using an app or a mobility station interface. Inaccessible interfaces may frustrate individual autonomy. Specific needs could be communicated pre-ride:

> "It should be possible to enter the disability before the start of the journey, but then not only the mobility restrictions but also the restriction in communication, so that it is then clear: 'Hello, here is someone who needs support'." [P5]

People with impairments struggle during *Onboarding* and *Offboarding*. For instance, people with low-vision need assistance with navigation including signaling noises preceding exits and people with physical impairments an entry/exit ramp. Again, familiarity generates autonomy:

> "Then the next problem is getting out, i.e., the person must be spatially oriented in such a way that he also finds the place where he wants to go. There are many people with intellectual disabilities who travel by bus without any problems and have if they always make the same routes..." [P5]

When something unexpected occurs while *riding*, like an alternate route, a missed stop, or an accident, people with certain impairments need help. Persons with cognitive impairments might require assistance in an unfamiliar environment.

> "So that in an emergency [she/he] can actually press a button and there a person is switched on, maybe even somehow by video chat that I can imagine that can be calming, if the persons unsettled, that what is happening right now or where it goes, that is really again a person who listens and then somehow maybe trained and communicates in easy language with him and can somehow find out what the problem is right now." [P8]

Emotional Impact

Journeys might be *positive* or *negative connotated* for users. Unlike the journey to a beloved friend, the route to the dentist may cause anxiety or panic attacks. Another example of an emotionally charged situation is a hungry toddler seeing a McDonald's restaurant from the car. Designers can control (un)wanted triggers, e.g., by changing the view using an AR-Windshield display [Pad+21].

Route Familiarity

The path might be *known*, *unknown*, or in between. Most people with impairments can handle the recognized routes, but as described, unknown situations might be a challenge: How long will the journey take? Can they wait? How many stops are there? Users with physical limitations need to know whether there is a wheelchair-friendly station once they reach their target, while users with cognitive impairments feel anxious and cannot go alone on an unfamiliar route. Low-vision users may need to count the stops till the destination. In sum, unknown journeys need extra assistance. Training could make routes more familiar, making journeys predictable and less risky for passengers.

Road Conditions

In contrast to*perfect* road conditions, *poor* conditions affect certain users' journeys. Gravel roads make touch engagement with assistance systems difficult. Wheelchair users, for example, need to be able to connect their wheelchair throughout the journey.

> "Wheelchair users have anchors in the buses, for example, in the buses we use at the school so that the wheelchair cannot slip away during the journey." [P7]

Traffic Density

Traffic may be *sparse* or *dense*. Like road conditions, this characteristic determines the quality of assistance systems interaction: High traffic density may impact voice assistant interaction. Compared to a free road, intense traffic might stress passengers, which affects their emotional response to the journey. Door exits in high-traffic regions demonstrate traffic's effects:

> "Well, if I now look at people with mobility impairments, then it is, of course, the case that they would like to park, provided they have their vehicles, preferably in front of their doctor's office, meaning to find there also a sufficiently dimensioned parking space, which is wider, which allows the exit in preferably not the flowing traffic, but at a distance from the flowing traffic..." [P2]

Travel Duration

Travel may be *short* or *long*. Longer trips need greater patience along with additional rest and stimulation needs.

5.2.3 Mobility Service

Future mobility moves beyond car-dominated transportation. These transportation services might vary by user type and evolve over time. Thus, we pose our third framing question for designers: *How does the transportation service look?*

Means of Transport

Users may utilize motorized services for transportation, such as a *train*, a *tram*, a *(shuttle-)bus*, or a *car*. For shorter trips, taking the *bike* or going *by foot* are alternatives that we included that fall not in the category of "traditional" mobility services. On the one hand, these alternatives are unsuitable for people with physical impairments. On the other hand, they are often the only way for people with mild cognitive impairments to travel nowadays. Given that bikes are "practically comparable to cars for ordinary people, so the bike must also be stylish, be speedy, be good" [P3]. Autonomous mobility services may enable longer self-directed journeys and autonomous personal mobility.

> "So basically, the cared-for people who can now ride a bike on their own, they could also, once you've practiced that a little bit, then travel autonomously." [P8]

But there are also challenges regarding space consumption of different transportation means:

> "When you now make a public space attractive for pedestrian traffic, ban cars from the neighborhoods [...] but what happens when people who are getting old or have a disability still use their vehicle, particularly in [the city] an issue. Or, what possibilities are there to open up alternative mobility concepts for people with disabilities. So, a bike station... are there also tricycles? So that people with disabilities could also use them, for example." [P8]

Privacy

Vehicle ownership may be *private*, *shared - selected*, or *shared - public*. Shared transportation involves vehicle co-use with selected people or anyone. When someone with physical impairments needs assistance boarding a public bus, having others present is helpful. For a person with sensory or cognitive impairments, others might cause stress.

Availability

Ownership affects mobility service availability. *Constant* availability gives the most personal freedom, yet *on-demand* ideas like shuttle buses have wait periods, while *scheduled* concepts like public transit are bound to "regular" work and school hours. Autonomous transportation improves availability.

Connection

Mobility services may be directly linked from start to destination with one mode of transportation or include many modes, such as last-mile transportation. People with physical impairments may prefer a route with less-changes that is slightly longer. The number of changes a user requires for a journey is important, particularly if it disrupts routines of cognitive limitations.

5.2.4 Assistive Technology Interaction

It is typical to engage with several HMIs that help the user throughout various travel phases and activities, such as booking a ticket by smartphone, viewing a movie on virtual windshields, or stopping the ride with a mechanical button. Because the journey involves several interaction situations (see framing question 3), we focus on *service experience* rather than vehicle characteristics. Thus, our fourth framing question for mobility designers is: *How to interact with the service?*

Application Context

We created *application context* categories using the literature research, associated design spaces, and interviews. These include *safety*, *convenience*, *ride configuration*, *orientation*, *communication*, *productivity & entertainment*, and *connection aids*. Table 5.2 exhibits use cases for inclusive mobility interaction.

Location

During a trip, users can interact with *internal* or *external HMIs*, *user devices*, or stationary *public devices* such as ticket machines. For low-vision or blind people, e.g., public bus speakers that announce the line number and destination are beneficial external HMIs. On the other hand, public audio displays interfere with hearing impairments.

Initiative

The *user* or *system* may initiate interaction. Most interaction is user-initiated and assistive technology may help users with cognitive limitations convey their needs and goals to the system. E.g., location-based security could detect route anomalies:

> “We can see with GPS trackers when they leave the premises, then that would certainly be a possibility that you then get a warning.” [P1]

Nevertheless, these techniques must protect privacy [P6]. Users, therefore, need a transparent design of proactive assisting technologies.

5.2.5 Training

Most users facing mobility barriers require a dependable routine. Knowing the infrastructure, travel duration, and other travel parameters facilitates self-determined mobility, particularly for people with cognitive impairments:

> "Mobility training is clearly for people who are a bit fitter, who can orient themselves independently, at least if you've shown them a few times. That doesn't have to mean we have to be able to read the map, but it can also be an aid to help them find their way. And then we look at how we can teach them, some can only take one line at first, so they know that this is the stop where I get on the bus, and then I get off again." [P4]

Thus, our fifth framing question for designers is: *How to train for the journey?*

Environment

A user may train their journey with a vehicle and all required interaction processes in various mixed reality settings [Mil+95]: In the *real world*, *virtual*, or somewhere in between in *mixed reality*, e.g., augmented reality or augmented virtuality. Real-world training requires a safe environment and constant supervision that leads to assisting efforts. VR training [SS11; Tho+05; TBB20] has helped people overcome phobias by repeatedly exposing them to anxiety triggers and re-framing emotional events. In the same way, a virtual journey may be halted, paused, and replayed for training. Consequently, mobility training in virtual or augmented environments before attempting an independent journey in the real world may be effective and safe.

Trainer

The training environment offers the travel scenario. This virtual or real world can be visited in *self-training*, using a system like a *virtual avatar*, or with a genuine person like an *assistant person*.

5.3 Application

Our framework facilitates mobility designers to think about inclusive design aspects and, debate potential trade-offs, new possibilities, synergies, and understand the implications of a design choice. Next, we demonstrate the framework's application in a hypothetical design process.

Use Case and Designers

A ridepooling app seeks a new reference selection technique. They prioritize inclusive design. Two freelancers develop and build the feature's UX. Designers have distinct abilities and interests. *Alice*, a 32-year-old computer scientist, started working in the industry following her Bachelor's thesis. She is skilled in web programming. Alice implements the feature's graphical user interface (GUI). She implemented W3C accessibility and search engine optimization guidelines, but she lacks a theoretical background in UX design. *Bob*, 49, is a automobile UX designer working in industry for 15 years. Bob recently finished a user-centered design training. He prefers conceptual design over implementation.

Using the Framework

Alice and Bob rarely design inclusive software features. Bob prints the Design Framework for Accessible and Inclusive Future Mobility (Figure 5.2) with Alice to start. They start with the framing questions.

They soon agree that ridepooling preferences are input in *single user mode* and matched before the ride. Since app users are unclear, they are unsure about the *user state/traits* options. Alice states that users first specify their unique requirements in the app, aligning with their unique needs and goals. Alice adds her W3C implementation expertise to the app's design. She aims to make the dialogs easy to comprehend and utilize recognizable forms and symbols whenever possible so that those with dyslexia or poor eyesight may use the GUI. Bob recommends a chatbot for non-GUI users. Alice asks Bob how to approach young or intellectually limited users. Bob believes this group will not utilize ridepooling *independently*, yet they should keep them in mind since their caring persons may use the app and desire nearby seats. Bob discovers arguments for all *accompaniment* options. Most individuals travel *alone*, but others require *on-site* or *remote assistance*. Alice and Bob agree that the ridepooling software should enable people to be *autonomous*. Bob also suggests adding other needs depending on the destination, such as *relatedness* when visiting friends, *competence* when heading to work, or *safety & control* when assisted. He proposes developing personas for the user types with abilities and needs to remind them of their discussion later in the design process.

As they expand on the ridepooling service, Alice and Bob can easily determine the *travel* and *service* dimensions. The application is obviously at the *ordering* stage. Bob recognizes that the *familiarity* and *emotional impact* of the route are unclear. Alice argues it should be allowed to define or avoid routes and destinations and, at some point, develop a filtering mechanism. Bob approves. Yet he believes one should also be able to purposely choose unfamiliar, exciting routes. The ridepooling app is only accessible in Modelcity, so they know that the roads are mostly in *good condition* and the traffic is *relaxed* except during peak hours, and *routes* are *short*. Bob identifies *Car* for the ridepooling service's *means of transport*. The user orders and shares the cars, therefore they designate *ownership* as *shared*, *availability* as *on-demand*, and *connection* as *one transport mode*.

Their application is classified as *ride configuration* and they start looking at linked projects in that area. Alice and Bob agree that the *user* should take *initiative*. Users will set preferences on a *user device*. Alice further recommends public displays at popular stations to use the ridepooling service. Since there are numerous preferences, Alice suggests pre-filling the configuration form based on usage at a specific time or location. Bob finds that interesting and suggests recommending locations automatically based on the user's movements, but Alice says this could make users feel monitored, and they could quit using the app. They agree to deactivate automatic recommendations by default and inform initially of such functionalities.

Although usually not required, Alice and Bob value *training* because it familiarizes users with the route. Bob believes a tiny *VR* preview area in the GUI might assist customers who are mobility-impaired in identifying suitable halting spots. They classify the idea as *self-training*.

Alice and Bob start the design procedure by discussing several relevant inclusion issues using the generated personas, the list of ridepooling extensions, and the ideas for the preference-selection mechanism. These insights help guide their further design process to be more inclusive.

5.4 Conclusion

Automotive practitioners and academics have to acknowledge that they are part of an inclusive design process. They should involve individuals with varied backgrounds and special needs and goals or their representatives in future mobility service design to make it inclusive and accessible. Following the universal design approach, we provided inclusive future mobility use cases, a design framework, and a showcase of how to apply it in this chapter. Prior work, comparable taxonomies, and inclusive facility specialists' mobility experiences informed our framework. It helps communicate, ideate, and reflect for designers about future mobility accessibility and inclusion needs and goals. We encourage extending and refining the framework with additional perspectives, such as from people with specific impairments and take the next steps of universal and inclusive design by incorporating the framework to design guidelines that help to construct and assess new mobility artifacts accessible to all.

`Users`

1. What are the users' needs and capabilities?

User Mode	Single User ↔ Multiple Users
Special User State/Trait	Intellectual Disorder, Hearing Impairment, Visual Impairment, Physical Impairment, Communication Disorder, Autism Spectrum Disorder, Development State
Accompaniment	Alone ↔ with support (remote) ↔ with support (on-site)
Needs & Goals	Autonomy, Competence, Relatedness, Meaning, Stimulation, Safety & Control

`Journey`

2. What is the journey's context?

Travel Phases	Planning, Ordering, Onboarding, Riding, Offboarding
Emotional Impact	Positive Connotation ↔ Negative Connotation
Route Familiarity	Known Route ↔ Unknown Route
Road Conditions	Perfect ↔ Poor
Traffic Density	Sparse ↔ Dense
Travel Duration	Short ↔ Long

`Mobility Service`

3. How does the transportation service look like?

Means of Transport	Train, Tram, (Shuttle-)Bus, Car, Pod, Bike, By Foot
Privacy	Private, Shared - Selected , Shared - Public
Availability	Constant, On-Demand, Scheduled
Connection	One Transport Mode ↔ Many Transport Modes

`Assitive Technology Interaction`

4. How to interact with the service?

Application Context	Safety, Convenience, Communication, Productivity & Entertainment, Accessibility
Location	Internal HMI, External HMI, User Device, Public Device
Initiative	User ↔ System

`Training`

5. How to train for the journey?

Environment	Real-World ↔ Mixed Reality ↔ Virtual Reality
Trainer	Assistant Person ↔ Virtual Avatar ↔ Self-Training

Figure 5.2: Summary of the Framework – Framing questions (dimensions) and answer options (parameters).

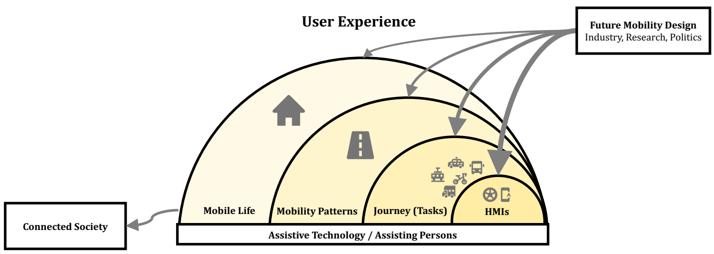


Figure 5.3: The METUX [PCR18] framework adapted for autonomous mobility user experience — Mobility designers can impact a user's life by providing an outstanding HMI, task support, and behavioral support. Users' needs may be fulfilled or deprived of each sphere. From the inclusion standpoint, autonomous mobility experiences are tied to the artifact and interdependence with assisting people and technology. Future transportation may foster individual participation and a stronger interconnected society.

Category	*Sub-Category*	*Use Case Examples*
Safety	Emergency Stop	Simple "panic"-button for emergency stop [I] Voice-controlled emergency stop [BK18]
	Breakdown Assistance	Automatic connection to emergency contact person [I] Auditory information of the problem and necessary steps to resolve it [BK18]
	Surveillance	Passenger camera [I] Warning if someone leaves geofenced area [I] Tracking of the vehicle [Ayo+20]
	Remote Vehicle Control	Configuration of speed, seat belts, temperature, etc. [Pad+21; Car+21]
	External HMIs	Crossing message, representing intent and instruction [CR20a] Engine sounds for vehicle detection [WLN14]
	Anchoring	Automatic door locks that open regularly only at on-/offboarding points [I] Automatic seat belt aids [I] Automatically connecting safety anchors for wheelchairs [I]
	Reducing Emotional Triggers	AR Windows that block triggering views, e.g., MCDonalds on the route for a child [Pad+21]
Convenience	Interior Adjustment	Automatic seat adjustment [I]
	Vehicle Finder	Key chains designed to vibrate based on proximity to the vehicle [Bri+20]
Ride Configuration	Ordering	Pre-ride selection of multiple accessibility features [Car+21], [I]
	Navigation	Conversational interface for destination input (Siri-like) [BK18; Bri+20] Brain-controller to enter destination [Bi+16]
	Direct Vehicle Control	Steering wheel and pedals with assistance lateral or longitudinal as needed [Yop15] Gesture-based control [Mey+18] Voice controlled take-over for car correction [BK18] Joystick to control the vehicle [Hon+08; Mit+14]
Communication	Exchange with Remote Person	Ride assistance through other clients in facility control center (community support) [I] Video chat caregiver-passenger [Pad+21; Ayo+20]
Orientation	Vehicle Identification	Automatic detection and auditory transmission of available bus lines [Kau+18], [I] Visually simplified IDs of public transportation vehicles [I]
	Interior and HMI Sensing	Visual feedback of all buttons and action for deaf people [I] Auditory feedback of all buttons like a screen reader, "voiceover" feature [BK18; Bri+20]
	Ride Status & Progress	Tactile compass that informs about travel direction [BK18] Conversational interface for current GPS location [BK18] Location verification backup system during offboarding [Bri+20]
	Training	User training of interaction procedures, locations, switches, etc. [I]
	Environment Sensing	Refreshable braille display for environmental information [BK18] Object-indicating vibrating steering wheel [BK18] Vehicle attached "stick" to detect potholes [BK18] Accessibility information through virtual twin [KS15] Walking aids that detect and warn about potholes [ISB20] Sonar-like environmental sensing with walking stick (hold in direction) [BK18]
Productivity & Entertainment	Gaming	Child games [Ayo+20]
	Work	Homework assistance [Ayo+20] Joint appointment preparation and sheduling [I] Going to work and traineeships [I] Storage for medication [I]
Connection Aids	On-/Offboarding Aids	App guide to fixed stopping positions of on-demand vehicles [I] Ramp system [I]
	Personal Mobility Aids	Autonomous tricyle at bicyle station [I] Autonomous scooter [NLL12] Autonomous wheelchair [Mad+86]

Table 5.2: Inclusive and autonomous mobility – Use case categories including examples from literature (marked with reference) and/or interviews (marked [I]).

Part II – Summary

In this part, we looked into the changing driving activity context with a focus on the user perspective. We glimpsed into the future use of an autonomous mobility service (Chapter 3) and gathered user needs and goals (Chapter 3, Chapter 4, Chapter 5).

With our WoZ study (Chapter 3), we directly observed the usage of autonomous mobility services and found that smartphone and laptop use for work and entertainment are likely future activities. Users expect to use autonomous mobility services for medium to long (routine) trips. In consequence, by supporting work and entertainment activities, e.g., through interior design and virtual windshields, vehicle designers can address an important user experience factor. Before all, participants mentioned safety to be the most crucial acceptance factor. However, in the study, users did not fully trust the systems' capabilities to be equal to the safety drivers yet they tend to adapt to the vehicles' driving after they experience the car to move safely.

In our online q-method survey (Chapter 4), we found four prototypical attitudes that diverge around the (non-)enthusiasm for the topic as well as a social, service, or technology focus of that group. Thereby, we demonstrated that a one-fits-all perspective on acceptance (which acceptance models try to capture) might not exist in the context of autonomous mobility services. In addition, we provide a perspective to capture these needs and goals through user clusters (e.g., to use with personas).

The use of people with disabilities or their assisting persons extends the potential of autonomous mobility services and their needs and goals must be considered in early design. We provided a list of potential use cases and a design framework for inclusive and accessible future mobility based on interviews and literature (Chapter 5). The framework helps to discuss existing and ideate new use cases while considering important design parameters for inclusion of non-average users needs and goals.

Overall, the presented insights and the framework of this part help designers to take a look forward into the changing activity context and of autonomous mobility services. Thus, it helps them to better understand the needs and goals of future mobility users.

III

Bridging the Gulf of Execution in Automated Driving

Outline

From a users perspective, there are situations during autonomous driving where users' goals change and they might want to intervene and override or completely take over the driving task from the system, e.g., when driving without a concrete destination, for the last-mile, or when simply overtaking a truck that blocks the view on a highway. Given the changing activity context through parallel execution of NDRAs, current driving task interfaces (steering wheel and pedals) might not be the most useable solution. To reduce this *gulf of execution* (cf. Norman's 7 stages of action model [Nor08]), instead of performing fine-grained vehicle control on stabilization level, control on guidance level is much closer to user goals and promises higher comfort in terms of *action specification*. In terms of *action execution*, natural user interfaces like touch, voice or mid-air gesture interfaces could further minimize the required interaction effort. In this part, we therefore develop a command set for maneuver-based driving (a form of guidance control with atomic maneuvers, e.g., turn left) that complements existing touch interfaces [KSB10; Fra+12] with voice and mid-air gesture control (Chapter 6). Then, we compare it against touch control and in context of NDRAs (Chapter 7).

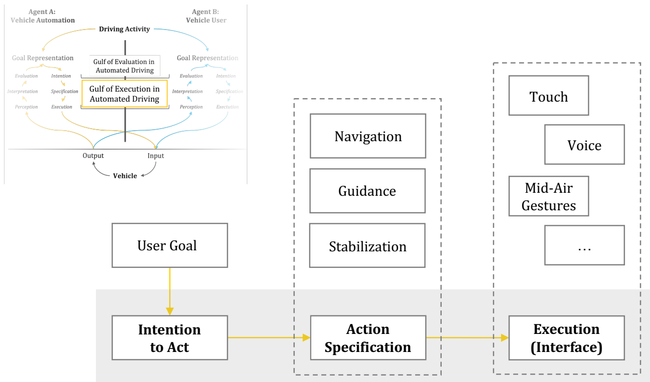


Figure 5.4: *Gulf of Execution in Autonomous Driving* – When having the *intention* to intervene in the driving, e.g., to overtake a truck (goal), the *specification* of the required action could be done on stabilization or (more likely) on guidance level since the car is expected to perform the stabilization task autonomously and safe. The comfortable *execution* of the action depends on the provided car interfaces and the NDRA.

Chapter 6

Voice and Mid-Air Gesture Alphabet

This chapter is based on the following publications:

Henrik Detjen, Sarah Faltaous, Stefan Geisler, and Stefan Schneegass. "User-Defined Voice and Mid-Air Gesture Commands for Maneuver-based Interventions in Automated Vehicles". In: *Proceedings of the Mensch und Computer 2019 (MuC '19)*. 2019. DOI: 10.1145/3340764.3340798

In this chapter, we develop a voice and gesture alphabet based on simple maneuvers to intervene in autonomous driving. In a study, we explore how users would perform driving maneuvers with direct, contactless interaction modalities and the potential consensus/dissensus between users' expressions (cf. *RQIII_1* – How would users express maneuvers via voice or mid-air gestures?).

Future cars will incorporate new in-vehicle interior designs that may be radically different from today's automobiles. Even if AVs offer typical control devices like haptic interfaces or touch panels, the passenger may not be able to reach them comfortably, for instance, if (s)he tilts the seat back to watch a movie. Further, people are cautious about transferring control to an artificial entity [Röd+14; EG15] and providing control can help build trust. However, it is unknown how drivers want to intervene in future AVs. In consequence, it might be necessary to provide different levels of control and to provide different modalities.

MBIs simplify driving to maneuver input like “park” or “lane change” (cf. Section 2.3.2). Touch solutions for MBIs [Fra+12; KSB10] exist, yet alternative natural interaction options, such as explicit, contact-less interaction, which might benefit future AV designs, are still unexplored. Tscharn et al. [Tsc+17] studied “non-critical, spontaneous interventions” in scenarios like picking up a friend or selecting a parking lot with multimodal interfaces. Speech or touch to choose maneuvers like parking and pointing motions to locate them (e.g., which parking lot). Speech was more natural, intuitive, and less stressful than touch. Given this and the previously described shift in-car use with innovative cockpit designs, we choose speech and mid-air gestures as interface modes for our initial study. Unlike the more complex maneuvers used by Tscharn et al., our work aims for a comprehensive maneuver catalog as created in the conduct-by-wire project [MMR09].

The following elicitation study aims to determine (1) how speech and gesture commands for MBI should be designed and (2) how feasible contact-free interaction is from a user’s perspective. We employ a user-centered design methodology (consensus set) to develop voice control and free-hand gestures. Further, we evaluate execution times and user impressions to answer the second question.

6.1 User Study

We used Wobbrock, Morris, and Wilson’s approach for tabletop motions to study speech and free-hand gesture interaction from a user’s perspective. It is a user-centered design method that generates commands from the user by

Figure 6.1: We examine voice and gesture control for MBI in a stationary automobile setting to simulate the constrained in-vehicle space: A gesture for stopping the vehicle.

displaying her/him the effect of an action (also referred to as *referent*) and asking him to cause it (also referred to as *sign*). We show the user a particular driving maneuver (referent) and ask him to execute a suitable gesture (see Figure 6.1) or vocal command (sign).

6.1.1 Setup & Procedure

The test took place in a stationary vehicle to simulate driving (Tesla P60). A simulator-generated autonomous ride was shown on a canvas in front of the car (see Figure 6.2). As a maneuver started in the video course, we presented a referent for ten seconds (modified from Kauer, Schreiber, and Bruder, see Figure 6.2) and participants responded with their sign.

The eight-minute video featured all driving maneuvers (start, straight, lange change left/right, turn left/right, hold at side-strip, hold at stop-line, parking). The first four minutes of the program familiarized users with the study setting. And in second phase (around 4 minutes), we used an action cam to capture data for our analysis. The track was driven twice (voice/mid-air gesture commands) in a counterbalanced within-subject design. After two runs, respondents answer a custom questionnaire regarding acceptance (1 item on a 6-point Likert scale), preferred input style (2 items on a 6-point Likert scale), overall feedback (free text).

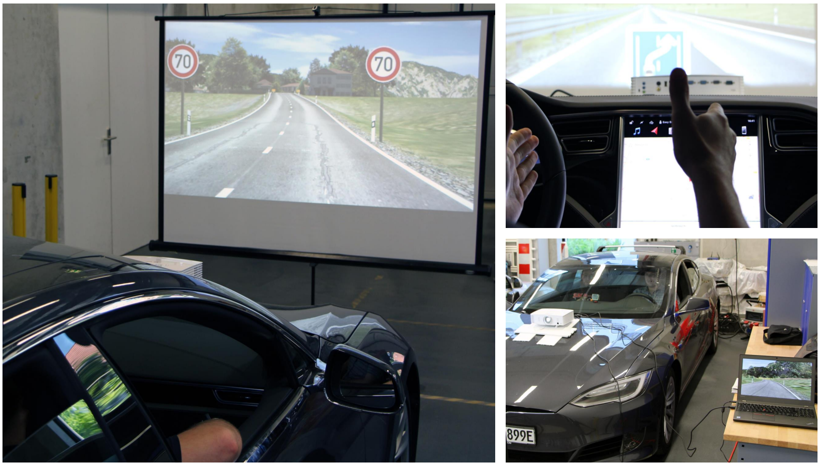


Figure 6.2: Experimental setup – A Tesla P60 and projection screen showed driving maneuvers (referents).

6.1.2 Participants

The average age of our 20 participants ($m = 14$, $f = 6$) was 31.5 years ($SD = 13.1$, $Min = 19$, $Max = 61$). Nine utilized voice assistants (e.g., Google Search, Smarthome). One participant has free-hand gesture experience (MS Kinect). After explaining the test protocol without referring verbally to the maneuver referents, the trial started.

6.2 Results

We cluster user study results and identify a compact set of free-hand gesture and speech commands. First, we classify gestural responses by performance nature, form, and handedness. We then analyze the characteristics, usability, and user perceptions of both interaction modalities to address their general feasibility.

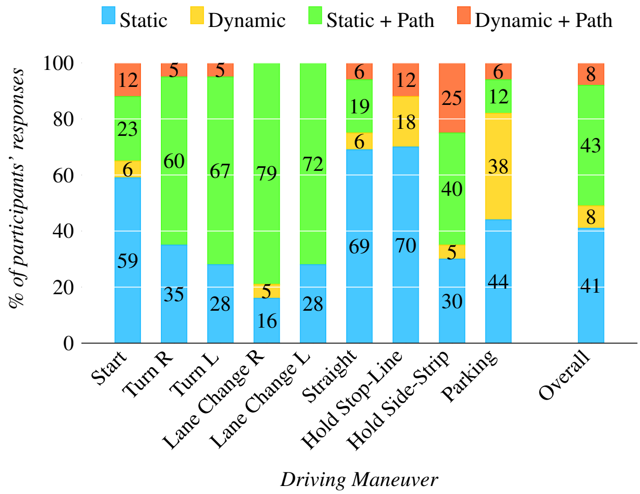


Figure 6.3: Mid-air gestures' form – For most maneuver referents, static gestures (following a path) predominate.

6.2.1 Mid-Air Gesture Classification

To develop a mid-air gesture set, we categorized all gesture video samples. Form, nature, and handedness were the classifying dimensions. The *form* dimension corresponds to movement and indicates whether a gesture is performed static, dynamic, or along a path [WMW09]. Figure 6.3 demonstrates the forms of gestural responses. Most mid-air gestures were static or static along a path.

Nature defines the general type of gesture performance. We integrate Geiger's [Gei03] gesture taxonomy to reinterpret Wobbrock, Morris, and Wilson's [WMW09] nature aspects (symbolic, physical, metaphorical, abstract) for the automobile environment:

1. **symbolic**: visual depictions
2. **deictic**: pointing gestures, special case of symbolic

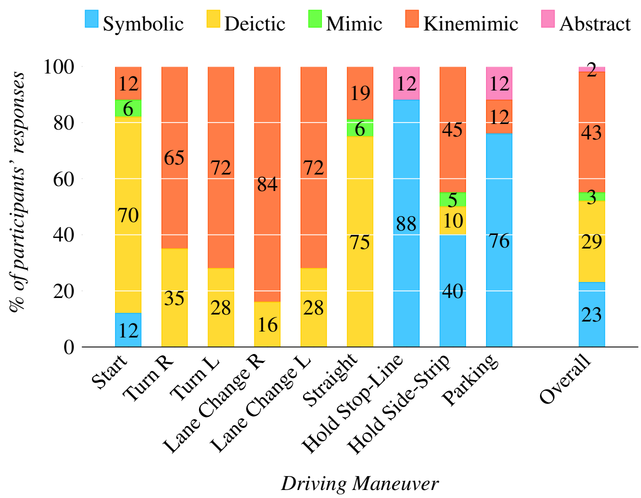


Figure 6.4: Mid-air gestures' nature – Directive maneuvers are mostly of kinemimic and deictic nature and stopping maneuvers mostly of symbolic nature.

3. **metaphorical/mimic**: gestures acting on, with or like something else
4. **kinemimic**: gestures imitating a movement, special case of metaphorical/mimic
5. **abstract**: not fitting in one of the categories before

Figure 6.4 displays the gestural response nature distribution. For referents *Start* and *Straight*, most participants responded with a deictic gesture; for maneuvers *Turn* and *Lane Change* they tend to choose a kinemimic gesture, and for maneuvers *Hold at Side-Strip*, *Hold at Stop-Line* and *Parking* they primarily used symbolic gestures.

In terms of *handedness*, we observed: The dichotomous maneuvers (*Turn L/R*, *Lane Change L/R*) were mirrored by most participants using their right hands. When using both hands for a sign, one hand imitated the other, e.g., for halt

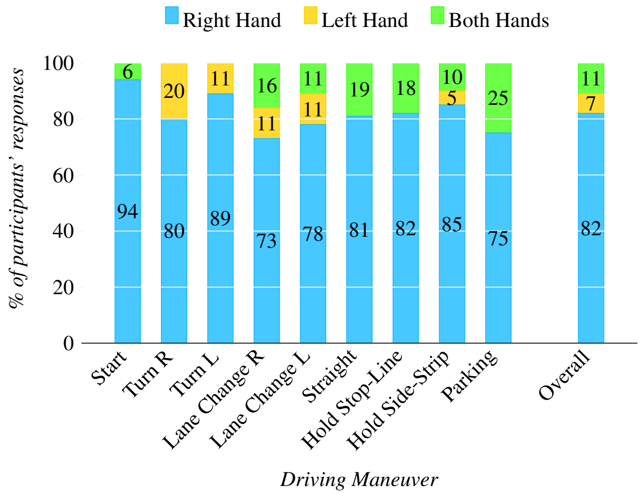


Figure 6.5: Mid-air gestures' handedness – The right hand is preferred over the left hand or both bands.

maneuvers to emphasize the command's urgency. The nature of the gesture determines the involved finger count (flexed or not). For swipe movements, participants used all fingers, whereas pointing (deictic sign) was done with one finger (index and middle finger). The distribution of participants' gestural answers' handedness is shown in Figure 6.5. In conclusion, the right hand was utilized most of the time, and the left hand or both hands seldom.

6.2.2 User-Defined Voice and Mid-Air Gesture Command Set

After classifying gestures, we clustered similar gesture and voice signs for each referent. We then allocated these clusters to our suggested command sets.

Maneuver	A_{Speech}	$A_{Gesture}$
Start	.19	.31
Turn R	.81	.48
Turn L	.81	.46
Lane Change R	.22	.45
Lane Change L	.17	.41
Straight	.65	.43
Hold Stop-Line	.68	.61
Hold Side-Strip	.15	.17
Parking	1	.26
Overall	.51	.40

Table 6.1: Agreement score by maneuver — Interpretation [VW15]: *<.1=low*, *.1–.3=medium*, *.3-.5=high*, *>.5=very high* agreement.

User Agreement

We used the clustering agreement score [WMW09] to assess user consensus (see Table 6.1). Higher agreement ratings come from larger clusters. Our participants highly agreed on voice and gesture signs for most referents (Voice: $M = .51$, $Min = .15$, $Max = 1$; Gestures: $M = .4$, $Min = .17$, $Max = .61$).

Mapping of Clusters to a Command Set

We mapped clusters of user signs to our maneuver-specific speech and mid-air gesture command set, i.e., an alphabet for expressing maneuvers. Our mapping only employed clusters with $n >= 3$, excluding single replies and minor clusters that may have been coincidences. However, our final mapping covers most answers despite this barrier. The mapped speech and gesture command sets cover 90% (voice alphabet) and 86% (mid-air gesture alphabet) of all samples, respectively. Figure 6.6 and Table 6.2 show gesture and speech command mappings.

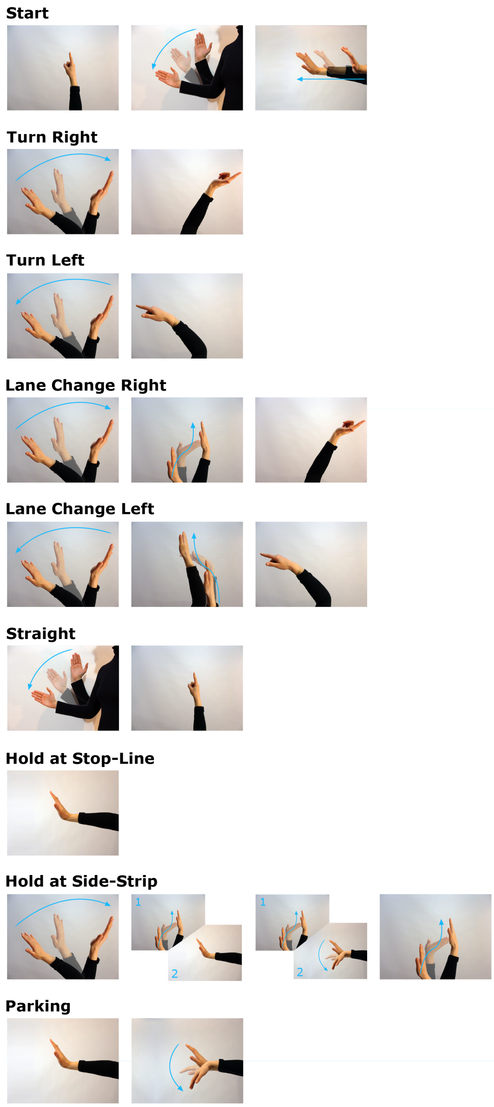


Figure 6.6: User-defined mid-air gesture commands — Bird's-eye view or side-view for better up-down movement view.

Maneuver	Keyphrases (in EBNF)
Start	set off, start [(drive | straight ahead)], begin, straight, go [straight]
Turn R	turn right
Turn L	turn left
Lane Change R	[(move to | select)] right (lane | track), lane change [to the] right, [keep] right [ahead]
Lane Change L	veer [to the] left [and continue], [on] left lane, lane change [to the] left, (pass | overtake | pull ahead) left, [drive] left
Straight	[(go | follow the road)] straight, continue [driving] straight [on]
Hold Stop-Line	stop [at the line], hold [independently]
Hold Side-Strip	stop [right], (pull | right) over, hold [right [on the edge of the roadway]]
Parking	park

Table 6.2: User-defined voice commands – The maneuver referents and linked clusters of high consensus signs.

6.2.3 Execution Times

If the interface is rapid enough for practical applications, it is a matter of the execution time. For instance, when we drive 100 km/h (27.8 m/s) on a highway and want to intervene for an exit in 100m, we have a 3.6-second time frame for the command. The time frame includes system-side detection, processing, and execution. To assess interaction time, we monitored each participant's response execution time. German voice instructions were translated into English. Then, we utilized the Google Cloud Text-to-Speech API to produce command audio files (voice: "en-US-Wavenet-D"). We then transmitted the audio recordings to the Google Cloud Speech-to-Text API to retrieve command duration. We stopped mid-air gestures from muscular tension to relaxation. As illustrated in Figure 6.7 and Figure 6.8, the command duration depends on the maneuver. A few static gestures used the full referent window in the study (10s). For *Hold at Stop-Line*, participants held their gestures until the vehicle stopped. In comparison voice instructions ($M = 0.88s$, $SD = 0.29s$, $Min = 0.2s$, $Max = 2.1s$) are significantly quicker ($t(153) = 1,98, p < .01$)

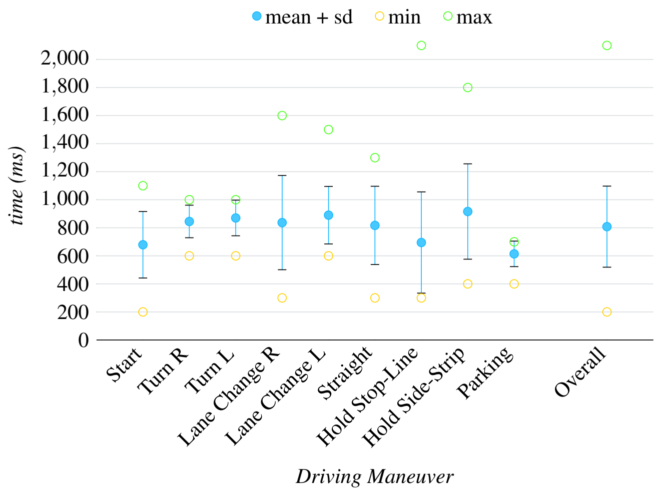


Figure 6.7: Execution times for voice commands – Most took less than a second.

than mid-air gestures ($M = 2.76s$, $SD = 1.66s$, $Min = 1.0s$, $Max = 10.1s$). For our highway exit scenario above, voice control is efficient, but mid-air gesture control may be too slow.

6.2.4 Acceptance & Preferences

Speech and gesture interfaces' acceptability is essential. In previous work [Det+18], people could envision utilizing speech control for maneuver-based driving ("You can also tell a person the route"), yet gesture control imagination was ambiguous ("unclear gestures", "acceptance", "freedom of movement"). Our video investigation supported this. On a 6-point Likert scale, participants rated voice control rather good ($M = 4.65$, $SD = 1.11$) and free-hand gesture control rather bad ($M = 3.3$, $SD = 1.15$). Hence, 14 of 20 participants (70%) chose voice control over gesture control for MBI.

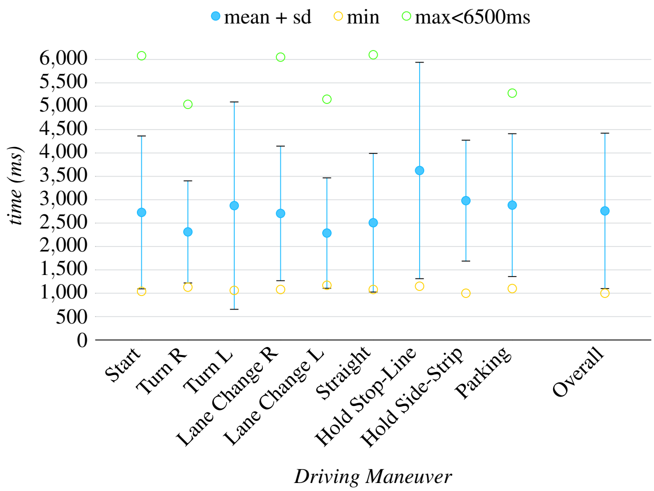


Figure 6.8: Execution times for mid-air gesture commands – Most took around 3 seconds.

6.3 Discussion

We discuss our methods, participants' mental models, and research limitations below.

6.3.1 Applied User-Centered Method

Our applied user-centered design method by Wobbrock, Morris, and Wilson differs from expert-based gesture design like Nielsen et al.'s approach and has been debated, e.g., in activity-centered design [Nor05] that embraces both approaches. Following the latter approach, our findings will help experts design the voice and mid-air gesture command sets for driving maneuvers by providing them with insights into execution times, user preferences, and mental models.

6.3.2 Simplification of Command Mapping based on Mental Models

Participants simplified the maneuvers *Lane Change* and *Turn* by saying only the direction (“right”, “left”) and performed comparable gestures for *Turn L/R-Lane Change L/R*, *Start-Straight*, and *Stop-Parking*. Thus, the signs for these referents overlap, i.e., the same commands were uttered for different maneuvers. Overlapping instructions appears problematic at first. Commands should be concise and consistent. Yet, none of the maneuvers with overlapping commands would occur simultaneously. "Right [turn]" and "Right [lane change]" may be distinguished at any moment by providing the context, assuming the vehicle is crossing one line at a time. This add-on makes the mapping conflict-free. Users’ simplification of maneuvers suggests that their mental model of maneuvering does not match the used maneuver catalog. We encourage more research on users’ mental models for MBI since the user interface may be dramatically simplified to a few commands on the input side: **Straight** (*Straight*, *Start*), **Stop** (*Hold at Side-Strip*, *Hold at Stop-Line*), **Left** (*Turn L*, *Lane Change L*), **Right** (*Turn R*, *Lane Change R*), and **Parking** (*Parking*).

6.3.3 Limitations

This study’s command sets are limited by participants’ culture, language, and vehicle properties, specifically room and equipment. Our sample was mostly male, well-educated, and German, thus findings may change for a more diverse group. Future research could employ a more representative sample and address the user configuration of the system.

6.4 Conclusion

To address the need for control in future autonomous mobility services, we investigated how drivers might use mid-air gesture and voice commands for maneuver-based driving interventions. To increase participants' perception of space and sound, the research was done in a real automobile. Voice and gesture interaction fit MBI differently. Voice control is two seconds faster per command faster and more popular and accepted. Consequently, speech may be the main input for maneuver selection and mid-air gestures may serve as a backup interaction mechanism, e.g., in a noisy environment. We developed voice and mid-air gesture alphabets for MBI from participants' referent clusters. These command sets can be used as a foundation for future MBI system design.

Chapter 7

Control Intervention Modalities

This chapter is based on the following publications:

Henrik Detjen, Stefan Geisler, and Stefan Schneegass. "Maneuver-based Control Interventions During Automated Driving: Comparing Touch, Voice, and Mid-Air Gestures as Input Modalities". In: *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, 2020, pp. 3268–3274. ISBN: 978-1-7281-8526-2. DOI: 10.1109/SMC42975.2020.9283431

Henrik Detjen, Stefan Geisler, and Stefan Schneegass. "Driving as Side Task: Exploring Intuitive Input Modalities for Multitasking in Automated Vehicles". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. Ed. by Yoshifumi Kitamura, Aaron Quigley, Katherine Isbister, and Takeo Igarashi. New York, NY, USA: ACM, 5082021, pp. 1–6. ISBN: 9781450380959. DOI: 10.1145/3411763.3451803

In this chapter, we present two experiments that investigate the users' experiences of direct user interface modalities (voice, touch, mid-air gestures) for maneuver-based control interventions in two driving simulator studies. Thereby, we are interested in the general feasibility of these modalities and in the feasibility during various NDRAs (cf. *RQIII_2* – Which direct input modality is most feasible for expressing driving maneuvers?).

Future vehicles could provide alternative natural user interfaces (see earlier Chapter 6) for maneuver-based car control. Depending on users' NDRA, contactless interaction via voice or mid-air gesture control can be beneficial, e.g., when touch interfaces are not in reach yet, it is not clear *which input modalities are when are feasible* for such new control concepts and which not. Given the changing in-car activity context, when occupants want to intervene in the driving process, they must shift their attention to the new task, and the current activity must be interrupted. Such interference between NDRA and driving related activity (DRA) because of similar requirements for spatial/verbal cognitive resources (cf., [Wic02]) might lead to performance breakdowns. Thus, it is also crucial to understand the interplay between NDRA and control intervention modality.

While the definition [PS15], prediction [PRB16; Det20; HDB20; Hec+20], and automated recognition [Pec+19] of NDRAs, as well as their effect on take-over request performance [Rad+14; GBB15; Nau+18; Dog+19; Win+19], have been studied, but their effect in less critical multitasking scenarios like maneuver-based intervention has not. Generally, input modality switches for side tasks while driving may facilitate efficiency relative to unimodal situations and do not increase task completion time, according to Roider et al. [Roi+19]. These findings show that the side task's modality, i.e., the maneuver-based intervention's modality, not transition procedures, distracts from the primary activity. Consequently, during autonomous driving, the system should encourage modality switches between activities so users may benefit from each modality's efficiency and adaptability. For instance, it may be useful not to use voice control while listening to music or not to use touch control while being on a smartphone. To investigate the utility of different input modalities for MBI, we use the user-defined speech and mid-air gesture alphabet for MBIs from the previous chapter (Chapter 6) and integrate it with the recommendations from an internal expert workshop with $N = 8$

university staff members (see Section VII for the workshop materials). We compare contact-less interaction, i.e., voice and mid-air gestures as interaction modalities, with touch interaction (as a baseline) for MBIs and explore the feasibility of all input modalities in the context of NDRAs.

This chapter presents two experiments that investigate the users' experiences of natural user interface modalities for control interventions in two driving simulator studies. In the first study, we compare the general eligibility of our voice and mid-air gesture alphabet with the existing touch interaction concept as a selection mechanism for driving maneuvers. Thereby, we evaluate the three intervention modalities' usability, affective quality, induced load, and preference in a *single task context*. In the second study, we create situations with five likely NDRAs (being idle, eating, smartphone use, conversation, listening to music) where participants freely intervened in the driving process, using either touch, voice, or mid-air gesture interaction. We investigated interaction patterns and multitasking performance. Our investigations help us understand which interaction modes are generally viable and which are used naturally and in various NDRAs.

7.1 User Studies

To investigate the feasibility of MBI input modalities, we conducted two user studies. First, we present a study in a single task setting (Section 7.1.1), i.e., users were idle, watched the driving process, and then intervened with a maneuver command. This study aimed at collecting the users' subjective experiences with the interaction modalities in general – modality after modality. Second, we present a study in a multitasking setting (Section 7.1.2), i.e., performed a NDRA while they had to intervene in the driving process with maneuver commands with any of the three possible modalities. The second study aimed at collecting the modality preferences through observation of the used modalities for commands and by the situation, i.e., while performing different NDRAs. In the following, we describe both studies in detail, before we, for better readability, discuss their results together.

7.1.1 Experiment 1 – Single Task Setting

The investigation was done in the lab of the University of Applied Science Ruhr West. Participants controlled an autonomous car through touch, speech, and mid-air gestures via a driving simulator in a within-subject experiment ($N = 12$) with three repetitions/conditions – one per interaction type. Conditions were balanced.

Interaction Design

The maneuver catalog of [M S+10] was utilized for interaction tasks. Table 7.1.1 displays commands for all tested modalities.

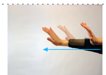
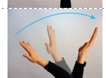
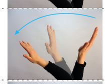
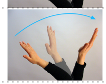
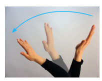
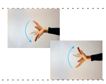
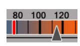
Action	**Initiation**	**Mapping per Modality**		
		Voice Commands [Det+19]	*Mid-Air Gesture Commands* [Det+19]	*Touch Commands / HUD Symbols* [KSB10]
Maneuvers				
Hold Stop-Line	System	not necessary	not necessary	
Follow Lane	System	not necessary	not necessary	
Hold Side-Strip	Human	stop [right], (pull ǀ right) over, hold [right [on the edge of the roadway]]		
Start	Human	set off, start [(drive ǀ straight ahead)], begin, straight, go [straight]		
Turn R	Human	turn right		
Turn L	Human	turn left		
Lane Change R	Human	[(move to ǀ select)] right (lane ǀ track), lane change [to the] right, [keep] right [ahead]		
Lane Change L	Human	veer [to the] left [and continue], [on] left lane, lane change [to the] left, (pass ǀ overtake ǀ pull ahead) left, [drive] left		
Straight	Human	[(go ǀ follow the road)] straight, continue [driving] straight [on]		
Parking (not tested)	-	-	-	
Parameters				
Speed	Human / System	increase ǀ decrease [speed], faster, slower, drive x [km/h]		
Eccentricity (not tested)	-	-	-	

Table 7.1: Maneuver command overview – Initiation and mapping by maneuver.

Figure 7.1: Experimental setup and interfaces – left: touch interface mounted on steering wheel, top right: participant performing a mid-air gesture, bottom right: HUD during voice condition.

For the command mapping, we used the voice and mid-air gesture alphabet form the previous chapter (cf. Chapter 6). We reproduced the touch interface developed by [KSB10] and employed the same visual design to convey system status and feedback for the other modalities through a HUD (cf. Figure 7.1). Color, border, and opacity indicate status. Non-selectable moves are less opaque but visible, whereas selectable movements are blue and opaque. Current actions have glowing yellow borders.

Setup

The experiment used a static driving simulator (see Figure 7.1). The simulator has three 42"-LG HD TV monitors, a wooden platform with a Sony play seat, a hardwood table with Logitech G920 pedals and steering wheel, and a wooden platform with a Sony play seat. The software *SILAB 5.0*[4] simulated

[4] https://wivw.de/en/silab

our driving scenarios. The researcher was a passenger while the participants drove to get acquainted with the situation, addressed their queries, and offered clarification.

Similar to the conduct-by-wire interface used by [KSB10], a 9"-tablet was installed on the steering wheel for touch interaction. Participants could choose driving maneuvers on this tablet. We adopted a WoZ strategy (cf. [DJA93] or [GW85]) for speech and gesture interaction to mimic the implementation. This setup lets us test interaction ideas without being bound to existing technology. Consequently, under the speech and mid-air gesture condition, the study was assisted by a second study assistant (referred to as "wizard"). The wizard analyzes participant activities. We told the wizard to ignore all user inputs except the ones from our voice and gesture alphabet. If a known command is detected, the wizard inputs commands into a wizard app interface, a remote duplicate of the tablet interface from the touch condition with an extra button to signal detection errors, such as an unfamiliar gesture. Every successful input from the participant or wizard led to feedback on the virtual HUD (cf. Figure 7.1). Feedback appeared for three seconds.

Driving Scenario

This experiment's driving route included highways and rural roads. The 20-km route took 15 minutes to travel at the speed limit (100-130 km/h). The scenario for participants was:

> "You are on the way home from work and stop at a highway rest area. A friend calls and tells you that he is standing on the side strip of another highway due to a car breakdown and needs your help. Because the friend cannot tell you the exact address, but you are familiar with the area, navigate with the help of the signs and waypoints. You use a cooperative driving mode, in which the car follows the road safely according to speed regulations at all times, but requires user input at specific decision points, e.g., if it should turn left or right".

The path has signage to the freeway. We might influence user choices by presenting this story. We created the track sections to repeat such choice moments (see Figure 7.2):

We marked the route using highway signs. By creating this scenario, participants needed decision points along the journey, provoking them to interact with the system. Participants encountered such decision points many times (see Figure 7.2):

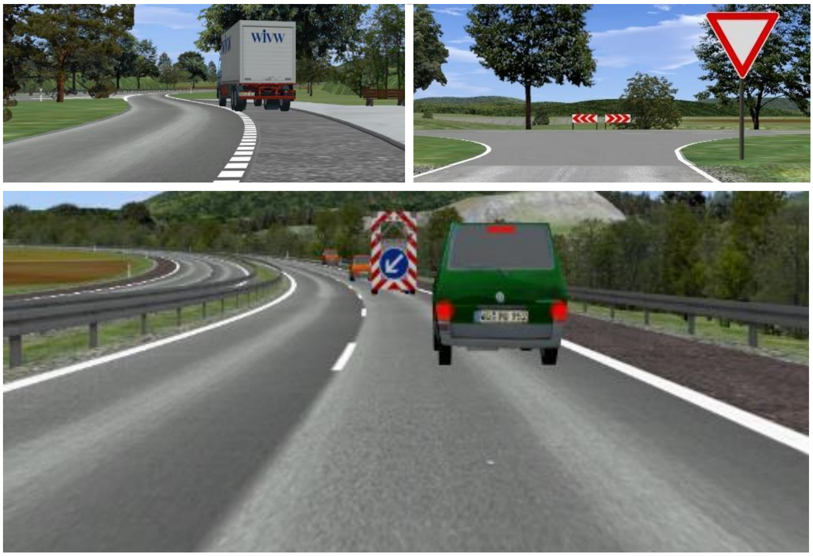


Figure 7.2: Exemplary situations on the test track that required users to intervene – top left: start maneuvers, top right: turn decision, bottom: overtaking maneuver.

1. From a parking area onto the highway requiring the user to start the ride and set the initial speed
2. Free highway driving (further input optional)
3. A construction site vehicle on the right lane behind leads to a traffic jam. The traffic is getting slower and slower, but the car follows the car

ahead at a certain distance, encouraging the user to adjust the distance (optional) and overtake the traffic jam by changing lanes and increasing the vehicle speed again. After a while, in case of no intervention, the co-driver (study director) encourages the user to overtake

4. Taking the highway exit ramp requiring a lane change
5. The car slows down and stops at a t-intersection. The car waits for the user to decide to go left or right (a sign indicated the right way shortly before, but we designed the track so that both directions lead back to the right way)
6. Free rural road driving (further input optional)
7. Another crossroad becomes a t-intersection due to a road accident that blocks the straight direction, forcing the user to take an alternative route and decide to drive left or right (again, we placed a sign indicating the right decision, but both navigation decisions lead to the right way)
8. From a parking area onto the highway requiring the user to change the lane start and increase speed
9. As the friend's broken-down car comes into sight, the co-driver (study director) informs the user who has to stop the car at the side-strip

In summary, we encouraged participants to intervene at least eleven times in the driving process, covering the maneuver set (cf. Table 7.1.1). Participants could perform any maneuver between decision points.

Measurements

Our research investigated input styles' perceived eligibility for cooperative driving. We compared the three input types' eligibility based on perceived usefulness, emotional state, induced load, and preference. We utilized the system usability scale (SUS) [Bro96] to assess input style usability (effectiveness, efficiency, satisfaction). The SUS is a 0-100 unidimensional score based on ten items with a 5-point Likert scale ($\sum i = 1^{10} 2.5 * rating(itemi)$). We employ a short version of the Positive and Negative Affect Scale (I-PANAS-SF) [Tho07] to measure participants' emotional responses to input styles. I-PANAS-SF scores are the mean values of two dimensions (positive/negative affect) with five items on a 5-point Likert scale. We utilized the NASA task load index's raw version (Raw-TLX) [HS88] to calculate an input style's induced workload. NASA-TLX analyzes input style load in six aspects (mental demand, physical demand, temporal demand, performance, effort, and frustration) on a 100-point scale with 5-point increments. Raw-TLX calculates the final score directly from the six dimensions instead of ranking all pairs first. Studies show that Raw-TLX is similarly effective [Har06] and it is also faster.

Procedure

Upon arrival, we informed participants of the study's goals and method (5min). According to the EU General Data Protection Regulation, we utilize their data strictly for scientific reasons and anonymously. Following the briefing, participants signed consent forms, and the study began. The 5-minute pre-questionnaire asked participants about age and linked experiences to technology and driving. We then described input maneuvers to participants using textual and visual material like in Table 7.1.1 (5min). The researcher openly asked participants whether they understood the orders and clarified if needed. After learning about the interaction styles, participants traveled in the driving simulator for the 15-minute scenario. The instruction and scenario were repeated three times for each input style in a counterbalanced sequence. For each run, participants completed usability, emotion, and induced load questionnaires (10min). Post-questionnaire on input style preferences (5min). The debriefing concludes the study (5min). Figure 7.3 illustrates the protocol. The study took about one hour and forty minutes.

Participants

We recruited twelve university students ($m = 10, f = 2$) that were mostly in the younger age groups (18–30 years: $n = 9$; 31–45 years: $n = 3$). As they held a license for nine years ($M = 9.17, SD = 3.24$), they were experienced drivers. Using a 5-point Likert scale, we asked participants how frequently they utilize a system to retrieve relevant pre-experiences in the following categories. We

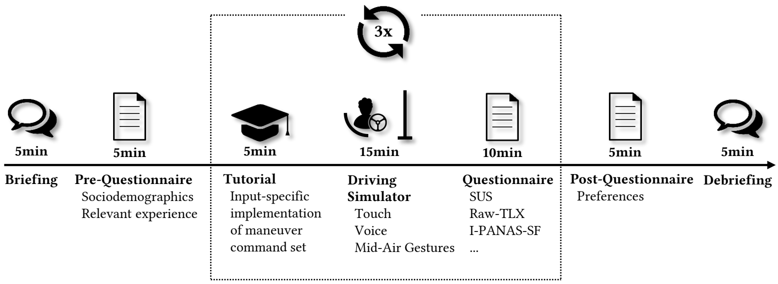


Figure 7.3: Experimental Protocol.

used the modus to aggregate answers for the same question into a single value. The participants had...

...moderate experience with automation systems such as cruise control, ACC with stop&go, ACC without stop&go, and lane-keeping ($M = 3.17, SD = 1.53$),

...rather high experience with simulation systems like driving simulators, computer games with a steering wheel, and video games with mouse and keyboard ($M = 3.5, SD = 1.38$),

...no experience with HUDs ($M = 1.0, SD = 0.0$),

...very high experience with touch-controlled systems such as smartphones, tablets, or touchpads ($M = 4.8, SD = 0.5$),

...no experience with mid-air gesture-controlled systems like MS Kinect or other infotainment ($M = 1.33, SD = 0.89$), and

...little experience with voice-controlled systems like smart home or car navigation ($M = 1.83, SD = 1.03$).

Results

We examined the three input modalities' performance, workload, emotional state, and user preference. We analyzed the experimental conditions' effects using a repeated-measures ANOVA with Greenhouse-Geisser correction (sphericity confirmed using Mauchly's test, $p > .05$) with Tukey HSD posthoc tests to distinguish effects by conditions. We employ bivariate correlation analysis after Pearson to examine aspects like the relation between load and preference.

Perceived Usability Figure 7.4 displays participants' system usability evaluations. Usability is "good" [BKM08] in all three scenarios. Input style did not affect usability ($F(1.01, 11.09) = 3.61, p = .70, \eta^2 = .14$).

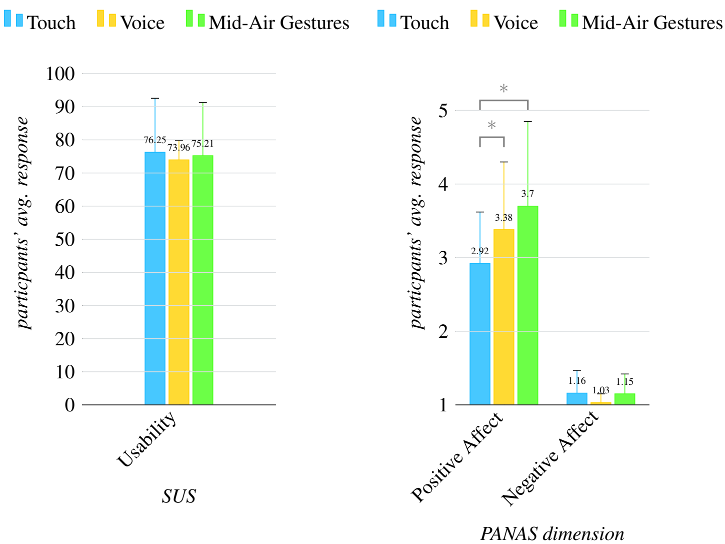


Figure 7.4: The SUS (left) and I-PANAS-SF questionnaire (right) results, with error bars representing standard deviation. All inputs are usable. Speech and mid-air gesture input improve participants' emotional state.

Emotional State Figure 7.4 illustrates participants' emotional state assessments. Negative emotions are low, whereas pleasant emotions are neutral to high. Input style had a significant main effect on positive ($F(1.01, 11.91) = 3.22, p = .1, \eta^2 = .23$) but not negative emotions ($F(1.34, 14.76) = 9.84, p <$

$.005, \eta^2 = .47$). The input style's influence on positive emotional state is medium ($f = .53$) after Cohen. For positive affective states, posthoc tests show that mid-air gestures and voice lead to significantly higher ($p < .05$) ratings than the touch condition.

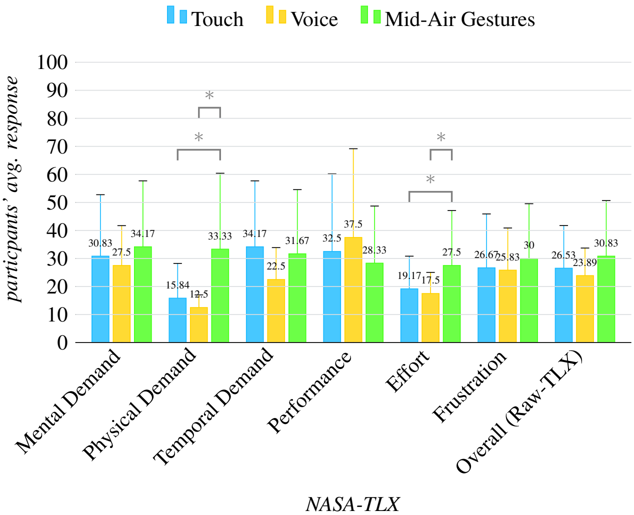


Figure 7.5: NASA-TLX responses (Raw-TLX score), error bars indicating standard deviation – Mid-air gestures lead to higher physical demand and higher effort than touch and voice control.

Workload We discovered no significant influence on the mean Raw-TLX load ($F(1.33, 14.58) = 2.06, p = .15, \eta^2 = .16$). We observed no impacts on the TLX subscales (see Figure 7.5) for Mental Demand ($F(1.33, 14.58) = 0.55, p = .58, \eta^2 = .05$), Temporal Demand ($F(1.33, 14.58) = 1.62, p = .22, \eta^2 = .13$), Performance ($F(1.33, 14.58) = 0.79, p = .49, \eta^2 = .07$), and Frustration ($F(2, 22) = 0.68, p = .52, \eta^2 = .06$). Physical Demand ($F(1.33, 14.58) = 6.13, p < .05, \eta^2 = .36$) and Effort ($F(2, 22) = 3.97, p < .05, \eta^2 = .27$) had significant impacts with medium effect sizes after Cohen ($fPhysicalDemand = 0.75; fEffort = 0.61$). Posthoc tests show that mid-air gestures are physically harder than speech or touch interaction and have a

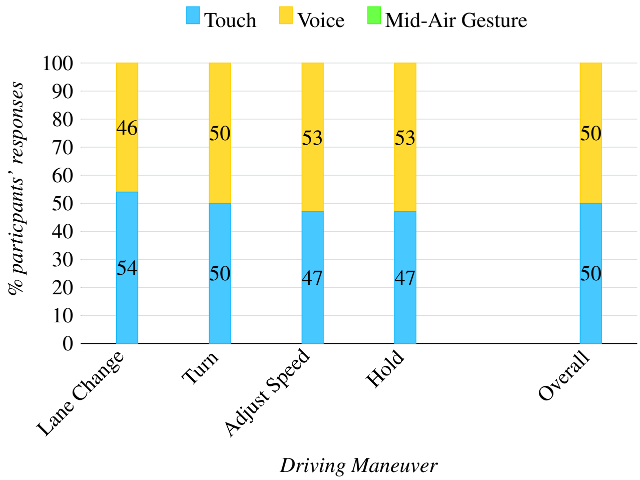


Figure 7.6: Overall user preference by maneuver type – Users favored either voice or touch interaction over mid-air gestures.

greater perceived interaction effort ($p < .05$).

Interaction Errors We observed how often participants made an interaction mistake, e.g., performed a non-existing mid-air gesture or voice command, or pressed a disabled button. In sum, they made only six mistakes. Touch and voice interaction had only one mistake each, whereas mid-air gesture interaction counted four errors.

Influence of Experience There was no significant correlation between participants' experience (driving, automation, HUD, gaming, input style) and dependent variables (load, usability) in the conditions, except for experience with touch controls.

Preferences We asked which input modality participants preferred for each maneuver and in general. Answers are consistent across maneuvers and similar to the general tendency: Participants preferred either touch or voice over mid-air gestures (see Figure 7.6).

7.1.2 Experiment 2 – Multitasking Setting

In a follow-up investigation ($N = 20$), we used the same driving simulator setup to examine the control intervention modality in *multitasking situations*. We expect that (1) the NDRAs would impact control intervention input modalities choice and (2) the selected modality would vary from the other activity's modality. Participants executed five NDRAs scenarios in a counterbalanced within-subject design. In each scenario, they intervened four times in the driving process at the decision point of a small test track (reduced track from the previous experiment). They could use voice, touch, or mid-air gestures for each intervention. Overall, this equals 20 choices per participant (4 choices x 5conditions) or 80 choices per condition (4 choices x 20 participants).

Task A: Driving-Related Activity

We informed participants they would ride a safe driving vehicle (cf. autonomous driving during SAE level 3–5) in a cooperative driving mode that required their control on maneuver level. We advised riders to follow this protocol to intervene in autonomous driving: A1) start the car (*start maneuver*), A2) drive onto the motorway from the rest area (*lane change maneuver*), A3) exit the highway at the next rest area (*lane change maneuver*), and A4) park at a rest area (*park maneuver*). Participants could pick speech, touch, or mid-air gestures for these maneuvers. We chose these modes because they enable direct control. Further, we employed the user-defined command set for speech and mid-air gesture interfaces (cf. previous Chapter 6) and a maneuver-board interface on a touchpad for touch interaction identical to [KSB10].

Task B: Non-Driving-Related Activity

We reviewed frequent activities and their possible influence on driving-related interventions based on research on predicted NDRAs (cf. [HDB20; DPS20; PRB16]). We then chose five likely activities to engage people in diverse ways. We provided participants with the following instructions for the chosen tasks in addition to Task A (cf. Table 7.2).

NDRA	Additional Instructions	Resource Involvement
Do Nothing	-	-
Eating	“Please choose one of the following snacks [saltines, crackers, flips] to eat while driving. Please take the entire bowl and don’t put it down anywhere.”	Manual demand, and limited ability to speak
Smartphone	“Please pick up your cell phone and go to YouTube to watch a cat video while driving.” End of Smartphone situation (if video too long): “Okay, that’s it! Please stop the video and put your smartphone aside.”	Manual and visual demand, high cognitive involvement
Conversation	“And now I’ll distract you a bit with a conversation...” “What are you studying here with us? ...why?”, “Which was your favorite module so far? ...why?”	Auditory demand, cognitive involvement
Music	“Now please start with the echo dot music of your choice.”	Constant auditory demand

Table 7.2: Condition-specific instructions and multitasking demands.

Setup

The investigation employed the SILAB 6.0 driving simulator from the previous experiment with audio (see Figure 7.7). Engine noise was low enough to allow conversation and music. A Microsoft Surface Pro touch tablet was mounted on the steering wheel to enter maneuvers. We simulated automated system behavior using the Wizard of Oz (WoZ) approach [DJA93]. A backstage “wizard” interpreted touch, voice, and gesture input. We told participants they would use an actual system prototype. No participant said that (s)he noticed the mediation after the experiment. The visible researcher (not the wizard) prepared the conditions and served as the co-passenger in the conditions *Eating* (reaching food) and *Conversation* (asking questions).

Figure 7.7: Experimental Setup – The wizard simulated the system while the participant sits in the driving simulator’s primary seat and the visible researcher next to her or him.

Procedure and Measurements

The visible investigator briefed participants and requested informed consent. Task A (intervention) began with a brief introduction to the driving simulator and instructions. To practice control modalities, they overtook vehicles on a tutorial track. In a counterbalanced within-subject design, each participant completed five experimental conditions (same route). The visible investigator started each condition with standardized Task B instructions. He departed in conditions or participated as a co-passenger in *Eating* and *Talking*. During non-driving-related activities (Task B), people intervened four times (see Task A) in the autonomously driving vehicles' behavior (operated by the "wizard"). Participants could use touch, voice, or mid-air gesture control. The research protocol was filled out by a third investigator. Each condition took 2 minutes and after completion, participants did the NASA-TLX ([HS88]; 6 questions on a 100-point slider scale) questionnaire to assess their subjective workload. After all conditions, participants completed a general feedback and modality preference questionnaire and got debriefed. It took 30 minutes to complete the study.

Participants

We conducted the experiment at the University of Applied Sciences Ruhr West lab. Twenty computer science students ($m = 17; f = 3$) aged on average 22.45 ($SD = 4.55; Min = 18; Max = 33$) participated.

Results

We examined modality shares and consistency for each NDRA. We also looked into subjectively rated interaction workload and input modality preferences.

Modalities' Shares Table 7.3 displays interaction frequencies. To investigate the effect of a non-driving activity on the modality choice for a driving-related intervention, we use Pearson's chi-squared tests (goodness of fit) to compare the distributions of *Eating*, *Smartphone*, *Conversation*, and *Music* conditions to the baseline distribution *Do Nothing*.

Activity	Interaction Frequency *n (%)*				Interaction Variability *mean, sd*	
	Voice	Touch	Mid-Air Gesture	Σ	Flexibility	Change Ratio
Do Nothing	19 (24)	35 (44)	26 (32)	80 (100)	.25 ± .3	.23 ± .31
Eating	13 (16)	39 (49)	28 (35)	80 (100)	.25 ± .30	.22 ± .27
Smartphone*	19 (24)	45* (56)	16* (20)	80 (100)	.28 ± .30	.25 ± .30
Conversation	22 (27)	39 (49)	19 (24)	80 (100)	.18 ± .34	.15 ± .31
Music*	10* (12)	43 (54)	27 (34)	80 (100)	.23 ± .34	.23 ± .36
Overall	83 (21)	201 (50)	116 (29)	400 (100)	.24 ± .32	.22 ± .31

Table 7.3: Distribution of modalities' (voice, touch, mid-air gestures) use frequency by condition – contrast of distributions among baseline (*Do Nothing*) and other activities, $*$-signs show significant differences with $p < .05$. Flexibility (cf. equation 7.1) and Change Ratio (cf. equation 7.2) reflect variability across modality choices.

The distribution modalities in the *Eating* ($\chi^2(2, N = 80) = 2.51, p = .29$) and *Conversation* ($\chi^2(2, N = 80) = 2.82, p = .25$) conditions are not distinct from the baseline, whereas *Smartphone* ($\chi^2(2, N = 80) = 6.70, p < .05$) and *Music* ($\chi^2(2, N = 80) = 6.13, p < .05$) significantly differ. Bonferroni-corrected binominaltests ($p < .025$) reveal that participants chose significantly less voice interaction in the *Music* condition and significantly more touch and less mid-air gesture interaction in the *Smartphone* condition. Generally, participants used touch input (50%) as frequently as voice (21%) and mid-air gesture control (29%) combined.

Modalities' Consistency We analyzed two indices of modality choice consistency: a) *Flexibility* and b) *Change Ratio* per condition. The interaction Flexibility and Change Ratio give strong and easy-to-interpret indices of modality choice fluctuation over time in a collection I of n subsequent interactions (in our case: $n = 4$). The Flexibility indicator displays the usage of unique modalities relative to all interaction modes in the conditions, showing whether participants adhere to one interaction type over time (Flexibility$(I) = 0$) or utilize all interaction modes (Flexibility$(I) = 1$). For a collection of interactions I with M alternative modalities, we define Flexibility:

$$\frac{\{I \cap M\}}{M - 1} - \frac{1}{M - 1} \tag{7.1}$$

The Change Ratio for a set I of n consecutive interactions is the number of times a modality choice m is different from the prior modality:

$$\sum_{i=1}^{n-1} \frac{m_{I_i} \neq m_{I_{i+1}}}{n-1} \tag{7.2}$$

The Change Ratio indicates overall interaction variability over time regardless of the specific modality. For instance: If participant A interacts in the order $\{Voice \rightarrow Touch \rightarrow Voice \rightarrow Touch\}$ and participant B in the order $\{Voice \rightarrow Touch \rightarrow Touch \rightarrow Touch\}$, both have the equal Flexibility (A: 0.5, B: 0.5), but A's Change Ratio (A: 1, B: 0.33) is higher. Table 7.3 illustrates sample variability. Participants switched modalities around every fourth time ($M_{ChangeRatio} = .24, SD = .32$) and generally used one or two interaction modes ($M_{Flexibility} = .22, SD = .31$).

Multitasking Workload Figure 7.8 exhibits NASA-TLX dimensions. A repeated-measures ANOVA (sphericity confirmed using Mauchly's test, $p > .05$; degrees of freedom corrected after Greenhouse-Geisser, if $\varepsilon <= .75$, otherwise after Huynh-Feldt) was conducted to analyze the conditions' workload. We used Bonferroni-corrected posthoc tests to compare conditions (see Figure 7.8).

Examining the NASA-TLX subscales, we found no significant effects for Physical Demand ($F(1.69, 32.18) = 2.54, p = .1, \eta^2 = .12$), Temporal Demand ($F(2.28, 43.23) = 1.26, p = .3, \eta^2 = .06$), and Frustration ($F(4, 76) = 1.58, p = .19, \eta^2 = .08$). For Mental Demand ($F(4, 76) = 5.99, p < .001, \eta^2 = .24$), Performance ($F(4, 76) = 3.61, p < .05, \eta^2 = .16$), Effort ($F(2.67, 50.71) = 4.94, p < .01, \eta^2 = .21$), and Overall Score ($F(4, 76) = 4.55, p < .01, \eta^2 = .19$), we found significant and strong effects after Cohen ($f_{MentalDemand} = 0.56; f_{Performance} = 0.44; f_{Effort} = 0.52; f_{Overall} = 0.49$). Posthoc testing shows that the *Smartphone* condition increases perceived load more than the *Do Nothing* condition. Modality choices did not significantly correlate with the workload.

Preference After the experiment, participants gave voice ($M = 4.30, SD = 0.73$), touch ($M = 4.00, SD = 1.26$), and mid-air gestures ($M = 3.70, SD = 1.22$) high ratings. A repeated-measures ANOVA (sphericity confirmed using

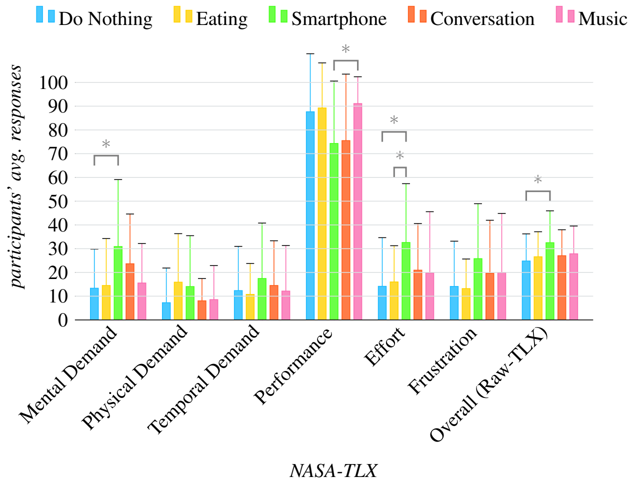


Figure 7.8: Multitasking workload (NASA-TLX Questionnaire) error bars indicating standard deviation, significant differences with $p < .05$ are marked through $*$-signs – The smartphone condition affects mental demand (>nothing), performance (<music), effort (>nothing, eating), and perception (>nothing).

Mauchly's test, $p > .05$) shows no effect of modality on rating ($F(2,38) = 1.81, p = .18, \eta^2 = .09$). Hence, there is no clear preference for a particular modality yet visual inspection shows a non-significant trend with voice being higher rated than touch and touch higher than mid-air gestures.

7.2 Discussion

We will describe both experiments' results, suggest opportunities for further research, and highlight limitations.

7.2.1 General Feasibility of Modalities

In the first experiment, we examined the *general* feasibility of various NUIs for MBI. All input settings yielded good vehicle control system usability ratings. These results suggest that the tested input modality does not affect the control intervention's usability in a single-task setting. Nonetheless, mid-air gestures caused more load and interaction effort. So, if intervention happens frequently, mid-air gesture interaction quality may decline quicker than voice and touch control due to the increased physical burden. In our user study, the intervention task was not time-critical and within a limited time frame. Future research might examine how repetition affects input modalities' perceived usefulness over time.

Our participants had low-to-moderate experience with automation systems, HUDs, voice or mid-air gesture-controlled systems, and high experience with touch-based systems. Experience with touch interaction lowered the task load and negative emotions. Yet, it also lowered load in the mid-air gesture condition. This indicates that participants could apply their more developed mental models of touch gestures to mid-air motions, such as smartphone swipes, which are analogous to lane change mid-air gestures. Future studies may address these symbiotic effects. Touch interaction is more familiar, hence our results may be predisposed. This could also explain why voice and mid-air gestures evoke greater positive emotional reactions than touch – participants might perceive them as more novel and exciting.

Based on user feedback, mid-air gestures are not the preferred input mechanism. Therefore, voice and touch interaction appear to be more viable options. Each has its advantages and disadvantages. For instance, voice interfaces offer a hands-free experience in the car, but external noises or other passengers may interfere with the interaction. Touch, on the other hand, is more dependable and easier to understand and implement, but it requires the user to interact at a specific location.

In conclusion, we believe that *combining* voice and touch interactions is beneficial for automated driving. Both methods should be prioritized as primary ways of interacting with the system, as they offer ease of use, low cognitive load, and are favored by the majority of users.

To ensure reliable interaction and inclusion, future vehicles should have multiple control options, such as voice and touch. Further research can explore how effective these input styles are in various usage contexts such as teleoperation.

7.2.2 Feasibility of Natural Input Modalities in Non-Driving-Related Activity Context

In the second experiment, we looked into the *situation-specific* feasibility of different NUIs for MBI. For this experiment, we allowed participants to choose their own modality switches instead of controlling them.

Our hypothesis was that (1) the use of NDRAs would impact the choice of input modalities for control interventions and (2) that the modality selected would differ from the one used for the main task. Our experiment fully confirmed the first assumption and partially confirmed the second.

We found that participants utilized more than one interaction modality per condition in terms of multitasking modality switch patterns (Change Ratio > .22 / Flexibility > .24). These changes could be explained by the study of Roider et al., which shows that transitioning between interaction modalities can increase efficiency compared to unimodal conditions. Further, we observed that the Eating (chewing) and Music (acoustic interference) conditions lead to comparatively less voice interaction, while mid-air gesture input is less used for the Smartphone (manual demand) and Conversation (supporting gestures) conditions. These findings suggest that users tend to avoid resource conflicts by occupying a modality for control intervention, which is in line with our second hypothesis. Therefore, future vehicles should provide redundant control mechanisms to accommodate various non-driving-related activities during a trip. The system could promote the most feasible modality choice by tracking the occupants' activities. Furthermore, future studies could investigate the promotion of side-task interaction for common NDRAs and develop strategies to train users to maximize the use of each input modality from the beginning, for instance, through User Onboarding.

During the smartphone condition, we noticed a significant rise in touch interaction, which contradicts the second assumption. Furthermore, we discovered that the smartphone condition differs from the baseline in terms of overall multitasking load. Based on the multiple resources theory [Chr08], the high combined spatial (typing/watching) and verbal (typing/listening) demand on all processing stages in the smartphone condition could explain the results. As the use of smartphones is the most anticipated NDRA in automated vehicles, it will be challenging to design systems that *shift users' attention* and facilitate the switch to other tasks. Future concepts may consider integrating the use of smartphones in multitasking procedures (cf. Wintersberger et al. [Win+19]).

Due to the higher total multitasking workload in the smartphone condition, users may have fewer cognitive resources available to use non-familiar interaction styles. This could explain the tendency to stick to known touch interaction patterns, despite their mid-ranking in the users' overall modality preferences. Future research could explore task switching efficiency, as an already demanding modality might decrease interaction efficiency (cf. Roider et al. [Roi+19]).

It is worth noting that in comparison to the first experiment, mid-air gestures performed better in the second experiment. This suggests that allowing users to choose the modality that suits a particular situation leads to a better perception of mid-air gestures.

7.2.3 Limitations

The studies we presented had a relatively small and homogeneous sample size, mainly consisting of young male students with a strong technical background. To strengthen the generalizability of the findings, it is imperative to conduct future research with a larger and more diverse user sample.

It is important to note that we used a WoZ system in our studies. The error rate of voice and mid-air gesture recognition systems would be higher in a real implementation, and therefore, findings might vary.

Moreover, social norms play a significant role in the interaction behavior of individuals, and factors such as eating while talking to someone might be considered impolite. Additionally, using an "expressive" interaction style like mid-air gesture or voice interaction might be socially inhibited in some contexts.

7.3 Conclusion

This section explored direct and natural interaction methods for MBI in single-tasking and multitasking scenarios. In particular, we discovered:

- in the single-task setting, input modalities did not significantly impact general usability, with contactless interaction (voice, mid-air gestures) being perceived more positively
- in the single-task setting, mid-air gestures were the least preferred option and resulted in a higher task load
- in the multitasking setting, we observed that users tend to avoid using an input modality that is already occupied when performing a task, such as using voice interaction less frequently while eating or listening to music
- in the multitasking setting, when the workload is high, users tend to stick to a specific interaction style, as we found with touch interaction during smartphone use

In general, we suggest implementing control concepts that rely on multimodal interfaces to accommodate the various situations and activities that may arise with autonomous vehicles. While further research is needed to improve vehicle multitasking support, our findings can help designers consider the context of interaction when designing new vehicle interiors and interfaces – thereby addressing users' need for control.

Part III – Summary

In this part, we focused on the future implementation of driving-related interventions by examining how the driving activity may evolve. Specifically, we created and assessed direct, natural ways of interacting with maneuver-based control commands (such as “turn left” or “stop”).

In our user-centered elicitation process, we have developed voice and mid-air gesture commands (Chapter 6) to extend the previous works on MBI [Fra+12; KSB10] interfaces, which were mostly touch-based. Voice control is generally faster and preferred by most users, with higher acceptance rates. By clustering users’ mental modal of formulating intervention commands, we believe that the catalog of commands can be reduced, given that users often use the same commands for similar maneuvers.

Regarding different input modalities (Chapter 7), usability seems to be comparable, but mid-air gestures may lead to a higher task load. Contactless interaction, on the other hand, leads to a more positive emotional perception of the interaction. In the context of different NDRAs, users generally avoid using modalities that work on the same resources, such as voice interaction becoming less frequent when listening to music. However, the overall workload and experience with the modality may moderate this pattern, with users tending to stick to a known interaction style during high multitasking workload. Users generally prefer voice and touch interaction, while mid-air gestures, as the only input option, were rated less acceptable.

Overall, our work is a first step towards the *activity-optimized development* of in-car HMIs for driving-related control interventions in AVs with natural input modalities, helping to overcome the gulf of execution in automated driving.

IV

Bridging the Gulf of Evaluation in Automated Driving

OUTLINE

During automated or autonomous driving, accurately evaluating the performance of the driving task depends on the system's capability to communicate its present state and the users' ability to comprehend and perceive that state, as depicted in Figure 7.9.

There are various obstacles that impede a satisfying user experience and can lead to discomfort, frustration, or even safety hazards. For example, distraction or intransparency on the perception level and non-understanding or non-predictability on the interpretation level. To reduce this *gulfs of evaluation* (cf. Norman's seven stages of action model [Nor08]), it is important for automated vehicles to prepare users and provide feedback/feedforward so that users can evaluate the driving task performance. With AR, e.g., through in-vehicle displays (HUD or windshield display (WSD)), there are new possibilities to communicate the vehicle's ability and state. In this part, we therefore investigate the potential of AR in terms of *understandability* of automated driving functions through User Onboarding (Chapter 8). Further, to improve situational awareness and *predictability*, we examine the effect of AR displays with vehicle motion intentions (Chapter 9) and of hazard warnings (Chapter 10) on UX and safety during autonomous driving.

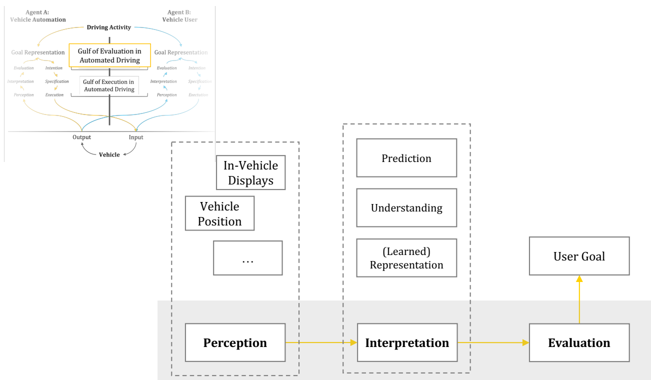


Figure 7.9: *Gulf of Evaluation in Automated Driving* – When driving automated or autonomously, the users' goal is, e.g., to feel comfortable and safe in the situation (needs). The *evaluation* of the vehicle's driving actions depends on the users' mental model of how to reach the goal (e.g., "using the car feels safe") or what is required to reach it. The evaluation depends on the correct perception and interpretation of the vehicle's actions in the environment. The *interpretation* of the vehicle state is formed through users' cognition, emotion, and behavior (e.g., "this turn feels comfortable"). The interpretation itself is acquired through users' *perception* of display information, vehicle speed, etc.

Chapter 8

User Onboarding

This chapter is based on the following publications:

Henrik Detjen, Robert Niklas Degenhart, Stefan Schneegass, and Stefan Geisler. "Supporting User Onboarding in Automated Vehicles through Multimodal Augmented Reality Tutorials". In: *Multimodal Technologies and Interaction* 5.5 (2021), p. 22. DOI: 10.3390/mti5050022

In this chapter, we present 1) insights from an online survey into the current use of vehicle assistant systems and their comprehensibility for users, and 2) a real-world study in a Tesla, where we compare the performance and user experience of automated parking between an AR smartphone app and a manual-based onboarding processes with inexperienced users. Thereby, we show where users have training needs regarding vehicle automation and provide a real-world evaluation of AR User Onboarding regarding mental models and trust (cf. *RQIV_1* – Can augmented reality benefit vehicle automation User Onboarding processes?).

Marketing often exaggerates the capabilities of the latest assistant systems, known as “autonowashing” [Dix19], leading to potentially dangerous mental models of assistant systems. Insufficient understanding of a system can lead to *negative user experiences* and rejection, causing inefficient interaction and risky behavior. A strong mental model can help detect problems faster [Gas+20; SLJ17] and increase perceived trust [DB17]. Further, *practical experience* is necessary to avoid complacency with automation failure [Ann12] but only if one experiences automation boundaries [Mat+15]. Hence, educating users about automation capabilities is crucial.

Onboarding is the process of introducing new employees to necessary knowledge, skills, and behavior [BE11] to overcome initial hurdles Crumlish and Malone. In software development, *User Onboarding* motivates new users to become regular users [Sin11]. User Onboarding is divided into three phases [Ren+14]: Onboarding, help and support, and re-entry. We focus on the first phase in this chapter. For a successful Onboarding process, aka “quick wins” and “aha experiences” [Hul14], users must recognize the system’s value quickly [Hul14] and be trained on how to achieve their goals faster [Bal16]. To apply effective User Onboarding processes, users must recognize the added comfort provided by automation and learn how to use the assistant system for that purpose, which also contributes to calibrating trust to a sufficient level (cf. Section 2.4.3).

When onboarding new users in automated vehicles, the traditional method involves providing them with *text-based manuals*. However, these manuals become obsolete quickly, especially in cases where dynamic software updates change the vehicle’s functionality. To address this issue, we explore the potential of using *multimodal augmented reality tutorials* on a smartphone to educate users about automated driving functions.

This AR approach can improve the User Onboarding because it creates a richer user experience through a combination of text, video, and audio elements and can communicate information locally, e.g., by overlaying the windshield with driving tutorials or by highlighting interface elements in the car interior. The Cognitive Theory of Multimedia Learning [May05] suggests combining information from auditory and visual channels improves memorization [PC+06]. Augmented reality can enhance learning by providing virtual information coupled with real-world objects. The use of AR elements can effectively convey information quickly and accurately, precisely when and where it is needed [She03; Lee12]. Thus, AR can provide an interactive and immersive experience that can enhance one's understanding of processes [MS14], e.g., for assembly tasks [Bla+17].

Research conducted by Mahdi Ebnali, R. Lamb, and Razieh Fathi [MRR20] analyzed various levels of interaction fidelity (video, low-fidelity virtual reality, and high-fidelity virtual reality) in vehicle assistant systems. The study showed that the level of tutorial interaction fidelity positively impacted task performance and trust over time. Similar results were observed in other studies involving simulator/video tutorials [Mah+19], VR and AR training [SPO18], and interactive education methods, such as quizzes [For+19; Yan+20]. The more interactive and engaging the pre-use tutorial, the better the user's performance in the future. Overall, these findings emphasize the potential of utilizing multimodal User Onboarding techniques for automated driving. However, currently, automated driving research focuses on the use, not the training phase. The potential of Augmented Reality applications for User Onboarding in automated vehicles has not been investigated so far.

To address this, we conducted two subsequent studies. In the first study, in order to identify any misunderstandings modern vehicle users may have about automation, we conducted an online survey to determine where they have encountered confusion. From this survey, we selected candidates to participate in a multimodal AR User Onboarding process. In the second study, we then conducted a real-world study with inexperienced users, testing the use of Tesla's "autopark"-assistant with previous Onboarding through either an AR app or the more traditional text-based manual. Our results provide valuable insights into vehicle users' current understandings of assistant systems and where they see a need for training, as well as a real-world evaluation of a multimodal AR User Onboarding process. These findings will aid vehicle designers in integrating and establishing new User Onboarding processes for autonomous vehicles.

8.1 User Studies

We carried out two consecutive studies to identify automation features that are well-suited for User Onboarding, followed by a second real-world experiment to assess various Onboarding approaches.

8.1.1 Study 1 – Online Survey on Vehicle Automation Use & Competence

We conducted an online study to comprehend users' misunderstandings regarding contemporary vehicle automation. For this, we picked six current ADAS and inquired if the participants had utilized them and, if so, how they fared.

Method & Procedure

The survey was accessed from home through the SoSciSurvey platform[5]. Prior to answering the questionnaires about their experience with various automation technologies, participants were given an overview of the study's purpose and informed about how their data will be used in accordance with the EU General Data Protection Regulation [EUR16]. Once they provided their informed consent, they were presented with six modern driver assistant systems to evaluate: 1) ACC, 2) active lane keeping assistant (aLKA), 3) active lane change assistant (aLCA), 4) traffic jam assistant (combination of ACC and aLKA), 5) remote parking, and 6) automated parking. Inquiring about both systems, we combined the first two questions as we were interested in their level 2 automation combination. For each assistant system, we posed questions that covered various aspects such as the frequency of assistant use, level of trust at first contact and presently, the need for training, incomprehensibility, experienced misunderstandings, and hidden functions noticed only after using the system for a while. We also inquired about the general trust in automated

[5] `www.soscisurvey.de`

vehicles and behavior in obtaining information about new functions in the vehicle. Finally, we debriefed the participants on the study's aims and expressed appreciation for their participation.

Participants

We conducted a study with a total of 58 participants ($m = 54, f = 3, NR = 1$) and had an average age of 41.11 *years* ($SD = 12.42$). To recruit participants, we contacted special interest groups on Facebook, such as "W213 S213 Mercedes Benz E-Klasse Deutschland", where we believed members may have access to a car with modern assistant systems. The majority of respondents (81 %) personally owned a vehicle equipped with at least one of the ADAS we were interested in studying, with their cars mostly being built in 2017 ($SD = 1.9$ years). We also measured participants' technical affinity with the ATI-S scale [TCD19], which consisted of four items on a 6-point Likert scale, and found that it was relatively high ($M = 4.53, SD = 0.95$).

Results & Discussion

	ACC ∪ aLKA	**aLCA**	**traffic jam assistant**	**remote parking**	**automated parking**
Persons who own it $n(\%)$	44 (75)	17 (29)	27 (47)	11 (19)	45 (78)
Owners who use it…					
…weekly	37 (84)	9 (53)	17 (63)	2 (18)	16 (36)
…monthly	2 (4)	3 (18)	4 (15)	1 (9)	5 (11)
…<monthly	3 (6)	5 (29)	3 (11)	5 (46)	15 (33)
…never	2 (4)		3 (11)	3 (27)	9 (20)
Trust at first contact $M(SD)$	3.5 (1.17)	3.47 (1.17)	3.26 (1.25)	3.64 (1.2)	2.96 (1.6)
Trust today $M(SD)$	4.23* (0.83)	4.41* (0.71)	4 * (1.14)	4.36* (1.02)	4.16* (1.1)
Training Needs	29 %	29 %	25 %	36 %	28 %
Incomprehensibility	59 %	52 %	51 %	36 %	64 %
Operation	9 %	5 %	25 %	9 %	31 %
System Understanding	20 %	17 %	3 %	9 %	11 %
System Boundaries	46 %	47 %	33 %	36 %	33 %
Experienced Misunderstandings	7 %	0 %	8 %	0 %	7 %
Hidden Functions	0 %	0 %	0 %	0 %	0 %

Table 8.1: Results from the online survey – * Perceived trust levels significantly increased ($p < .05$) over time based on a dependent t-test (homogeneity of variances checked via Levene-Test).

The survey results are summarized in Table 8.1.1. Participants expressed a high level of trust in assistant systems, which increased significantly over time.

However, despite this trust, they reported a need for training and found most assistants to be incomprehensible. This mismatch between trust and expertise can lead to misunderstandings that negatively impact the overall user experience and even lead to dangerous situations while using a car. The reported misunderstandings included unexpected error messages (*"spontaneous error messages, not trackable"*), situations where assistant usage was not possible, and unexpected behavior of the assistant system (*"Had to intervene in the automatic parking process. The car could not pass a pillar. Parking too hard and too fast."*). None of the participants reported discovering a "new" function, indicating that either all functions were evident from the start, or they did not further educate themselves about the system's capabilities. Thus, it is crucial to educate users of automated vehicle functions from the outset to address the reported training needs and ensure a safe and positive experience.

Although all assistant systems could potentially improve User Onboarding processes by around 30%, we chose the automated parking assistant for this chapter for several reasons. Firstly, participants expressed the least amount of initial trust in this assistant system, and we wanted to improve that. Secondly, automated parking is not yet widely implemented in middle-class cars so that we could recruit first-time users more easily. Finally, participants reported the most difficulty understanding automated parking, with 31% of the users saying they didn't fully comprehend the vehicle's behavior. Therefore, focusing on User Onboarding for automated parking would have the most significant impact.

8.1.2 Study 2 – Real-World Autopark Onboarding Experience with AR

We conducted a study to determine how multimodal AR User Onboarding affects the user experience with an automated parking assistant. Our goal was to build on previous simulator-based research, which focused on trust and task performance, and design an experiment that would test the User Onboarding process in real-world conditions. To achieve this, we conducted a study with a Tesla S 60 and its "autopark"-assistant, using a smartphone application that followed Tesla's design guidelines and presented the autopark process in a multimodal AR environment. We recruited 26 first-time users and used a between-subjects experiment to compare their experience using either the multimodal *AR* app (*AR group*) or the text-based manufacturer manual (*Manual group*). We didn't include a non-onboarding group since previous research has shown the benefits of system tutorials, and our focus was on comparing the different interaction modalities.

Stimulus Material: AR User Onboarding Prototype vs Paper-based Handbook

To engage in the autopark process, users had to follow these steps::

1. Slowly pass through the parking space until a "P" appears in the instrument cluster
2. Stop the vehicle
3. Engage reverse gear
4. On center screen, press button "Start"

Figure 8.1 illustrates the steps 1 and 4 of this procedure. The way in which users interact with this spatially distributed process may pose a challenge for those who are new to it. To examine the impact of our User Onboarding application utilizing AR technology on both user performance and experience, we conducted a comparison with the manufacturer's manual. Although both stimuli provide the same information regarding the autopark system, the manual[6] presents a two-page textual description of the procedure. In contrast, the AR app prompts users to consume the procedure information at the designated location. It does this by superimposing a video overlay on the instrument cluster display that shows the future state during the autopark process (notified by the "P" notification), highlighting the reverse gear, and augmenting the center display with the future state (activated by the "Start" button). The app

[6] https://www.tesla.com/sites/default/files/model_s_owners_manual_north_america_en_us.pdf

Figure 8.1: User interfaces during autopark procedure – left: instrument cluster screen; right: center screen. Elements relevant for interaction marked with blue circle.

Figure 8.2: Multimodal AR tutorial – The app introduces the user to the spatially distributed (instrument cluster and center screen) interaction process.

provides the ability to reverse steps and does not contain spoken instructions. However, auditory feedback is utilized for interface elements, such as after completing a step or pressing a button. Figure 8.2 provides an overview of the tutorial in the AR app.

Experimental Procedure

The research involves three main components: an initial survey, a driving evaluation on a test track, and a subsequent survey. Further explanation of each segment of the study will be provided below.

Pre-Questionnaire Before the experiment, participants were asked to complete an online questionnaire via the SoSciSurvey platform at home. Two days before the study, respondents received an access link to the questionnaire via email. The questionnaire began with an explanation of the experiment's objectives and procedures and a guarantee that personal data would be processed anonymously and solely for scientific purposes. Participants were given the option to consent to the processing of their questionnaire data and audio recording during the test drive. Additionally, socio-demographic data such as age, gender, technology affinity (ATI-S Scale [TCD19]), driving experience (km/year), and experience with driver assistance systems (selection from 6 common systems) were collected. The preliminary survey took approximately 20 minutes.

Driving on Test Track The driving test was conducted in a University parking lot (location hidden for privacy). The vehicle used for the test was a 2017 Tesla Model S60 equipped with an autopark assistant. The driver sat in the driver's seat, the test leader in the passenger seat, and a transcriber in the back seat. The test track had three stations (refer to Figure 8.3 and Figure 8.4): 1) an introductory briefing followed by the Onboarding process, 2) a driving training session where the driver interacted with all the relevant vehicle controls such as the accelerator, brake, and gear lever, and 3) an automated parking space test. More detailed information regarding the test procedure at each station is provided below.

Station I At the start of the test, the test main researcher greets the participants and invites them to take a seat in the vehicle. Another researcher (protocol/notes) was also introduced briefly. The experiment's procedure and stations are explained, and the participants are informed about the insurance and asked for their consent to audio-recording their thoughts during the experiment using the Think Aloud method [vBS94]. The participants are then presented with the car's automatic parking system, either through a manual or an AR app tutorial. They are instructed to take their time with the tutorial and let the team know when they feel ready to begin the ride. The first station typically lasts around 15 minutes.

Figure 8.3: Test track setup, Station III – The designated parking area is enclosed by mock vehicles for added security.

Station II Following the tutorial on autoparking, the participants were tasked with driving a designated course (refer to Figure 8.3). The objective was to acquaint them with the accelerator and brake pedals, as well as the acceleration patterns of the vehicle. The vehicle was initiated and terminated on a restricted parking lot, covering a distance of approximately 30 meters. In addition, the participants were trained on the automatic transmission and reverse gear by parking the vehicle forward and then reversing it. Following this, the participants proceeded toward the designated parking spot. Typically, this segment lasts for around 3 minutes.

Station III Participants should initiate automated parking at the last station by maneuvering their Tesla into a designated space between two artificial vehicle-shaped obstacles. These obstacles are made of lightweight moving boxes and real-sized prints of vehicle fronts on foam. This setup enables Tesla to detect the parking space and minimize the risk of potential damage to the surrounding vehicles. To successfully complete the autopark interaction procedure learned in Station I, participants need to follow a specific sequence of actions (cf. Section 8.1.2). Firstly, the "P"-symbol appears on the instrument cluster when the vehicle is within a distance of about 1m and driving at a maximum speed of 16 km/h. Secondly, engage the reverse gear, which prompts a new screen to appear on the center console display. Thirdly, start the autoparking

Figure 8.4: Test track setup – left: Station II, acceleration and deceleration test; right: Birds view on test area including I) Onboarding station with the app or paper manual, II) Vehicle familiarization, III) Autonomous parking task.

process by pressing the "Start" button on the center console. The car will then automatically park itself, and the rearview camera on the center console will activate. Participants can stop or end the process by applying the brake once or twice respectively, or by moving the steering wheel. We considered the number of interruptions as an indication of mistrust and intervened if participants were stuck and unable to proceed. The success of the autopark procedure, as measured by the absence of errors and interruptions, served as an indicator of task performance. The average duration of the third station was approximately 2 minutes.

Post-Questionnaire Upon completion of the third stage, the participants were asked to fill out a follow-up survey. To do so, they were directed to a parked vehicle where they could complete an online questionnaire via tablet. Similar to the preliminary survey, the survey was conducted through the SoSciSurvey platform and consisted of questions related to the pragmatic and hedonic aspects of the user experience (UEQ-S Scale [SHT17], eight items on a 7-point semantic differential scale) during the onboarding process and autopark system. Participants were also asked about their acceptance of the system (TAM Scale [Dav89], 14 items on a 7-point Likert scale), trust in the parking system (Trust Scale [JBD00], 11 items on a 7-point Likert scale), and their understanding of the autopark system through a self-created quiz consisting of six multiple-choice questions. The quiz aimed to test their knowledge of the sensors used, supervision tasks required, scenarios when the system should not be used, distance and size requirements for parking, and recommended speed. The follow-up inquiry lasted for approximately 20 minutes.

Participants

The research study consisted of 26 participants ($m = 23; f = 3$), most of whom were University students. Participants were recruited through the University's online forums, with the requirement that they had not previously experienced autoparking. On average, the participants were 21.77 years old ($SD = 3.75$). All participants possessed a valid driver's license, had moderate driving experience ($MDN =$ 5000-10000 $km/year$), were relatively familiar with driver assistance systems ($MDN = 2$ out of 6), and exhibited a strong affinity for technology ($M = 4.53, SD = 0.73$). These characteristics were similar across both experimental groups. Participants were assigned to one of two test conditions, alternating based on the order of their appointments. No financial compensation was provided to participants.

Results

We examined the variations between experimental conditions through the self-reported questionnaires and observations of participants' behavior and thoughts. To prove statistical significance, we utilized an independent t-test, with the homogeneity of variances verified by Levene's test ($p > .05$).

Observed Behavior Throughout the automated parking process, we monitored two key factors: 1) any interruptions in the system's behavior caused by participants pressing the brake, indicating *mistrust*, and 2) their *task performance*, which involved successfully initiating and completing the autopark without assistance.

Mistrust: Interruption of the Automated System Behavior Few users ($n = 3$) interrupted the autopark assistant due to skepticism about its ability to handle the situation without errors (*"It's a little... One doesn't quite trust that.", "I hit the brake when I saw that it [the UI] was quite red"*).

Task Performance: Completing the Autoparking Procedure without further Help Out of the two groups, the AR group showed a higher success rate in correctly performing the autopark process at 54 % ($n = 7$) compared to the manual group at 23 % ($n = 3$). Within the manual group, participants often displayed uncertainty, such as not knowing where the instrument cluster was located or where interaction was required on the screen (*"I think a key should be activated here"*). Many participants also attempted to operate the parking symbol in the instrument cluster.

Subjective Questionnaires Table 8.2 depicts the results from the subjective questionnaires in terms of UX, trust, acceptance, and mental model.

		Experimental Condition				
		Manual		**AR**		
Scale	Factor	*M*	*SD*	*M*	*SD*	T-test
		Station I (Onboarding)				
UEQ-S	*Pragmatic Quality*	5.26	.97	5.24	1.4	$t(24) = -0.061, p = .95$
	*Hedonic Quality**	3.85	1.27	5.7	1.08	$t(24) = 3.96, p = .001$
	*Overall**	4.5	1.05	5.47	1.05	$t(24) = 2.196, p = .038$
		Station III (Autopark)				
UEQ-S	*Pragmatic Quality*	5.52	.87	5.87	.85	$t(24) = 0.061, p > .05$
	Hedonic Quality	5.9	.89	6	1.03	$t(24) = 0.2, p > .05$
	Overall	5.71	.74	5.94	.69	$t(24) = 0.814, p > .05$
Trust Scale	*Trust*	4.7	1.3	5.44	.83	$t(24) = 1.6, p = .1$
	Mistrust	2.84	1.09	2.6	1.26	$t(24) = -0.463, p = .64$
TAM	*Perceived Usefulness*	5.46	1.55	5.35	1.5	$t(24) = -0.179, p = .85$
	Perceived Ease of Use	5.89	.98	6.02	1.01	$t(24) = 0.327, p = .74$
	Attitude Toward Using	5.86	1.07	6.01	1.21	$t(24) = 0.342, p = .73$
	Behavorial Intention to Use	3.38	1.1	3.65	1.02	$t(24) = 0.644, p = .52$
Quiz	*Overall (max 6 points)*	3.69	1.31	3.61	.86	$t(24) = 0.176, p = .86$

Table 8.2: Questionnaire results – * significant difference ($p < 0.05$) between conditions. While there is no perceived difference in the autoparking experience, the AR app group reports a better user experience for the Onboarding process.

The Onboarding process at Station I had different user experiences based on the conditions. The manual condition resulted in high UX ratings, while the use of AR also led to high ratings. At Station III, the automated parking process did not show significant differences in conditions. Users rated their experience highly, indicating trust in the system, but had a neutral intention to use it.

8.2 Discussion

In the following, we will be discussing the findings of the driving study, making comparisons to previous research and online surveys, highlighting limitations, and providing recommendations for future work.

8.2.1 AR User Onboarding Effect on Acceptance and UX

The two approaches to User Onboarding, namely the text-based manual and the multimodal AR app, both resulted in high perceived usefulness, ease of use, and a positive attitude towards the vehicle assistant system. However, the moderate intention to use the system in both cases suggests that other factors may have influenced the acceptance of the autopark feature. To better understand acceptance in the automotive context, it may be beneficial to use a specific acceptance questionnaire instead of the TAM questionnaire. During User Onboarding, the use of AR led to significantly higher user experience ratings in the UEQ-S questionnaire. Although the pragmatic quality was comparable, the hedonic quality of the tutorial improved through AR, suggesting that users would enjoy a multimodal AR User Onboarding process. This is important because a positive experience could *intrinsically* motivate users to use the system tutorials more often, which supports the *re-entry goal* [Ren+14] of User Onboarding. Further investigation of this could be done in a longitudinal study.

8.2.2 Trust in and Familiarization with Automation

According to our online survey, users have shown increased trust in vehicle assistant systems compared to their initial level, supporting the learned trust facet in the model proposed by Kevin Anthony Hoff and Masooda Bashir [KM15]. However, the survey also highlighted that users experienced incomprehensibility, misunderstandings, and the need for training, indicating an incomplete understanding of the vehicle assistant systems. This mismatch can be explained by the studies conducted by Dikmen and Burns [DB16], which showed that trust in "Autopilot" increases over time regardless of actual experience, Matthias Beggiato et al. [Mat+15], which demonstrated that system failures need to be experienced before they can be addressed, and Johannes Kraus et al. [Joh+20], which showed that trust decreases after experiencing system failures but can be reestablished after a period of error-free interaction. Automated parking trust ratings showed no significant difference between manual and AR conditions. Participants had a high level of trust but were willing to intervene if necessary. Maintaining skepticism is important to prevent overreliance on the system.

We have conducted a test for the initial interaction with the system. Based on our research, including the literature (e.g., [DB17]), and the online survey, we see that users' trust and performance measures may change over time, and their requirements may differ from those of first-time users, especially for more experienced ones. Therefore, it is important to refresh User Onboarding periodically and tailor it to users' expertise. Additionally, the higher the user experience of the AR system, the more likely users will revisit it. In the future, we can explore additional mechanisms for trust calibration to improve the revisitation system further.

8.2.3 Automation Understanding and Operation

The use of AR in User Onboarding reduces interaction errors during automated parking. Surprisingly, questionnaire and quiz results showed that the understanding of the autopark system was similar in both groups. However, upon closer inspection of our Onboarding strategies, we found that while system-related knowledge was conveyed textually in both conditions, information on how to interact with the system was visually displayed in the AR condition, while in the manual, participants had to rely on mental visualization, leading to imprecise mental models of the interaction procedure (*"I think a key should be activated here", "On the display you should see a park symbol like this, but I can't find where it is"*). This supports the dual coding assumption of Cognitive Theory of Multimedia Learning (CTML) [May05; PC+06] and previous work that found AR to be beneficial for task performance (cf. Blattgerste et al. [Bla+17]). AR tutorials help users build a more precise mental model of the interaction process by visually concretizing textual-encoded descriptions of the location of interaction processes at the right time. This study is a first step towards creating multimodal User Onboarding experiences, and future work could explore other multimodal approaches and their effects on the long-term retention of information.

8.2.4 Limitations

The online survey and real-world study were primarily conducted with male technophiles, which may lead to different results with other user groups such as females or technophobes. Additionally, the sample size of the driving study was relatively small, and as more participants are included, the perceived trust in AR and manual conditions may change.

Although the "autopark" function is not as critical as other assistants such as ACC or lane-keeping, users who require higher driving speeds may have different perceptions of safety. The risk-taking behavior of participants may also influence reported trust values. Future research could explore this effect.

Our AR approach relies on smartphones, which have freely orientable screens but may not be comfortable to hold for extended periods. As technology advances, lightweight AR glasses or lenses may become a viable alternative, providing an unobstructed field of view. Investigating these options in future work would be worthwhile. However, we focused on smartphone-based AR implementation in this study as these devices are already widely used and easily integrated into car manufacturers' digital service ecosystems.

8.3 Conclusion

This chapter explores the potential of multimodal AR User Onboarding for vehicle assistant systems as a means to bridge the gulf of transparency by educating users about the system boundaries. We conducted an initial online survey with modern vehicle owners and found that while they heavily rely on assistant systems, they often *misunderstand* them and see the *need for further training*. To test the usefulness of an AR Onboarding approach, we conducted a real-world driving study on automated parking with automation novices in a Tesla. Our findings suggest that:

- AR tutorials do not necessarily outperform traditional text-based user manuals in terms of system understanding
- AR has the potential to convey interaction procedures more precisely, leading to fewer task-related errors
- AR leads to higher hedonic experiences during Onboarding and could therefore increase the motivation to use a tutorial about a driving assistant system

Overall, vehicle designers can use multimodal AR User Onboarding as an opportunity to bridge the gulf of evaluation in automated driving: They can train customers and present new functions in an up-to-date, understandable, and interactive way.

Chapter 9

Motions Intent Prediction

This chapter is based on the following publications:

Henrik Detjen, Maurizio Salini, Jan Kronenberger, Stefan Geisler, and Stefan Schneegass. "Towards Transparent Behavior of Automated Vehicles: Design and Evaluation of HUD Concepts to Support System Predictability Through Motion Intent Communication". In: *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction*. New York, NY, USA: ACM, 2021, pp. 1–12. ISBN: 9781450383288. DOI: 10.1145/3447526.3472041

This chapter aims to generate and evaluate concepts that help to bridge the gulf of evaluation in automated driving by making autonomous driving transparent and thus more predictable for users. In specific, we communicate (upcoming) vehicle actions through the use of icons displayed on a planar HUD or through augmented reality on a contact-analog HUD. We conducted two user studies to evaluate the HUD concepts regarding user experience and safety. Based on our findings, we provide design recommendations to enhance future HUD designs for communicating vehicle motion intent (cf. *RQIV_2* – How to communicate the system's motion intents on the virtual windshield?).

As automation in driving increases, humans are becoming less involved in the task, leading to uncertainty about the vehicle's future actions. Research indicates that passengers tend to trust the system less as the degree of automation increases (e.g., [Röd+14]). Cooperative vehicle systems require *predictability* [Wal+17], which helps build trust and situation awareness (cf. Section 2.4.3). Efficient human-robot collaborations are possible when the system communicates its intent [Wal+18]. It is critical to design car interfaces that enable passengers to predict the car's actions [BL17]. Instead of providing feedback about the system's past state, "feedforwarding" [Koo+15] it to the user is beneficial. This feedforwarded action is the intent of the vehicle. In this chapter, when using the term *intent*, we refer to the *vehicle trajectory and motor actions* that occupants perceive or are about to perceive (motion intents). However, it is still unclear how to communicate the *system's intentions for action* to the user. Further research is needed to understand what information is necessary for passengers to predict vehicle intentions holistically.

Previous research has mainly focused on enhancing HUD design parameters, such as reducing obstruction of real-world elements [Pär+19]. However, in this chapter, our focus is not on optimizing the design of individual visualization elements but rather on comparing holistic concepts. Traditionally, HUDs are utilized for navigational tasks (e.g., [Pär+19]), and performance measures like workload and task errors are commonly assessed (e.g., Bolton et al. [BBL15], or Schomig et al. [Sch+18]). However, there are limited studies in the context of highly automated driving, where performance and human factors such as trust are essential. Augmented reality display concepts, such as navigational AR-cues (cf. Sawitzky et al. [Saw+19]), miniature maps (cf. Häuslschmid et al. [Häu+17]), or traffic coloring based on distance and required takeover-time (cf. Wintersberger et al. [Win+17]), have been shown to increase trust. Our analysis of previous studies identified four primary types of visualization concepts. The authors have referred to these types using various terms.

1. **AR, World-fixed** (Fishbone or Solid) [Saw+19; Sch+18; BBL15]
2. **Icon-based, Arrow, Conventional** [Saw+19; BBL15]

3. **Mini-Map** [Saw+19; Häu+17]
4. **Landmark-based** (arrow/box over point of interest) [BBL15]

Using a user-centered design process, we developed two concepts for displaying a vehicle's future actions in a head-up display. One of the concepts is a planar HUD with *icon-based* representation of the vehicle's future movements. In contrast, the other HUD concept uses a fixed real-world representation through *AR*. We tested both concepts in two subsequent experiments to see if and how they could increase user experience and safety. In addition, we conducted interviews to gather qualitative user feedback. In the first experiment, aiming at higher levels of automation (cf. SAE level 3–5 [SAE18a]), we tested the HUD's impact on *UX and trust*. In the second experiment, aiming at lower automation levels, where drivers have to monitor the environment constantly (cf. SAE level 1–2) or just shortly before a takeover happens (cf. SAE level 3), we tested the HUD's impact on *safety*. Out of our experimental insights, we compiled a list of recommendations for interface design, specifically on how to effectively convey vehicle actions to users to enhance their perception of system predictability, improve their overall user experience, and foster trust and safety. These insights are intended to assist researchers, designers, and practitioners in developing predictable transparent automation systems.

9.1 Concept Creation

In order to ensure our HUD designs meet the needs and requirements of users, we followed a user-centered design process. This involved evaluating information needs and gathering new design options. As part of this process, we held an ideation workshop with students from the "Automotive HMI" lecture ($N = 6$). During the workshop, we provided participants with paper templates depicting a car windshield and various traffic situations where the car was either preparing for or executing a driving maneuver (cf. Figure 9.1).

We identified three common traffic scenarios: turning right, changing lanes to the right, and parking. Each participant received six paper templates depicting vehicle behavior or preparation for these scenarios. Initially, participants

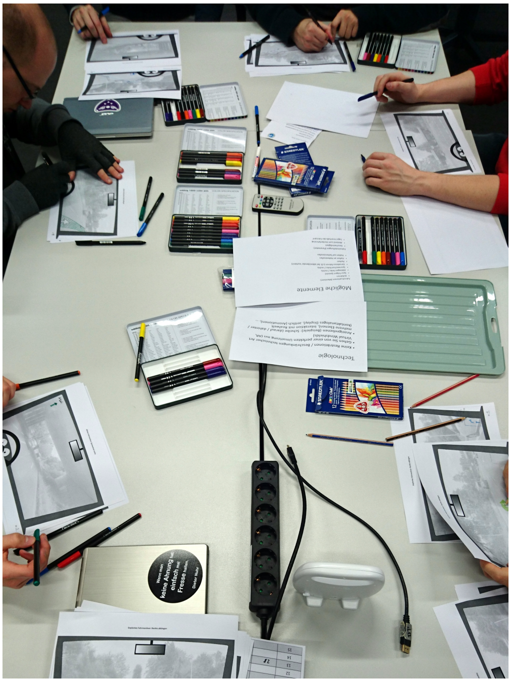


Figure 9.1: Ideation workshop – Generation of input for the visualization of vehicle current and upcoming behavior.

visualized the vehicle behavior for each template, using any display or interaction technique they preferred, without any technological limitations. This included virtual windshields, augmented reality, animations, and multiple layers. Afterward, we asked that they detail how they would incorporate explicit user control and various driving maneuver states (active, selectable, or non-selectable) onto their templates, both in written and visual form.

We thoroughly analyzed and organized all 36 sketches after the workshop. This enabled us to distinguish between two distinct design concepts as depicted in Figure 9.1: A) a planar HUD concept that utilizes icons to showcase the current and intended vehicle behavior (with a maneuver queue to preview

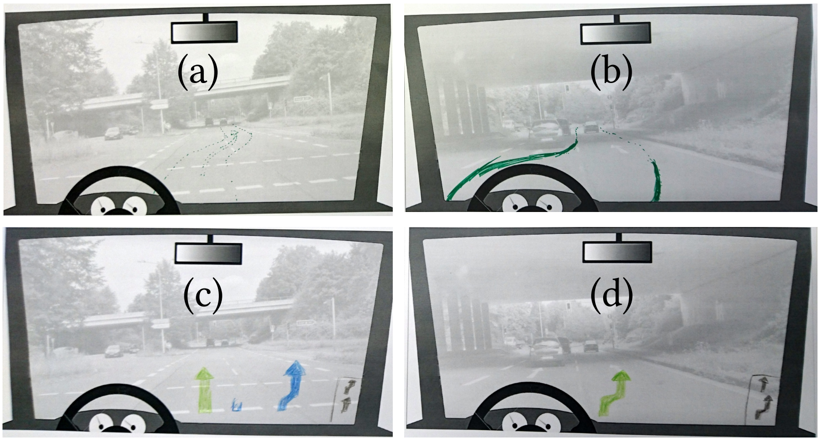


Figure 9.2: Sketches of the AR concept (*a* and *b*) and the icon-based concept (*c* and *d*).

upcoming maneuvers), and B) a contact-analog concept that enhances the real-world view by drawing the planned vehicle trajectory directly onto the road. Some of the sketches combined these concepts, such as displaying planar icons within a real-world setting at a fixed location. For reference, we refer to these as the *icon-based concept* (*IB*) and the *AR concept* (*AR*). Both concepts differ from each other in two key aspects that we discovered through our literature research:

1. **Required technology**: plain head-up display (*IB*) vs contact-analogue head-up display (*AR*)
2. **Display of vehicle behavior**: maneuver-based guidance level (*IB*) vs trajectory-based guidance level (*AR*)

In the final design concepts, we combined the design elements found in the literature (cf. [Saw+19; Sch+18; BBL15; Häu+17]) with the ideas generated during the ideation workshop. These included distance indicators to the next car, the visualization of parking and stop maneuvers using *IB* and *AR*, and the maneuver queue using *IB*.

9.2 User Studies

We conducted two experiments to explore how the visualization of vehicles' motion intentions affects users' experience, trust, and safety. These experiments represent two use cases, one with higher and one with lower automation levels. To assess the safety implications of visualization concepts, we exposed participants to scenarios where they had to intervene due to automation failure. This exposure to automation failure may negatively impact users' trust and experience with the system, as noted by Gold et al. [Gol+15]. To measure user experience and trust in a "perfect world" setting, we had participants view videos of the icon-based and AR concepts in a real car. We then conducted a second experiment in a driving simulator, where participants had to intervene in the driving process to assess the impact of visualization concepts on driver safety in take-over scenarios. Before discussing them together, we will describe both experiments' methods and results separately for better readability.

Participants We reached out to potential participants at the university by sending announcements via email and by promoting the study in a course related to the topic. A total of 27 participants ($m = 24, f = 3$) with an average age of 21.74 years ($SD = 2.65$) were invited to participate at the University of Applied Sciences Ruhr West. Of the participants, two wore glasses with ± 4 diopter and one with $+7$ diopter, but no one reported any visual impairments such as difficulty focusing visually or red-green weakness. The participants' annual driving ranged from 0-1000km ($n = 5$), 1001-5000km ($n = 8$), 5,001-10,000km ($n = 6$), 10,001-20,000km ($n = 7$), and over 20,000km ($n = 1$). They also reported a strong affinity for technology, as evidenced by a high score ($M = 4.64, SD = .65$) on the ATI Scale [TCD19] (6-point Likert scale). Furthermore, the participants had experience using various driving assistance features, including cruise control ($n = 19$), lane-keeping assistants ($n = 11$), adaptive cruise control ($n = 7$), and parking assistants ($n = 2$).

9.2.1 Experiment 1 – User Experience and Trust in Higher Automation Levels

The first experiment involved utilizing a video-based technique to examine the impact of automated vehicle intention visualization on user experience and trust. We also explored correlations between these aspects and factors such as driving experience. Additionally, we gained valuable insights into the subjective perception of both visualization concepts.

Method

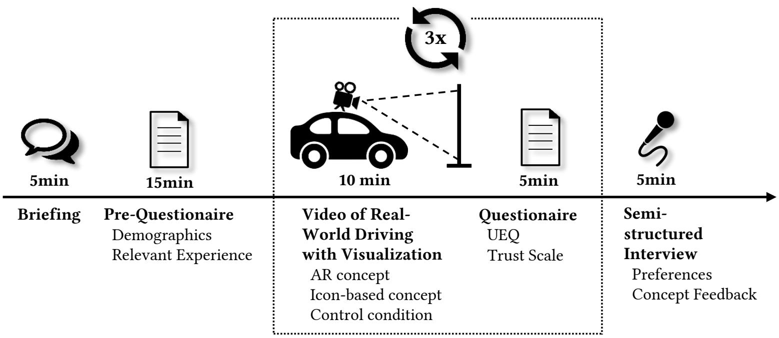


Figure 9.3: Protocol of the first experiment.

The experiment's setup involved using a real but stationary vehicle, as shown in Figure 9.2.1. We placed a canvas measuring 200*cm* x 112.5*cm* in front of the vehicle, similar to the setup proposed by Gerber, Schroeter, and Vehns in their study [GSV19]. We projected recordings of real rides onto the canvas, which were captured using an Action Cam in 4k resolution. Each recording was five to seven minutes long and comprised real-world driving material in a city setting for each condition. While the videos differed, we ensured that they all had comparable track conditions (traffic, light conditions) and vehicle behavior (speed limit, amount, and type of maneuvers). The car's driving behavior visualization included various maneuvers such as starting, turning,

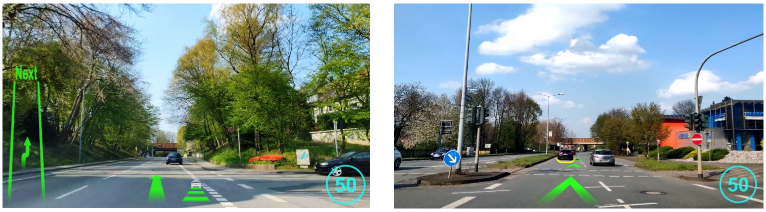


Figure 9.4: Visualization concept examples – left: icon-based concept (*IB*); right: Augmented reality concept (*AR*).

changing lanes, braking and stopping, following a vehicle ahead, and parking. We then added CGI-visualizations of either the AR concept or the icon-based concept to the videos using DaVinci Resolve 15[7], Adobe Photoshop, and Adobe After Effects[8]. Additionally, we included a control condition with no visual cues of the vehicle's actions (No visualization condition, abbr.: *NV*), which served as a baseline. Figure 9.4 illustrates the (implicit) maneuver of "follow lane" for both visualization strategies (*IB* and *AR*) in the video conditions.

To gain a better understanding, one can access both videos online (*IB*: `https://youtu.be/flVZlw5ME_Q`, *AR*: `https://youtu.be/LNYvFMxta24`). Each participant underwent all three conditions in a within-subject design in counterbalanced order. The process is visually summarized in Figure 9.2.1. We informed the participants that the car was driving autonomously, and thus, they had no option to intervene during the rides. After each video, we gauged the participants' perceived user experience and trust. For UX, we employed the User Experience Questionnaire [LHS08] (short: UEQ, 7-point semantic differential scales), while for trust, we used the Trust Scale [JBD00] (short: TS, 7-point scale) – see also Table 9.1. Finally, after completing all three conditions, participants rated the overall driving experience, indicating their preference for a particular condition (short: PREF, 7-point Likert scale)

[7] `https://www.blackmagicdesign.com/de/products/davinciresolve`

[8] `https://www.adobe.com/de/creativecloud.html`

Figure 9.5: Video study setup – A stationary car and the projection of the real-world driving video augmented with CGI-visualizations of the HUD concepts on canvas.

in all three conditions. We also interviewed them for their opinions on the visualization concepts, including what they liked or disliked and if they had any suggestions for improvements.

Results

Our first step was to ensure the reliability of all scales, as shown in Table 9.1. Unfortunately, we found that the Efficiency sub-scale of UEQ was not acceptably reliable, so we excluded it from further analysis. However, all other scales demonstrated consistent and reliable results, ranging from acceptable to excellent. The average responses for UEQ, TS, and PREF are displayed in Figure 9.6. In order to analyze the effects of the experimental conditions, we used a repeated-measures analysis of variances (ANOVA) with Greenhouse-Geisser correction after checking for sphericity with Mauchly's test ($p > .05$). Bonferroni-corrected posthoc tests were then utilized to identify any differences between experimental conditions (see Table 9.2.1). Finally, we analyzed

Scale	Factor	Items	Cronbach's α	Ref.
UEQ	*Attractiveness*	6	.89	[LHS08]
	Perspicuity	4	.74	[LHS08]
	Efficiency	4	.43	[LHS08]
	Dependability	4	.74	[LHS08]
	Stimulation	4	.75	[LHS08]
	Novelty	4	.81	[LHS08]
TS	*Trust*	12	.90	[JBD00; PHD16]
PREF	*Visualization Preference*	1		

Table 9.1: Subjective scales used in the experiment and their internal consistency – User Experience Questionnaire (UEQ), Trust Scale (TS), and overall driving experience preference (PREF).

the correlation between factors such as UX and preference using bivariate correlation analyses following Pearson.

User Experience There is a significant main effect of the visualization condition on all UX factors: Attractiveness ($F(2,52) = 19.41, p < .001, \eta^2 = .43$), Perspicuity ($F(2,52) = 14.73, p < .001, \eta^2 = .36$), Dependability ($F(2,52) = 14.90, p < .001, \eta^2 = .36$), Stimulation ($F(2,52) = 8.93, p < .01, \eta^2 = .26$), and Novelty ($F(2,52) = 18.21, p < .001, \eta^2 = .41$). The effect after Cohen that the type of visualization has on UX is medium for Stimulation ($f = .35$) and strong for Attractiveness ($f = .75$), Perspicuity ($f = .56$), Dependability ($f = .56$), and Novelty ($f = .69$).

In Table 9.2.1, a comparison of conditions is presented. The user ratings for Perspicuity and Dependability improve with any kind of visualization when compared to the baseline, and the type of visualization used does not affect the ratings. Additionally, ratings for Attractiveness and Novelty also improve when visualizations are used, with the AR concept leading to even better ratings than the IB concept. Only the AR concept leads to better ratings than the baseline for Stimulation. Overall, the absence of motion intent visualizations (baseline) results in lower user experience in all dimensions.

Scale	Factor	Significant Findings, $p < .05$
	Attractiveness	AR > IB > NV
	Perspicuity	[AR, IB] > NV
UEQ	*Dependability*	[AR, IB] > NV
	Stimulation	AR > [IB, NV]
	Novelty	AR > IB > NV
TS	*Trust*	[AR, IB] > NV
PREF	*Visualization Preference*	AR > IB > NV

Table 9.2: Post-hoc comparison of conditions for UEQ factors, TS, and PREF – Visualization improves trust and UX ratings.

Automation Trust The statistical analysis revealed a significant main effect of visualization on trust ($F(2,52) = 21.443, p < .001, \eta 2 = .452$) with a strong effect size of ($f = .91$) according to Cohen. Compared to the baseline condition, both the *IB* and *AR* led to a higher level of trust in the system (cf. Table 9.2.1). Or, vice versa, no visualization resulted in a lower level of trust.

Overall Driving Experience and Preference The visualization conditions had a significant impact on participants' ratings of their driving experience ($F(2,52) = 65.38, p < .001, \eta 2 = .72$), with a strong effect size ($f = 1.58$). Overall, the driving experience improved with the use of visualization, with the *AR* concept receiving higher ratings than the *IB* concept.

Correlation between Variables We conducted an analysis to determine potential moderators by examining the impact of personal driving and technology experience on our dependent variables. Our findings indicate that neither affinity for technology (ATI) nor the number of known driving assistance systems or driving experience had any significant influence (correlations were near zero) except for one. We discovered a positive correlation between driving experience and the baseline condition ($r(25) = .436, p < .05$), meaning that participants who drive more kilometers per year are more likely to trust an autonomous driving system without visualization. Additionally, we examined correlations between the dependent variables and found high co-dependence

		Experimental Conditions					
		NV		**IB**		**AR**	
Scale	**Factor**	*TS*	*PREF*	*TS*	*PREF*	*TS*	*PREF*
UEQ	*Attractiveness*	**.85****	**.59****	**.77****	**.59****	**.70****	.48*
	Perspicuity	**.57****	.31	**.57****	.31	.41*	.47*
	Dependability	**.82****	**.56****	**.85****	**.56****	**.80****	**.56****
	Stimulation	.19	.25	.35	.25	.47*	.46*
	Novelty	**.53****	.46*	.32	.46*	**.56****	.18
TS	*Trust*	1	**.67****	1	.42*	1	**.52****
PREF	*Visualization Preference*	**.67****	1	.42*	1	**.52****	1

Table 9.3: Correlations between trust and overall driving experience with other dependent variables (UEQ, TS, PREF) by condition – Strong correlations ($> .50$) in bold text, $*p < .05$, $**p < .01$.

between UX factors, trust, and the overall driving experience. Specifically, Attractiveness and Dependability strongly correlated with trust and whole driving experience in almost all conditions. Table 9.2.1 depicts these intercorrelations.

Qualitative Feedback During the interviews, we requested feedback on the visualization concepts and suggestions for improvement. We conducted a qualitative content analysis using an inductive coding process to summarize all the responses. Although the majority of participants had a positive perception of both concepts, some specific strengths and weaknesses were also identified.

Icon-Based Concept Out of the participants, a majority ($n = 13$) appreciated the icon-based concept due to its intuitive and simple design of the display elements. The display of upcoming maneuvers in the queue ($n = 6$) was especially helpful in understanding the behavior of the autonomous vehicle. However, one participant ($n = 1$) criticized the increased space requirements of this element. Some participants ($n = 4$) found the stop-sign metaphor for breaking confusing (P6: *"The stop sign – that confused me a little bit. I connect it less with the situation than with the sign. The real sign"*). To improve this, it was suggested to display only the typeface. Lastly, two participants ($n = 2$) expressed the desire for more detailed information (P3: *"I didn't know if*

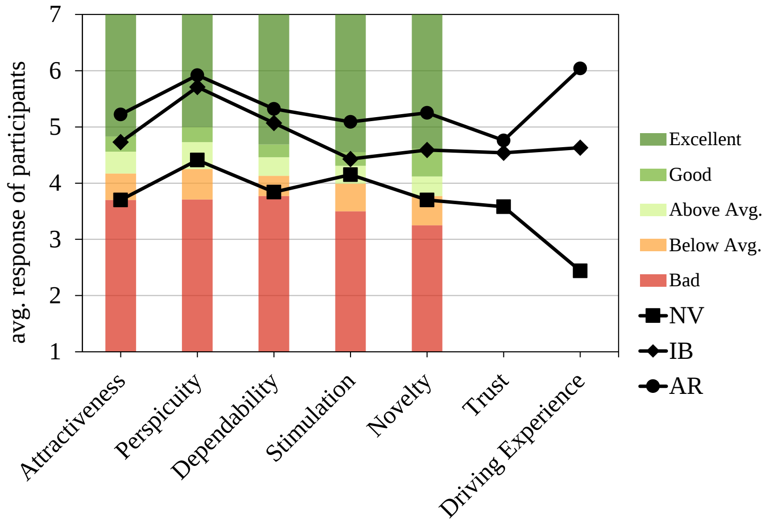


Figure 9.6: Mean values for UEQ factors, TS, and PREF by condition (lines) – The color scale denotes UEQ benchmark from other systems/products (401 studies). Visualizations (*IB* and *AR*) outperform the baseline. *AR* is even better in most (sub-)scales.

it wanted to go left or right"). In conclusion, the majority of participants appreciated the intuitive design and display of upcoming maneuvers, while disliking the metaphor for breaking.

Augmented Reality Concept Based on the feedback from participants in the AR concept, it was noted that the aesthetic design was well-liked ($n = 13$). Additionally, the detailed display of the vehicle's trajectory ($n = 8$) was deemed helpful as it allowed users to follow lanes with greater ease ($n = 3$, P3: *"I felt more secure knowing that it accurately indicated its intended path"*). Furthermore, users were able to determine the exact stopping position of the vehicle ($n = 4$, P5: *"It allows for intervention if necessary"*). In regards to the stop visualization, one participant ($n = 1$) suggested that the visual elements corresponding to the impacting G-forces should be made thicker. However, highlighting the vehicle driving ahead as an indicator of safety distance was not clear for one participant ($n = 1$). Another participant suggested displaying the behavior of the vehicle ahead too ($n = 1$, P18: *"Turning the bar red if the car ahead brakes"*). Finally, three participants ($n = 3$) recommended applying the highlighting for cars on other lanes as well. In conclusion, participants particularly appreciated the aesthetic design and the vehicle's trajectory display.

Visualization in General Regarding both concepts, a few participants (*IB*: $n = 3$, *AR*: $n = 2$) suggest displaying maneuvers a bit earlier, while the majority of participants ($n = 19$) wish to see the current speed in addition to the maximum speed. Other ideas for improving the concepts include displaying recognized traffic signs and rules ($n = 3$, P18: *"Did the system recognize 'left yields to the right'? Did it notice you were on a priority road?"*), having a visual cue to indicate vehicles in the blind spot during lane changes ($n = 3$, P5: *"If the system's autopilot recognizes the cars on the side, an orange light could be illuminated"*), highlighting pedestrians near the road ($n = 1$), and showing the actual route on a small map ($n = 1$). When asked if they had any difficulties understanding a symbol or visual element, none of the participants reported any problems except for the stop sign, which was confusing for some participants in the *IB* condition. One participant ($n = 1$) suggested integrating the maneuver queue into the AR concept to combine the best of both concepts (P18: '*'I wish the waiting line would be included... that would make it even better"*). Overall, participants desire earlier display of maneuvers, want to see the current speed, and have additional ideas such as displaying traffic signs and blind-spot recognition.

Driving without Visualization At the conclusion of the study, we inquired about the participants' emotions when vehicle behavior was not visualized. The results showed that without visualization, some participants expressed feelings of insecurity ($n = 3$, P23: *"I felt uncertain, not knowing what was going to happen next"*), tension ($n = 2$, P15: *"I had to concentrate the entire time because I didn't know where the vehicle was going, whether it was turning left or right...I couldn't adapt to it"*), or boredom ($n = 1$, P16: *"The vehicle was driving and at some point, I thought, 'Yeah, I can use my smartphone"'*), and a loss of control ($n = 2$, P12: *"Not having visualization didn't work for me* *because I like to keep track of the vehicle's movements and have some level of control"*). Additionally, one participant ($n = 1$) speculated that these effects may be linked to one's experience with autonomous driving (P20: *"If you have been using autonomous driving for an extended period, then visualization may not be as crucial"*). In summary, the absence of visualization caused some participants to feel insecure, tense, and less in control.

9.2.2 Experiment 2 – System Failure in Lower Automation Levels

In the second experiment, we conducted a driving simulator study to explore how the display of an autonomous vehicle's intentions affects human performance when the system fails.

Method

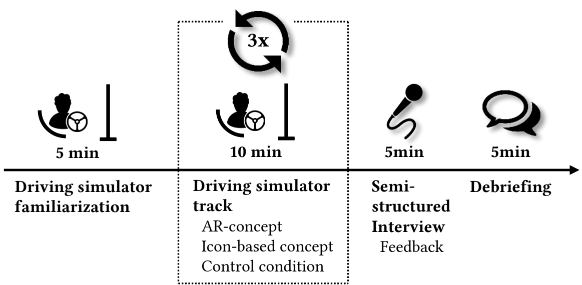


Figure 9.7: Protocol of the second experiment.

The experiment involved using a driving simulator (refer to Figure 9.2.2) after a short break (10-15 minutes) from the first session. The simulator comprised a wooden platform with a Sony play seat, a wooden table with Logitech G920 pedals and steering wheel, a Smart Eye Pro eye-tracking system, and three

Figure 9.8: Driving simulator setup.

42-inch LG high definition (HD) TV monitors. The SILAB 6.0 software[9] was used to simulate our test scenarios. To familiarize themselves with the controls, participants drove a demo track before driving three different but comparable routes (counterbalanced order) consecutively with an activated autopilot in the driving simulator. Participants were instructed to observe the machine's behavior, and visualizations were implemented for each route, which they knew from the first test. The routes consisted of a section of motorway, a section of a country road, and a section of driving in the city. Throughout the trips, the vehicle only executed known maneuvers from the first part of the study, like keeping the lane, adjusting its speed, keeping a safe distance from other vehicles, braking and stopping, and performing maneuvers such as turning and lane changing. Participants were informed that the autopilot was a semi-autonomous system and should intervene if necessary. The autopilot would immediately shut down if the accelerator or brake pedal or the steering angle was changed. Without the participants' knowledge, two errors occurred on each track, based on different types of automation failure:

[9] `https://wivw.de/de/silab`

Figure 9.9: Provoked take-over situations by error type and condition – upper row: ERROR.1) system is about to ignore a stop sign; lower row: ERROR.2) system is about to perform a lane change despite an obstacle on the other lane; example for the *IB* concept (a and b), *AR* concept (c and d), and control condition (e and f).

- **Error 1**: Ignoring a stop sign, The user needs to take action as the intention to stop *is not visible* due to a silent automation error.
- **Error 2**: Lane change despite obstacle, the user must react to a lane change because the intention to switch lanes *is visible*

We chose these specific errors instead of sudden accidents to allow users enough time to intervene during the driving process and to avoid too critical failures. In each track, we slightly altered the timing and situation of the errors, so participants could not anticipate when they would occur (cf. Figure 9.9). The automated vehicle initiated and displayed the maneuver three seconds before any obstacles appeared, consistently across all conditions. We observed the participants' interventions and recorded their reaction times using an eye-tracking system during each trial. The process is summarized in Figure 9.2.2.

Results

In this analysis, we will examine how visualization impacts the performance of taking over. Specifically, we will assess the success rate, speed, and gaze behavior of participants in response to system failure.

Error Detection and Take-over performance

In Figure 9.2.2, the participants' responses to system failures for two types of errors are displayed. We identified three kinds of reactions, namely timely intervention, delayed intervention, and no intervention at all. The baseline condition ($n = 23$) and the *IB* condition ($n = 20$) demonstrated numerous instances of no reaction to system errors. However, in the *AR* condition, only two system failures went unnoticed ($n = 2$). Additionally, ERR2 (illegal lane change) was detected more frequently than ERR1 (stop sign violation), but participants still intervened late in several cases. Only three ($n = 3$) participants successfully intervened in all conditions. Overall, we noticed successful takeovers occurring more often in the *AR* condition for both types of errors.

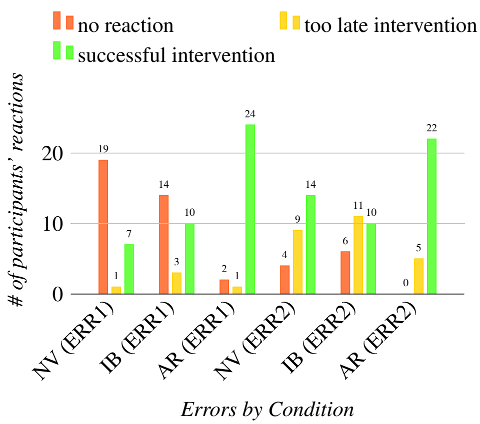


Figure 9.10: Reaction on ERROR 1 (stop sign) and ERROR 2 (lane change) by condition – Without the AR visualization, errors occurred more often.

For all successful interventions, we have gathered data on the time elapsed between participants' intervention, such as braking or steering, and the moment when the system fails, resulting in a collision with an obstacle. This data

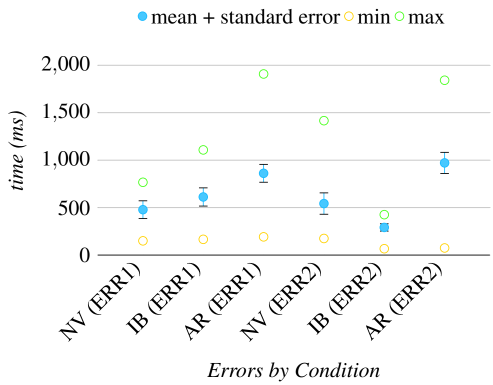


Figure 9.11: Remaining time until the impact of the errors by conditions – *AR* leads to slightly faster TOR.

pertains to all successful interventions. Figure 9.2.2 illustrates the remaining time for both errors in all conditions. Higher values indicate earlier intervention. In comparison to the baseline, the *IB* condition results in slightly faster interventions for Error 1, but slightly slower interventions for Error 2. The *AR* condition, on the other hand, leads to people intervening about twice as fast as in the baseline condition for both errors. This suggests that the *AR* concept enables people to detect system failure earlier.

We combined the data from both errors to ensure the accuracy of our findings. We simplified the intervention categories to a binary yes/no by merging the "no reaction" and "too late intervention" categories. The condensed data is presented in Table 9.2.2. To determine if visualization conditions influence the success rate of interventions, we conducted Pearson's chi-squared test for independence. Results showed that the visualization condition has a medium effect size on take-over success ($\chi^2(2, N = 162) = 32.326, p < .001$) after Cramer ($V = .32$). To determine which visualization differs from the expected distribution, we used the success rate in the baseline condition (.39) as an indicator. We compared this expected rate with the actual rates in the *IB* and in the *AR* condition using an exact binomial test corrected after Bonferroni

($p <= 0.025$). The *IB* concept showed no deviation from the baseline ($p = .89, n = 54$), but the *AR* concept differed significantly ($p < .001, n = 54$). The recorded eye-gaze data revealed no unusual gaze patterns, but supports this finding: With the *AR* concept, participants gaze at the ignored stop sign or the ignored car on the other lane more often.

	Conditions		
Successful Intervention	*NV*	*IB*	*AR*
yes	21	20	46
no	33	34	8
success-ratio	.39	.37	.85*

Table 9.4: Intervention rates (successful / {too late, no reaction}) for ERR1 (stop sign) and ERR2 (lane change) by conditions – *AR condition differs significantly from the baseline (NV), ($p <= 0.25$).

Preference and Further Observations

Once the experiment is concluded, the participants are expected to evaluate the level of error detection support provided by the two concepts on a 6-point Likert scale. Based on the results, the *AR* concept ($M = 1.96, SD = .76$) was rated significantly better than the *IB* concept ($M = 2.7, SD = .61$) as demonstrated by the dependent t-test ($t(52) = 3.95, p < .001$).

During the experiment, it was noticed that some participants tended to move their hands and feet towards the steering wheel and pedal when the vehicle needed to perform a driving maneuver without visualization. This was done to enable them to intervene quickly in case of any need. As a result, the participants appeared more anxious in the baseline condition. Although the brake pedal was slightly touched, only three individuals intervened in situations where the system was functioning correctly. On the other hand, three other participants detected errors early on while driving with the AR concept but chose to wait until the vehicle acted.

9.3 Discussion

In the following, we demonstrate how our research on the transparent behavior of automated vehicles aligns with related literature. Additionally, we acknowledge the limitations of our work and identify areas for future research.

9.3.1 Effect of Vehicle Intention Visualization on UX and Trust

Based on our research, it appears not only visualization but also the type of visualization used to convey an automated vehicle's behavior and intentions has a significant impact on the user experience. While trust and most UX factors (Attractiveness, Perspicuity, Dependability, Novelty) are positively influenced by any type of visualization, the Stimulation factor is only effective with *AR* visualization. Interestingly, *AR* visualization also leads to higher Novelty, Stimulation, and Attractiveness ratings. This is not surprising, given that the *IB* concept is similar to well-known navigation apps (P5: "Looked professional, like a navigation device"). Efficiency ratings were inconsistent, likely due to the passive role of the study participants. Perspicuity is a crucial factor in building trust with an automated vehicle, and it increases with any type of visualization. Therefore, we recommend: *To increase the transparency of an automated vehicle, visualize its intentions and behavior, even during autonomous driving*.

Regarding trust, we can support the findings of Sawitzky et al. [Saw+19]. They discovered that displaying visual cues of vehicle behavior had a positive impact on trust, regardless of whether it was in their "Arrow" condition (~IB concept) and "world-fixed" condition (~AR concept). It's not crucial how the vehicle's intentions are visualized, but without any visual representation, participants felt less secure and less in control, indicating a deprivation of these needs. In summary: *To increase trust in an automated vehicle, visualize its intentions and behavior, even during autonomous driving*

9.3.2 Correlation between User Experience and Trust

The correlations between UEQ factors Perspicuity and Dependability with trust appear reasonable, but we also discovered a strong correlation with Attractiveness in all conditions. This could be due to the *halo effect*, where people tend to link perceptions of a person's dominant property, such as attractiveness, with other properties like conviviality. Frison et al. [Fri+19b] demonstrated this effect in the context of automobile systems, showing how an attractive user interface can mask poor system performance in the eyes of users. Our research indicates that the type of visualization used affects the Attractiveness of a HUD, with the *AR* concept rating the most attractive. However, there is a risk that an attractive visualization could lead to overtrusting behavior. Nonetheless, a reasonable level of trust is essential for detecting and responding quickly to system failures, particularly in SAE Level 3, where the driver may need to take control in potentially hazardous situations. Therefore, we suggest the following, in line with the findings of [Fri+19b] and our observations: *When using novel, stimulating, and attractive visualizations in SAE Level 3 (or lower) automated cars, users should be informed that the system may fail, enabling them to adjust their trust accordingly.*

9.3.3 Effect of Vehicle Intention Visualization on Safety

Our study revealed that the take-over rate is more effective in the *AR* condition than in the *IB* concept. Surprisingly, the *IB* concept was slower in detecting lane change errors and did not lead to better take-over rates. A possible explanation for this is the reduced spatial information provided by the *IB* concept, which describes the vehicle's actions more abstractly through maneuver icons. We observed that participants hesitated to intervene within the *IB* concept until the car acted, which could explain why about 40% intervened too late in the lane change error condition. This hesitation may be due to people expecting the car to perform the lane change after passing an obstacle, and the display of a lane change icon kept them in false safety. A similar effect was found by Bolton, Burnett, and Large [BBL15] for less critical navigation tasks, where participants made more errors in the "conventional" condition (~IB concept) compared to the "augmented reality" condition.

Our research has shown that this "Level of Detail"-effect, which compares maneuver-based guidance to trajectory-based guidance, applies not only to navigational tasks but also to take-over situations. Trajectory-based guidance improves situational awareness, which can increase the speed and success of takeovers. Therefore, we recommend following the findings of [BBL15]: *To increase take-over speed and success, feedforward the world-fixed vehicle trajectory to communicate the vehicle's intentions*.

9.3.4 Configuration of User Interfaces

Our research has revealed that the level of trust in a vehicle is influenced by the driver's experience, even without vehicle behavior visualization. Experienced drivers tend to be more comfortable with driving scenarios and better understand how a vehicle behaves in certain situations than novice drivers. This is due to their acquired system knowledge and trust, which develops over time (cf., [KM15]). Hence, some visualization elements may not be as essential to experienced drivers as to novices. For instance, adapting the speed display, as suggested by P18: "I'd show the speed in town, but not on the freeway". Similarly, drivers' experience with a specific automated system may also influence their trust level. Over time, people may become accustomed to the vehicle's behavior. Therefore, based on our observations and interview findings, we recommend: *Visualization elements should be configurable or adapt depending on the users' driving expertise with automated vehicles*. Future research should explore the long-term effects of visualization on the user experience and trust.

9.3.5 Design for Motion Intent Communication

In this study, we developed a user-centered design concept with the help of literature. Our small sample of users generated designs that were consistent with our literature review. Our focus was on comparing the traditional icon-based concept for HUDs with the AR concept, as they are fundamentally different. Future work should investigate how these concepts perform when combined, such as in a landmark-based concept or by overlaying both concepts. Additionally, the influence of design parameters on both approaches should be explored. While the color, size, and transparency of elements are similar, they do not match exactly, which could be a moderator of our findings. In the *AR* concept, movement in space alters the visualization, but the queue of future vehicle actions from the *IB* concept was found to be helpful by participants to interpret the time dimension. To help passengers understand the vehicle's intentions, it is important to inform them about current and upcoming actions. Our recommendation for design is: *When visualizing vehicle intentions, feedforward the upcoming actions, e.g., in the form of future trajectories or in a queue element*. Although the *AR* concept has advantages in terms of safety, the *IB* concept has the potential to show information in a more condensed form, which may be necessary for higher automation levels if applications share the windshield screen space. Additionally, the technical hurdle for the AR display is higher because it requires more processing power to generate a real-time and stable overlay on the road scene. Therefore, there is no definitive recommendation for one of the concepts at higher automation levels, as both have advantages and disadvantages depending on the use case.

9.3.6 Limitations

The studies we conducted were conducted in controlled environments that differ from real-world scenarios, particularly regarding motion and auditory perception. Our setups also had a limited field of view, which could affect users' perception of the visualization concepts related to trust, user experience, and overall performance. It's worth noting that the UX can be influenced by automation failures, which were not accounted for in the study. Additionally, we only recruited students from our university who are young, educated and have a high affinity for technology. Therefore, the results must be interpreted cautiously when designing for other user groups with different backgrounds and ages. Regarding technical feasibility, both concepts require parts of the windshield display to be occluded, potentially obscuring crucial information from the road scene. Although the *AR* concept achieved higher UX and trust scores than the icon-based concept, one should keep in mind that the *IB* concept can display information in a more condensed form.

9.4 Implications for Design

We have summarized the implications for design that can help enhance the design of future automated vehicle HUDs for each of the discussed themes.

1. To increase transparency of and trust in an automated vehicle, visualize its intentions and behavior, even during autonomous driving
2. When using novel, stimulating, and attractive visualizations in SAE level 3 (or lower) automated cars, users should be informed that the system might fail, so that they can calibrate their trust accordingly
3. To increase take-over speed and success, feedforward the world-fixed vehicle trajectory to communicate the vehicle's intentions
4. Visualization elements should be configurable or adapted depending on the users' driving expertise with automated vehicles
5. When visualizing vehicle intentions, feedforward the upcoming actions, e.g., in the form of future trajectories or in a queue element

9.5 Conclusion

As the actions of automated vehicles become more complex, it becomes harder to communicate their intentions. In this chapter, we explored two different visualization concepts to communicate the vehicle's intentions: 1) an icon-based concept that indicates the maneuver-based guidance level, and 2) an augmented reality concept that shows the trajectory-based guidance level. We evaluated these concepts for two use cases: 1) the user experience and trust for higher automation levels, and 2) the safety for lower automation levels. We found that:

- AR with its more detailed display of the vehicle's trajectory, led to better safety in terms of take-over rate and speed
- for higher automation levels where trust and user experience are critical factors, both concepts (IB, AR) outperformed the baseline condition, indicating that predictability is an important user experience factor during automated driving

Generally, feedforwarding vehicle intentions can help foster UX and trust, even if people become less involved in the driving task. This will help speed up the transition to automated driving by increasing user acceptance. Overall, our studies provided (1) user perceptions of the HUD concepts, (2) provided insights into the required level of detail for communicating the vehicle's motion intention, (3) validated HUD concepts regarding UX, trust, and safety, and (4) presented design implications for future vehicle systems that help bridging the gulf of evaluation in automated driving.

Chapter 10

Repeated Warning Exposure

This chapter is based on the following publications:

Henrik Detjen, Sarah Faltaous, Jonas Keppel, Marvin Prochazka, Uwe Gruenefeld, Shadan Sadeghian, and Stefan Schneegass. "Investigating the Influence of Gaze- and Context-Adaptive Head-up Displays on Take-Over Requests". In: *Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Ed. by Yong Gu Ji and Myounghoon Jeon. Seoul, Republic of Korea, 2022

In this chapter, we aim to bridge the gulf of evaluation in automated driving by investigating the optimal point between the dose of warnings on head-up displays and the required attention of users and potential effects on UX and safety. Therefore, we conducted a driving simulator study where we varied the required attention by the presence of head-up display warnings (absent, constant, and TOR-only warnings). In addition, we tested a gaze-adaptivity mechanism for the warnings, where warnings fade after being seen by users.

Our study's results provide valuable insights for the design of future HUDs warnings in AVs (cf. *RQIV_3* – Should the system repeatedly warn about potential hazards on the virtual windshield?).

Mistakes in human perception can lead to dangerous situations on the road. In fact, almost half (47%) of all traffic accidents in Great Britain in 2019 were caused by drivers not properly scanning their surroundings, and in 8% of cases, drivers *overlooked* pedestrians [Sta21]. To prevent these accidents and protect vulnerable road users, it's essential to develop driving assistance systems that enhance drivers' visual perception. An expert workshop by Riegler, Riener, and Holzmann [RRH20] emphasized the importance of extending human perception for safety purposes, such as *highlighting potentially critical objects*, in the design of HUDs. These displays also improve transparency by communicating the vehicle's status or perception of the driving environment, leading to a better user experience and acceptance, especially during autonomous driving (cf. previous Chapter 9). Nevertheless, displaying too much information on the HUD can overwhelm the driver and reduce situational awareness [Cur+21], which is especially risky in safety-critical or time-limited situations, such as during TORs. When it comes to level 3 automated cars, using the HUD to convey important information for safety and user experience creates at least three paradoxes that need to be considered:

1. **Transparency Paradox**: *During NDRAs*, an intended increasing transparency feature, such as highlighting critical objects on the HUD, may *distract* the user from the NDRA, thus worsening UX.

2. **Scene Parse Paradox**: *During a TOR*, an intended safety feature, such as highlighting critical objects on the HUD, may add *complexity and distraction* to the driving scenery and decrease the driver's situational awareness, reducing safety.

3. **Exposure Paradox**: *During a TOR*, an intended safety feature, such as highlighting critical objects on the HUD, could be *ignored* over time due to repeated "false" alarm exposure in non-critical situations (stimulus overexposure, cf.: Banner Blindness [Ben98] or cry-wolf-effect [Fu+19]).

The paradoxes mentioned bring up the issue of whether it is essential to have a continuous visual warning on the HUD during the entire ride, and what the potential effects on safety and UX might be.

In terms of transparency, it has been suggested that highlighting detected objects in the surroundings or warning about potential hazards can improve trust and enhance the user experience [Col+21a; Col+21b; Win+19]. On the other hand, a recent study by Eisma et al. [Eis+21] found that augmented visual feedback can make tasks easier, but it also leads to misunderstandings and visual attention tunneling. In contrast, communication about the driving environment and potential hazards can increase complexity and negatively affect situation awareness, as shown by Currano et al. [Cur+21]. In line with these mixed findings, according to a study by Kim and Gabbard [KG19], the effectiveness of Heads-Up Displays (HUDs) varies depending on the visual elements presented, with some being informative and others being distracting. One way to address this is through *gaze interaction*, where elements can be removed once recognized by the user. This approach has been used in the automotive context, e.g., for selection tasks, e.g., for selection tasks [Ker+10; Rie+20]. While studies have shown that HUD elements can improve safety and user experience, the distraction impact on NDRAs and TORs is still unexplored.

This chapter aims to examine whether displaying visual warnings on the vehicle's HUD for the entire journey is necessary and what potential impacts it may have on safety and UX. To achieve this, we conducted tests to estimate the optimal duration of visual warnings and the ease of deactivating already-seen warnings through gaze using the low-effort remove object salience on gaze (ROSOG) interaction method. We compare to a baseline without any HUD elements. Our goal is to gain a better understanding of HUD design for safety and user experience in level 3 automated vehicles (level 3 automated vehicles (L3-AVs)). Our experimental investigation focuses on (1) the advantages of continuously displaying critical objects on the HUD, (2) the effectiveness of the ROSOG mechanism, and (3) the "banner blindness" phenomenon in an automated driving context. Our findings can aid in improving future HUD designs for level 3 automated cars.

10.1 User Study

We conducted a study to investigate how the presence of warning displays in a VR setup affects safety and user experience. The study used different types of HUDs, which varied in whether they appeared constantly, only during TORs, or not at all. Additionally, HUDs responded to the user's gaze (no gaze response, deactivation on gaze-focus). In combination, we tested five conditions in a within-subjects study (see Figure 10.1.c).

To address the Exposure Paradox, users perform numerous TORs during a workload-inducing NDRA. To address the Transparency Paradox, our system continuously provides warnings on the HUD or only during a takeover. To address the Scene Parse Paradox, we are testing a gaze-interaction mechanism that eliminates visually prominent warnings from previously viewed objects, thereby increasing the visual prominence of the remaining objects (ROSOG).

10.1.1 Hypotheses

Previous work has shown that the constant presence of visual warnings on the HUD makes the system more transparent and will improve overall user experience during NDRAs (cf. [Det+21b; Col+21a; Win+19]). However, we think that (**H1**) the constant presence of visual warnings in the peripheral field of view distracts the user during NDRA performance and decreases user experience (cf. *Transparency Paradox*).

The constant presence of visual warnings on the HUD will help prepare for the takeover by increasing situational awareness and improving takeover performance (cf. [Bor+16]). Yet, we think that (**H2**) the constant presence of visual warnings becomes annoying over time, and participants will start to ignore them, impeding the takeover performance (cf. *Scene Parse Paradox*).

In addition, we pose that (**H3**) the gaze-adaptivity of HUD elements reduces complexity and distraction; thus, it helps with scene parsing by removing visual salience from already-seen objects, leading to better takeover performance (cf. *Exposure Paradox*).

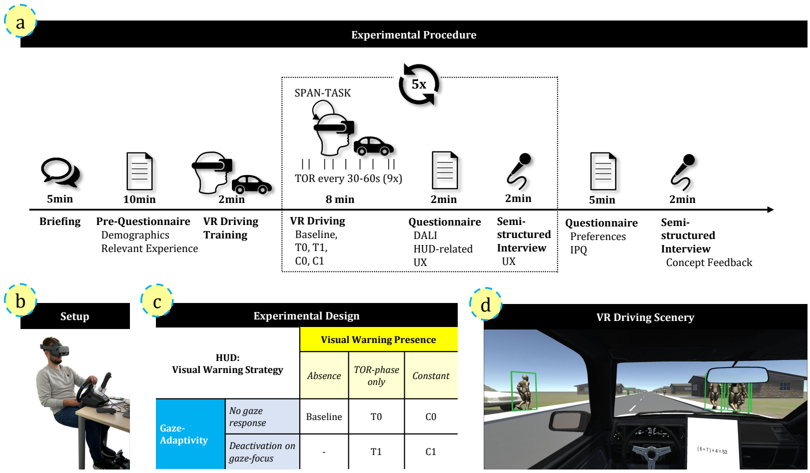


Figure 10.1: (a) Protocol of the experiment; (b) VR setup; (c) Experimental conditions (HUD warning mechanisms); (d) Driver's view – NDRA is on the right and potential hazards get highlighted.

10.1.2 Driving Scenario

To test our hypotheses, we constructed a driving simulation in a suburban area using VR. This scenario was designed to mimic the driving experience after a period of autonomous driving on the highway. Participants were placed in a level 3 automated vehicle that drove on the right side of a two-lane road. The maximum speed limit for this road was set at 30km/h, and the route consisted of a long, straight street with sidewalks and residential gardens lining the path. The driver simply pressed a button on the steering wheel to activate the car's autonomous driving mode. Throughout the simulation, participants faced various hazards that required a reaction time of 5 seconds. These hazards included a pedestrian crossing the road from behind a parked bus on the left, a loose tire rolling into the road from the right, and a ball rolling in from the left.

Simulation setup

We simulated the scenario using VR. We used a tile generator to configure hazard events and mix them on the track. Our VR setup included a Logitech G29 Driving Force, which consists of a driving wheel and standard pedals. We also used a Pico Neo G2 VR headset with a native eye-tracking feature. The headset can track eye gaze, which is vital to our study design. We implemented the scenario using the Unity3D game engine and displayed it on the VR headset. The driving wheel and pedals were used to control the scenario. Please refer to Figure 10.1.b for a visual representation of the setup.

HUD Design

We created the HUD only to show warnings for potential hazards. These warnings are represented by green boxes that surround the hazard, as seen in Figure 10.1.d. To prevent the issue of looking but not seeing, the warning disappears once the hazard is checked. We determine if a hazard is checked by the duration of the fixations, which should last at least 300*msec*, similar to previous research [Rie+20]. If there are five hazards in the scene and the participant looks at three of them, only two will have warnings. Additionally, we use a sliding window that moves with the AV, highlighting all potential hazards within a time frame of 5*sec*, based on the 5*sec* Time to Collision (TTC).

Takeover Task

If the AV detects a hazardous situation, it will signal a takeover request with a beeping sound that lasts for *1 sec*. The audio frequency used is based on the research of Gray [Gra11]. The driver must then take control of the vehicle by steering the driving wheel and either pressing the gas or brake pedals. Once the driver intervenes, the autonomous driving feature stops and the driver must make the correct decision by braking and waiting if there is a person crossing, steering left if there is a rolling tire, or steering right if there is a rolling ball.

Non-Driving Related Task

In order to keep participants engaged in a non-driving task, we had them perform a working memory span task [Mal15]. The task involved verbally verifying mathematical operations, followed by trying to remember a series of consonants that appeared on a virtual tablet to the right of the driver, as in previous work [Fal+18] (as seen in Figure 10.1.d). After five operations and five consonants, the participants were asked to recall and state the previously displayed consonants aloud. The task was displayed on a virtual tablet in the scene. The tablet appeared to the right-hand side of the driver, as in previous work [Fal+18] (cf. Figure 10.1.d).

10.1.3 Measurement

To ensure the validity of our hypotheses during and after the driving scenario, we implemented the following measures to both qualify and quantify them.

Presence in the Simulation

To determine how closely participants' virtual experience matched a real-world experience, we asked about their sense of presence while using a virtual environment. To measure this, we used the IGROUP Presence Questionnaire (IPQ), which has established reliability and validity [RS02; SFR01]. The questionnaire assesses the overall feeling of "being there" on a 7-point scale with different dimensions. It also measures three specific sub-scales: (1) Spatial Presence - the sense of physically being in the virtual environment, (2) Involvement - the degree of attention and engagement in the virtual world, and (3) Experienced Realism - the subjective sense of realism in the virtual environment.

Workload and NDRA Performance

When driving a level 3 automated car, the driver's main concern is to perform NDRAs rather than handling takeovers. The design of the HUD warning can affect the performance of the NDRA task. To measure the success (calculations, memory) and speed of participants' NDRA performance, we use the task as previously described and collect subjective feedback through a questionnaire. We use the driving activity load index [Pau08] (DALI), which is based on the NASA-TLX [HS88], to assess the subjective task load. Unlike the NASA-TLX, the DALI removes the performance and physical demand dimensions and adds the dimensions of perceptual and cognitive load, interference, and situational stress. This adjustment makes it easier to identify the origins of users' impressions and improve the interpretability of the results. We adjusted the interference dimension of the DALI to our takeover scenario and computed a global score (comparable to the RAW-TLX [Har06]) for the DALI using a 100-point scale anchored from very low to very high to assess the overall workload per condition (see Section VII for the full questionnaire).

TOR Performance

When it comes to level 3 automated cars, the TOR presents a safety challenge that must be executed effectively and with caution. Situational awareness, which can be influenced by HUD concepts, plays a crucial role in determining the success of the TOR performance. In our study, we evaluate participants' takeover task performance by measuring the time it takes them to react once the TOR warning is issued and they begin braking/steering (TTR). To gauge the quality of their driving after the takeover, we record the amount of force applied to the brakes and steering wheel, as well as how close they come to any potential hazards. Additionally, we analyze participants' gaze data to see if they are looking at the hazard or other critical objects.

HUD Perception

We used various methods to evaluate how the participants felt about the different warning strategies displayed on the HUD. To quickly assess their driving experience, we asked them to rate it on two scales - positive and negative - using a 7-point Likert agreement score (ranging from very low to very high). We also conducted short interviews to understand the reasoning behind their ratings. We used the same type of Likert scale to measure their perception of the HUD in terms of distraction, helpfulness for task switching, situational awareness, transparency, trust, safety, and acceptance. Additionally, we asked participants to rate their overall preference for a particular HUD warning strategy on a 7-point Likert agreement scale (see Section VII for the complete questionnaire).

10.1.4 Experimental Procedure

The experimental procedure is outlined in Figure 10.1.a. The experimenter first greeted the participants and provided a verbal overview of the procedure. This was followed by a written description of the experiment and consent to participate and allow their data to be used. Afterward, the participants completed a questionnaire regarding their sociodemographics, driving experience, and familiarity with 3D technology. The experiment then commenced.

The participants sat down and became acquainted with the system. We let them know that the system might fail due to insecurities. They had a two-minute drive without a HUD or any other distractions, and there were two takeover prompts. This allowed them to get used to the takeover procedure. They experienced each of the five different conditions in a short 30-second phase, without any distractions or takeovers needed to become familiar with the (non)visualization. After the training phase, data recording of driving and gaze behavior began.

During each recorded run, there were multiple potential hazard events (HUD alerts) that repeated. At specific intervals of 45±15 seconds, one of these hazards required a takeover. As a result, there was a minimum of 30 seconds between two takeover requests. After each run, participants filled out questionnaires at a nearby PC station about their subjective workload (DALI [Pau08] questionnaire) and their experience with the system (custom questionnaire addressing UX, SA, distraction, trust, transparency, safety perception, utility, and acceptance). They were also encouraged to share their positive/negative/other comments about the ride during an interview. We provided all questionnaires through an online platform [10]. The entire process of completing a run, filling

[10] www.soscisurvey.de

out the questionnaires, and conducting the interview took approximately 15 minutes.

Following the completion of five runs, we conducted a conclusive qualitative interview with the participants to gather their overall impressions of the warning design of the HUD and their experiences during takeover situations. We also asked them to identify the strengths and weaknesses of the particular conditions. Finally, we provided the participants with a debriefing. The entire experiment lasted approximately 90 minutes.

Pilot Study

We conducted a pilot study with three participants ($N = 3$) to evaluate our study procedure and VR driving perception. Overall, the participants found the simulation convincing. However, they became accustomed to the fixed 3-second warning-to-hazard interval and began reacting automatically. As a result, we excluded these participants from the analysis and added variation to the time-to-react interval (random between $3sec$ – $7sec$) for the final study.

10.1.5 Analysis

To answer our research questions, we used a mixed-linear effects model (LMEM) [BDB08; FBK14] with the lme4 packagetextitlme4 [Dou+15] in *R*-script [R C21]. LMEMs are robust for analyzing Likert-scale data [Bro19; Kiz14; Sch+20b]. We controlled for participant variation as a random effect and analyzed the effect of conditions as a fixed effect ($response \sim condition + (1|participant)$). We then calculated estimated marginal means using the *emmeans* [Rus22] package and conducted planned contrasts on the conditions using *orthogonal sum contrasts* for our independent variables (warning presence, gaze adaptivity, and interaction effects) and *factor-wise treatment contrasts* for baseline comparison. LMEMs with planned contrasts provide a viable alternative to omnibus tests such as ANOVAs (cf. Schad et al. [Sch+20a]). We used Šidák corrections [Šid67] to account for multiple comparisons and estimated degrees of freedom using the Kenward-Roger procedure [KR97].

10.1.6 Participants

For the final experiment, we invited twelve participants (10 male, 2 female, $M = 25.83$ years, SD=3.56, MIN=22, MAX=32) affiliated with the University of Duisburg-Essen. Participants had a strong affinity for technology (ATI; $M = 4.77, SD = 0.63$) and were experienced with VR goggles ($M = 5.75, SD = 1.35$) and 3D apps ($M = 6, SD = 1.48$). They held a valid driving license for around 8 years ($M = 8.42, SD = 3.32$) and reported to be rather unfamiliar with current ACC and lane-keeping systems ($M = 3, SD = 2.09$) while using their cars relatively fewer times per year than the average driver ($\leq$5k: 6, >5k-10k: 2, >10k-15k: 2).

10.2 Results

10.2.1 Presence in the Simulation

The participants recognized the artificial driving scenery, but reported low experienced realism ($M = 3.48, SD = 1.15$) and medium involvement ($M = 4.06, SD = 1.08$). However, they felt present in the simulation spatially ($M = 5.42, SD = 0.75$) and generally ($M = 5.25, SD = 1.29$).

10.2.2 Workload and NDRA Performance

Figure 10.2 displays participants' estimated workload distribution (DALI [Pau08]) by condition. Participants reported high attention demand, substantial interference between tasks, and stress. They rated temporal and visual demand as mediocre, and auditory demand as relatively low. The overall workload was slightly above the middle of the scale. TOR-only warnings significantly decreased subjective demand compared to baseline for the auditory dimension (t(44)=-2.64, p=0.02, effect=-28.7, CI95[-50.5,-6.8]).

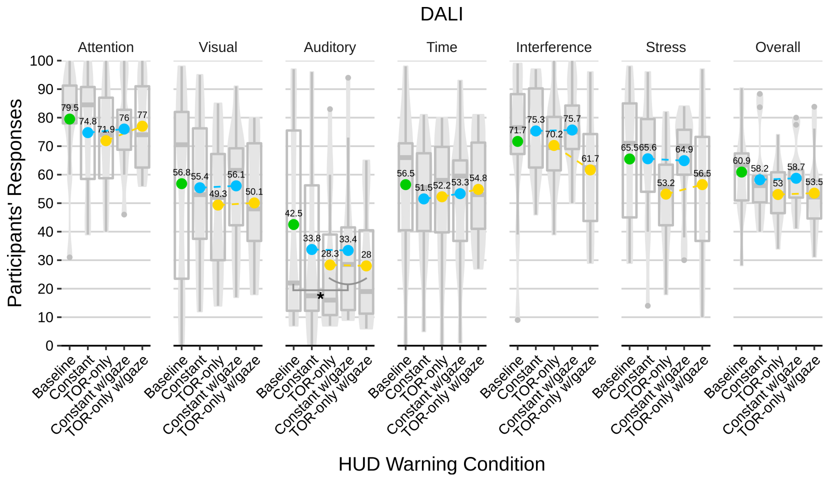


Figure 10.2: DALI ratings by condition – Mean response values are shown as points, while the distribution of responses for conditions is shown using Whisker and Violin plots. For easier comparison, we color-coded the baseline green and the factor *Warning Presence* blue (constant) and yellow (TOR-only). For easier comparison, we color-coded the baseline green and the factor *Warning Presence* blue (constant) and yellow (TOR-only). Significant differences marked with * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Participants completed approximately 60 math tasks in each condition, resulting in a speed of approximately one task every 10 seconds. There were no significant differences in performance between participants. The calculations and remembered letters were mostly accurate and comparable across all conditions (see Table 10.1).

10.2.3 Takeover Performance

Since the driving performance was measured for 9 subsequent TORs, we added the time element (hazard) as a further random intercept in our LMEM ($response \sim condition + (1|participant) + (1|hazard)$).

Table 10.1 displays the results for NDRA and TOR performance. Overall, Gaze-adaptive warnings reduce the safety distance during a TOR and constantly present warnings lead to more applied brake force compared to TOR-only warnings. In particular, gaze-adaptive warnings appear to minimize the safety distance to a critical level during a TOR, i.e., reduce the distance to the hazard significantly compared to non-adaptive warnings (t(514)=-3.25, p<0.01, effect=0.35, CI95[-0.56,-0.14]). Further, constantly present warnings lead to a significantly higher percentage of applied brake force compared to TOR-only warnings (t(514)=2.42, p=0.05, effect=.021, CI95[.004,.037]). The eye-gaze data show that there is a cross-over interaction between factors for the detection of the critical objects (t(516)=2.85, p=0.01, effect=.01, CI95[.003,.172]). With gaze-adaptivity, constant warnings lead to better detection, while without gaze-adaptivity, TOR-only warnings perform better, and the detection efficiency of constantly present warnings decreases. The effects are not different from the baseline. The baseline and the TOR-only condition have the lowest TOR fail rate with $N = 1$. In the other conditions, the TOR fail rate ranged from 4 (Constant, TOR-only with gaze) to 5 (Constant with gaze).

10.2.4 HUD Perception

To assess HUD perception, we used a structured questionnaire and semi-structured interviews after each condition and after all were accomplished.

HUD-related Questionnaire

We exclude the baseline comparison in the following because each question focuses on the perception of the HUD warning concept. Figure 10.3 displays participants' responses to HUD-related questions. Results show low distraction levels (Q1) during trials. In TOR situations (Q2), users rated the

	HUD warning condition					Significant Findings	
	Baseline (B)	Constant (C0)	TOR-only (T0)	Constant w/gaze (C1)	TOR-only w/gaze (T1)		
	$M(SD)$	$M(SD)$	$M(SD)$	$M(SD)$	$M(SD)$	factor effects	vs baseline
NDRT Performance							
Completed tasks *n*	60.00 (12.06)	60.83 (13.46)	62.50 (16.58)	62.50 (16.03)	61.25 (13.34)	-	-
Correct calculations %	.97 (.02)	.97 (.04)	.97 (.03)	.98 (.02)	.97 (.06)	-	-
Correct memorized words %	.85 (.12)	.86 (.10)	.84 (.14)	.83 (.13)	.84 (.11)	-	-
TOR Performance							
Time-to-react *ms*	1825.53 (606.48)	1872.77 (797.29)	1922.48 (797.62)	1964.43 (779.64)	1941.54 (882.62)	-	-
Min. distance to hazard *m*	3.12 (0.59)	3.20 (0.66)	3.37 (0.57)	3.1 (0.63)	3.12 (0.58)	Gaze-adaptivity***	-
Mean braking %	.06 (.05)	.05 (.05)	.07 (.06)	.06 (.05)	.07 (.06)	Warning Presence*	-
Mean steering %	.04 (.03)	.03 (.03)	.03 (.02)	.03 (.03)	.03 (.03)	-	-
Looked at critical object %	.96 (.19)	.98 (.14)	.92 (.28)	.95 (.21)	.99 (.10)	Gaze-adaptivity x Warning Presence**	-
Looked at potentially crit. obj. %	.62 (.45)	.62 (.38)	.62 (.36)	.70 (.40)	.65 (.38)	-	-
Unresponded TORs *n*	1	4	1	5	4		

Table 10.1: NDRA performance and driving performance measures during TORs by condition – "Significant Findings"-column comprises the results of the LMEM orthogonal sum contrasts labeled as "factor effects" and of the treatment contrasts labeled as "vs baseline". Significant differences marked with * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

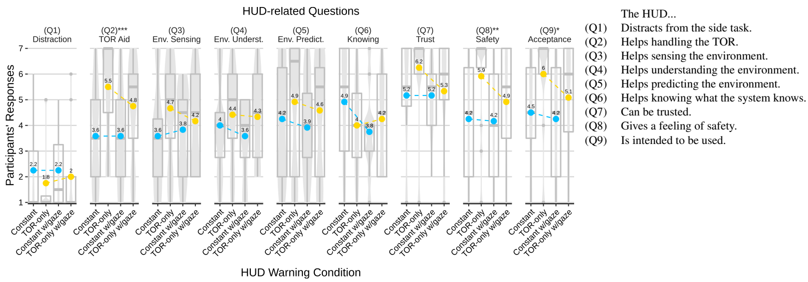
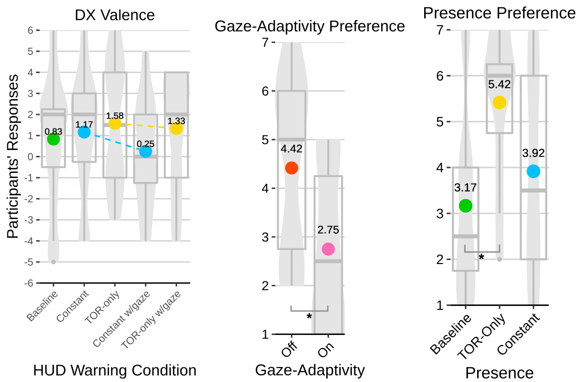


Figure 10.3: HUD-related questions by condition – Points and numbers show the mean response values, Whisker and Violin plots show the distribution of responses for conditions. For easier comparison, we color-coded the baseline green and the factor *Warning Presence* blue (constant) and yellow (TOR-only). Significant differences (next to question label) marked with * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

HUD concept significantly better when warnings were tor-only rather than constant ($t(44)=4.09$, $p<0.001$, effect=3.08, CI95[1.57,4.60]). Situational Awareness (Q3–Q5) support, transparency (Q6), and trust (Q7) were perceived as medium to rather high. Regarding safety (Q8), constant warnings were rated around in the middle of the scale, whereas TOR-only warnings led to a significant shift of that perception to a high level ($t(44)=2.78$, $p=0.01$, effect=2.41, CI95[0.78,4.01]). Similarly, TOR-only warnings significantly increased the participants' intention to use (Q9) the HUD ($t(44)=2.65$, $p=0.03$, effect=2.33, CI95[0.56,4.11]) compared to constant warnings.

Driving Experience

After each condition, we evaluated the driving experience using both a positive and negative 7-point Likert scale. Figure 10.4.a illustrates the difference in driving experience (positive ratings minus negative ratings) across conditions. While neither positive nor negative ratings differed significantly between conditions, they slightly leaned towards a positive driving experience.



(a) (b) (c)

Figure 10.4: Driving Experience and Preference Ratings – Shape and color-coding as in previous figures, plus factor *Gaze-adaptivity* in red (off) and pink (on). Significant differences marked with * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Preference

Participants rated their preferences on a 7-point Likert scale after experiencing all conditions. For *Gaze-adaptivity* preference, ratings significantly increased towards the middle of the scale without gaze-adaptivity (t(22)=2.55, p=0.03, effect=1.67, CI95[0.23,3.11]). For *Warning Presence* preference, ratings were rather low for baseline, medium for constant warnings, and rather high for TOR-only (see Figure 10.4.c). TOR-only warnings scored significantly better than the baseline (t(22)=2.74, p=0.04, effect=2.25, CI95[0.55,3.95]).

Qualitative Interviews

Similar to qualitative content analysis of cf. Mayring [May10], for the interviews, we quantified the number of codes by the number of mentions (i.e., $N = 12$). Participants in the driving simulation adapted to the virtual environment over time ($n = 8$). However, they found the TOR scenario repetitive and could predict TOR situations after a while ($n = 5$). No learning effects were observed in the driving data. Regarding the NDRA, users generally perceived the task as difficult ($n = 6$), stressful ($n = 7$), and tiring ($n = 1$) due to fatigue over time ($n = 7$). Nonetheless, some participants felt stimulated, excited ($n = 3$), or challenged ($n = 1$) by the task. They also felt competent and enjoyed driving ($n = 3$), and some did not find the TOR-assistive warning system necessary ($n = 3$, P2: *"I don't really need help, I am a real driver!"*).

During the study, participants reported that a beep was enough to shift their attention ($n = 9$) from the NDRA to the TOR task. However, one participant found the beep sound annoying. With regards to the TOR task, participants found visual warnings helpful as they increased awareness of the hazards (P12: *"[...] the HUD really helps to estimate the situation when the TOR arises."*). However, most participants found the TOR situation challenging ($n = 7$), especially without a visual aid. A few participants commented that they could not distinguish between the conditions with constant and TOR-only presence of the visual warnings due to the challenging NDRA ($n = 4$). Nevertheless, most participants said that the TOR-only warnings were less distracting and less annoying over time ($n = 11$, P5: *"While doing the tasks, I looked further down on purpose not to see the distracting boxes in my peripheral vision."*). On the other hand, the constant warning presence increased trust (P7: *"You know what the car knows."*).

One participant appreciated the gaze-adaptive warnings as a compromise to information complexity. However, half of the participants ($n = 6$) found the disappearing warnings confusing (e.g., P5: *"Did the car identify the person behind the bus as a hazard and now the box is deactivated or is there another person coming?"*) or actually distracting (e.g., P11: *"A disappearing box often triggers an attention switch to another box. That is the opposite of what was intended."*).

To improve the HUD, participants suggested highlighting occluded objects ($n = 8$), such as a warning about a person behind the bus, and adjusting the visualization ($n = 4$). Adjustments could include color-coding different objects to avoid missing important ones or providing more information such as hazard trajectory and velocity.

10.3 Discussion

In this discussion, we will analyze our data in relation to the HUD paradoxes, suggest areas for further research, and acknowledge the limitations of our study.

10.3.1 Transparency Paradox

Various studies [Det+21b; Col+21a; Win+19] suggest that having constant visual warnings on the HUD can make the system more transparent and improve the user experience during NDRA. Additionally, this can increase situational awareness and prepare the user for taking over control of the vehicle. However, in our experiment involving multitasking in level 3 automated driving, we found evidence that contradicts these assumptions. Our interviews confirmed **H1** that having constant visual warnings in the peripheral field of view during NDRA performance actually distracts the user and decreases the overall user experience. Instead, our participants preferred warnings to be presented only during TORs, while the constant presence of warnings was rated ambiguously. Users perceived the TOR-only warning system as safer and more acceptable, as it was less distracting and annoying over time.

Our findings suggest that the workload of NDRA can moderate the trade-off in the Transparency Paradox. We intentionally chose a challenging NDRA task for the experiment to ensure that the TOR task was not too simple, as this would have made it easy for participants to focus on and handle the TOR situations. In the future, a practical approach to the Transparency Paradox would be to adapt the presence of HUD warnings to the workload of NDRA. This could be achieved by hiding or reducing the salience of warnings when a potentially complex activity (such as smartphone use) is detected and increasing salience (such as hue) when a less complex activity (such as looking out of the window) is detected. Further research should be conducted to compare different NDRA load levels across warning presence to investigate the Transparency Paradox in more depth.

10.3.2 Scene Parse Paradox

We employed a gaze mechanism to reduce the visual clutter. Our hypothesis (**H2**) was that the gaze-adaptivity of HUD elements would reduce distractions and improve scene parsing, resulting in better driving performance. However, our findings were contrary to this hypothesis. We observed that participants were significantly less inclined to interact with warnings that responded to their gaze. This led to a decrease in driving quality, as the distance to potential hazards was reduced. We believe that this unexpected outcome may be due to participants not being accustomed to the gaze deactivation of visual warnings, which can be confusing or distracting at first. This unintended gaze-interaction phenomenon is known as the *Midas touch* problem [Jac91]. Our interviews with participants confirmed that half of them found the gaze interaction confusing or distracting. The distraction could be explained because removing visually salient HUD elements (color) from the scene can trigger another visually salient movement (disappearing), thus maintaining the complexity level of the scene parse. Additionally, after a HUD element disappears, focusing on critical objects and ignoring others that become more salient is more challenging, as stimulus-driven capture prevails over attention-driven capture. Future research could explore other techniques to reduce complexity or test gaze-adaptivity across different levels of scene complexity to understand the Scene Parse Paradox better.

10.3.3 Exposure Paradox

Our hypothesis (**H3**) was that constant visual warnings would become annoying over time and cause participants to ignore them, which would negatively impact their takeover performance. Through interview data, we have found that most participants did indeed find constant warnings to be annoying. However, the takeover performance was not measurably affected, and the baseline led to the most reliable responses with only one missed takeover request in total. It is possible that the adverse effect was induced just before the condition ended. On the other hand, participants also reported finding takeover requests more challenging in the absence of warnings. It appears that the anticipated trade-off of the Exposure Paradox exists. Nonetheless, future studies should examine the presence of warnings with varying task demands to determine the beneficial effects of constant warnings during less challenging tasks. Additionally, capturing data over a longer timeframe would help induce more substantial banner blindness/alarm fatigue.

10.3.4 Limitations

Our study was carried out in a virtual reality driving environment. Participants reported feeling immersed in the simulation, but rated the realism as relatively low and their involvement as medium. The virtual reality setup may have affected their perception of safety, trust, and overall user experience. We anticipate that these factors would change in a more realistic setting, such as a test track. However, our sample size was small, and the effects of the HUD conditions were not conclusive due to the wide confidence intervals. With a larger number of participants, we may observe statistical significance in some of the data trends. For instance, the TOR-only warnings appeared to perform better in terms of workload than constant warnings, based on visual data inspection.

It is worth noting that our sample predominantly consisted of individuals who were male, educated, technologically skilled, and of European background. As a result, it is possible that the outcomes of our experiment may differ for samples with different characteristics. However, we believe that our study serves as an initial exploration into the HUD paradoxes, and further research is needed to gain a deeper understanding of this topic.

10.4 Conclusion

Visual warnings can be beneficial and supportive as they enhance situational awareness, improve the takeover process, and improve the system's transparency. Nevertheless, it can also be bothersome and disruptive, resulting in the opposite effect of what was intended. This chapter investigated three potential design conflicts (we referred to these as Transparency, Scene Parse, and Exposure Paradox) in a VR simulator study. Thereby, we aimed to integrate previous findings from previous studies and attention theories. We reduced the required attention for HUD warnings systematically reduced through 1) situative display (constant, TOR-only) and 2) gaze-adaptivity. We compared all warning mechanisms in terms of UX and safety against each other and a baseline without any warnings. In particular, we found:

- regarding the presence of HUD warnings, it is subjectively more acceptable, helpful, and safer for drivers to have visual support during the TOR phase only
- reducing scene complexity is necessary, but adaptive scene complexity reduction through gaze bears the risk of distraction (disappearing color-box creates salience) for nearly half of the users
- users subjectively perceive constantly presented HUD warnings as annoying and distracting after a while

Interestingly, the need for safety was best matched with the TOR-only display of warnings. In conclusion, these findings highlight the need for (a) HUD adaptation based on passenger activity and potential TORs and (b) sparse use of warning cues in forthcoming HUD designs. We encourage future work to address HUD warning presence regarding the timing and complexity of level 3 HUDs to understand the design trade-offs better and not broaden the gulf of evaluation in automated driving before implementing these technologies on the road.

Part IV – Summary

In this part, we looked into the changing driving activity context with a focus on the user evaluation of driving task automation. More specifically, we explored the potential of augmented reality applications for automation transparency to increase understandability and predictability.

As supported through our online survey (Chapter 8), users do not fully understand their automation features – leading to misinterpretations of automation capabilities and non- or potentially dangerous use. As one of the first touchpoints with a system, the User Onboarding experience is important to build adequate mental models to interpret better when and how to use the automation. AR apps, compared to traditional text-based manuals, can increase the users' motivation to deal with Onboarding processes in the first place and improve spatial understanding of interaction procedures (Chapter 8). In addition to the a-priori understanding of vehicle automation, communicating the current perception and intent of the vehicle can further help to understand and predict the automation and thus help to evaluate one's goals with the current state. We showed that augmenting the driving scene through feedforwarding the upcoming vehicle actions increases UX and trust during autonomous driving (Chapter 9). When trajectories are spatially projected onto the scene, as in our contact-analogue HUD concept, users can detect automation failures better and take over the driving in time when driving automated. However, visual scene augmentation has to be designed carefully and adaptive to the activity context since these elements require users' attention. In the case of feedforwarding potential hazards (Chapter 10), constantly augmenting the driving scene with warnings is perceived as useful, but, at the same time, can be annoying for users and distract from NDRAs or from perceiving potentially critical parts in a driving scene during a TOR.

Overall, our work indicates that overcoming the gulf of evaluation in automated driving improves UX and the safety of future AVs. Further, it shows the potential of AR and helps to develop AR components for a holistic UX with vehicle automation before and during the ride.

V

Conclusion & Future Work

Chapter 11

Conclusion & Future Work

In this chapter, we first reflect on our research questions (Section 11.1). This includes the changing user needs and goals and the gulfs of interaction (cf., Section 1.2). Throughout the reflection, we point out recommendations for the design of future mobility services (Section 11.2). The recommendations relate to different areas of future mobility service design (see Figure 11.1).

In specific, they relate to the overall design process (P), the interior design (I), interface design for control (C), and interface design for visual communication (V). We highlight the scope of these recommendations, whether they apply to all levels of automation of the driving activity, and which design challenge (cf. Section 2.5.1) they tackle. After reflection of this thesis, we identify topics for future research (Section 11.3), namely the challenge of finding the right level of abstraction for control interfaces, the ecological validity of automated driving research, the adaption and integration of interfaces into different contexts, and the inclusion of people with different abilities. Lastly, we relate this thesis' finding to the bigger picture of transforming mobility (Section 11.4).

11.1 Reflecting on the Transformation of In-Vehicle Activities

In the following, we reflect on our contributions towards the user and context understanding of future autonomous mobility services (*RQII*) and the changing interaction regarding the driving task, i.e., the gulfs of execution (*RQIII*) and evaluation (*RQIV*) of automated driving, or, more generally, the gulfs of interaction in automated driving.

11.1.1 How to will user needs and goals change in autonomous mobility services?

Understanding the users' needs and the context of future autonomous mobility services contributes to a better understanding of the challenges for acceptance.

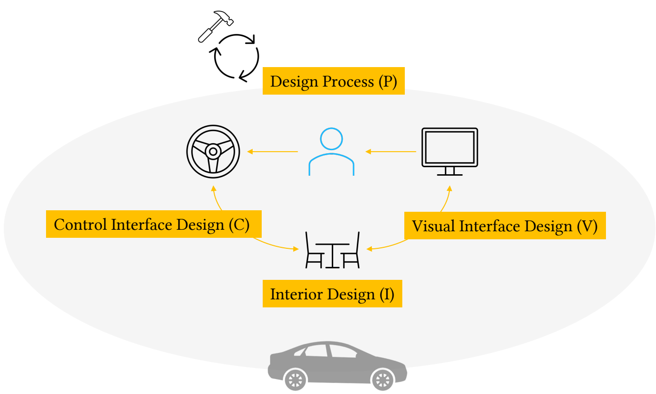


Figure 11.1: Design recommendation areas – Based on reflection of our findings, we pose design recommendations for the overall process (P), the vehicle interior (I), the control interface design (C), and for the visual communication (V).

When we know what users expect from a system, e.g., to be transparent, safe, controllable, and not boring, we can address their matters and create a pleasant journey experience for them. For that, in the tradition of user-centered design or co-design, we have to confront users with the new activity context in order to collect their feedback, e.g., through thought experiments in online surveys (cf. Chapter 4) or real-world experiences (cf. Chapter 3). Further, in the sense of activity-centered design, we can go beyond the user and look at the context of the future driving activity – and consider design possibilities that might not be available yet but bear the potential to create better user experiences. Technological possibilities include AR on WSDs, Vehicle-to-X (V2X), or seamless integration of user devices such as wearables in in-car services. Such technological possibilities enable new activities in the car, e.g., the mobile office. Nonetheless, one of the most promising possibilities from a societal perspective is the potential accessibility that autonomous driving bears. To facilitate ideation and discussion about the potential of future autonomous mobility services, we can provide design guides and frames, e.g., for the inclusiveness of autonomous mobility services (cf. Chapter 5).

Overall, we contributed to understanding changing user needs and goals within more and more autonomous mobility services (*RQII*). In that regard, we provided insights to the user-related research questions *RQII_1*, *RQII_2*, and *RQII_3*, which we will summarize in the following. These insights help to better understand the future driving activity context and corresponding requirements, such as non-driving-related activities or users' needs during the ride (cf. Figure 11.2).

Regarding *RQII_1* (How is a real-world experience changing needs and goals?), we observed the needs and perceptions of autonomous mobility service users in the real-world over multiple rides (cf. Chapter 3). The changing perception of WoZ vehicle was most notably the change of personal reliance on the system, users reported getting used to the service, and one person even wished for a less defensive driving style after appreciating the same style in the first rides. Therefore, we pose our first recommendation for design as follows (C1): *To increase trust in and acceptance of autonomous mobility services, make driving styles adaptable for users.* Regarding the users' activities, user devices will play an important role. We found that smartphone and laptop use for work and entertainment are likely future activities, comparable to other

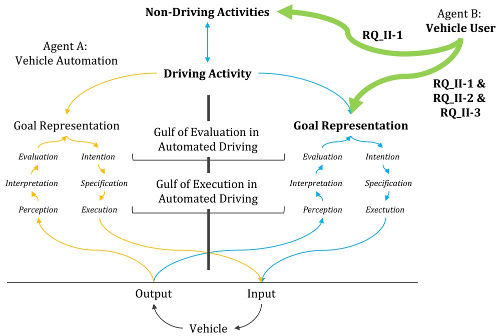


Figure 11.2: Contributions within the second part of this thesis towards understanding the concrete activity context and underlying needs & goals of users.

non-road bound (e.g., railway) transport modes. Thus, we recommend (I1): *Include possibilities to integrate user devices seamlessly into the changing activity context and automation modes, e.g., for work or entertainment during automated and autonomous driving.*

Regarding *RQII_2* (How to assess diverging patterns of needs and goals?), integrating diverse user needs and goals into a one-fits-all perspective is hard in the case of autonomous mobility services. We utilized the Q-Method to assess attitudes towards autonomous public transport services. We found four prototypical groups (cf. Chapter 4): Technical enthusiasts ("A system rather than a person will be more useful.") are enthusiastic about new technologies and do not care much about a human driver, while social skeptics ("You cannot trust technology.") concentrate on the social consequences of driving automation and report a diminishing feeling of safety without a human driver. Service-oriented non-enthusiasts ("I do not see the benefit from a service perspective of using a driverless system.") concentrate on the supposedly reduced service quality of an artificial driver, whereas technology-oriented non-enthusiasts generally have no problem with an artificial driver but fear that the system is not mature enough ("I believe that they might not be equipped to do what they are supposed to do.") and require, e.g., concrete vehicle status displays. These clustered attitudes help prioritize autonomous mobility users' design requirements and help to communicate, targeting the users' specific attitudes and goals.

Based on these findings, we make our third recommendation for design (D1): *To increase the acceptability of autonomous mobility services, consider the diversity of potential user attitudes, e.g., through creating personas based on technology-openness, service- and social-orientation.*

Regarding *RQII_3* (How to include users with special needs and goals?), to include the needs and goals of non-average users, designers must include them in their autonomous mobility services' creation process. We presented a design framework based on insights from interviews with experts in the care domain and a literature review on accessibility features (cf. Chapter 5). We constructed the framework along the characteristics of the users, journey context, mobility service, assistive technology interaction, and training. The framework systematically helps automotive designers and researchers ideate, approach, and document accessibility requirements. With such tools at hand, we recommend (D2): *To make future mobility services more inclusive, consider a broad range of users with potential impairments in the creation process as well as the journey context, mobility service, assistive technology interaction, and training.*

11.1.2 How to bridge the gulf of execution in automated driving?

During human-vehicle cooperation, the two agents' interaction cycles can be entirely separate (control transitions, vertical task sharing) or integrated (cooperation, horizontal task sharing). In this thesis, we focused on temporary control transitions that help to close the *gulf of execution* in automated driving. There are multiple situations during automated driving where users might want to overtake and intervene in the otherwise autonomous driving process, e.g., to overtake a truck or take the next highway exit. In order to express the intention to intervene, we used a low-level maneuver approach building upon an existing set from Schreiber [Sch12] that provides atomic driving

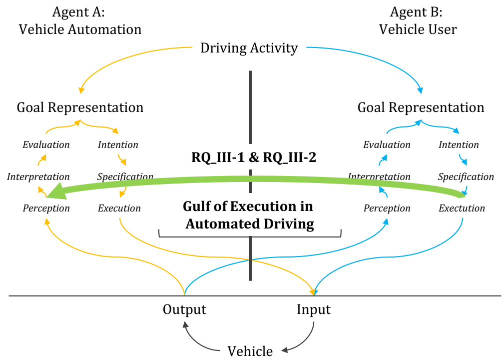


Figure 11.3: Contributions within the third part of this thesis towards bridging the Gulf of Execution in Automated Driving.

maneuvers like "lane change left". From this set, more complex maneuvers like overtaking can be constructed. The central contribution of the second part of the thesis lies in the action execution layer: We extended prior work that is based on touch interaction with other natural input styles (cf. Chapter 6), i.e., speech and mid-air gesture command sets, and compared their feasibility under different circumstances (cf. Chapter 7). We suggest combining touch and voice maneuver input mechanisms from our experiments in future AVs cockpits. Providing control over the driving activity to users satisfies their need for control. Thus, providing control interfaces could be one approach to tackle the challenge of *Competence & Control* Section 2.5.1, as well as to a more pleasant autonomous driving experience (cf. challenge of *Positive Experiences*).

In sum, we contributed to bridging the gulf of execution in automated driving (*RQIII*). We provided insights into the execution of maneuver-based control in the more specific questions *RQIII_1* and *RQIII_2*. These insights help to inform the design of future control interfaces for automated and autonomous driving (cf. Figure 11.3).

Regarding *RQIII_1* (How would users express maneuvers via voice or mid-air gestures?), users perform non-driving-related activities during autonomous driving where traditional car interfaces are not the best option. In a user-centered design process (cf. Chapter 6), we created a voice and mid-air gesture alphabet to communicate desired maneuvers to control the vehicle. Notably, one could reduce the maneuver to an even smaller set as directional commands (e.g., turn left and lane change left) often use the same voice or mid-air gesture so that these commands can account for most of the situations during autonomous driving. We found that voice control is preferred over mid-air gestures by users and is faster to execute. Based on these findings, we formulate our fifth recommendation for design as follows (C2): *Provide a memorable voice-controllable maneuver set to users to keep them in control during automated or autonomous driving.*

Regarding *RQIII_2* (Which direct input modality is most feasible for expressing driving maneuvers?), we compared direct and natural input styles in two experiments, i.e., touch, voice, and mid-air gestures. We showed that all modalities are generally feasible for control interventions regarding usability and workload. However, in multitasking settings, users utilize interaction styles that differ from the non-driving-related activity – with one exception: when users are on the phone, they tend to use touch interaction. Therefore, we recommend (C3): *To ensure directability during automated or autonomous driving in different situations, provide redundant control modalities.*

11.1.3 How to bridge the gulf of evaluation in automated driving?

During journey phases where no human control or supervision is needed (automated or autonomous driving), the vehicle could provide no driving-related information to users since, in today's cars, this information is only needed if the human takes control over and monitors the vehicle. However, driving with a black box automation system can be unsafe regarding task cooperation and handovers. From our studies, we argue that augmenting the users' journey with information about the system task performance leads to better cooperation experience and performance and thus helps to bridge the *gulf of evaluation* in automated driving. We have seen that drivers report training needs even after owning a vehicle for a while. Explaining upcoming interaction procedures by augmenting the Onboarding procedure with spatially explicit information can reduce interaction errors for the later task, automated parking in our case (cf. Chapter 8). Another way to reduce the gulf of evaluation is to communicate the vehicle *perception* to the users. Augmented perception is especially relevant for potential hazards during automated driving. However, communication should adapt to the current situation. During automated driving, users get distracted when too much information is displayed. Thus, providing *on-demand* feedback, e.g., only highlighting critical objects during critical situations, helps to increase the overall experience. For information such as the vehicle's motion intentions, there is also an impact on safety: users will know when the vehicle is about to make an error and intervene if necessary (cf. Chapter 9). Further, the feedforward helps to know what the vehicle does and is about to do, which increases trust and UX even if the vehicle drives safely without expected handovers. Giving users a better understanding of what the automation is capable of in a situation and how it will behave in a specific driving situation generally contributes to the challenges of *Trust & Transparency*. In situations where drivers might be required to take over also to the challenge of *Performance & Safety*.

Overall, we contributed to bridging the gulf of evaluation in automated driving (*RQIV*). We provided insights into the users' perception and interpretation of vehicle actions in the more specific questions *RQIV_1*, *RQIV_2*, and *RQIV_3*. These insights help to inform the design of future control interfaces for automated and autonomous driving (cf. Figure 11.4).

Regarding *RQIV_1* (Can augmented reality benefit vehicle automation User Onboarding processes?), in our online survey, we noticed that users of modern vehicles often trust their assistant systems. Nevertheless, they report misunderstandings and the wish for training simultaneously. In a real-world experiment with a Tesla, we educated users about automated parking through either a handbook or an AR App. The outcome was that the Onboarding process with the AR app was more pleasant to users, and they made fewer errors during task completion. Based on these findings, we pose our seventh recommendation for design (V1): *To increase task performance, provide pleasant automation onboarding to users (e.g., through AR instructions).*

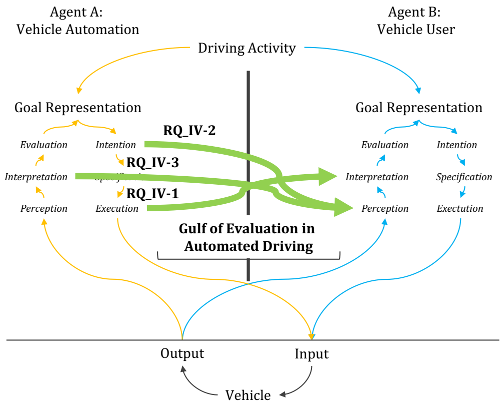


Figure 11.4: Main contributions within the fourth part of this thesis towards bridging the Gulf of Evaluation in Automated Driving.

We communicated vehicle intentions to users to make driving automation more predictable. Our experiments show that any intention visualization improves the user experience during autonomous driving, yet users perceived our AR approach as more novel and attractive. Thus, we recommend (V2): *To increase UX during autonomous driving, visualize vehicle motion intentions.* During assisted or automated driving, the AR approach can also improve the quality of takeover decisions. Based on this finding, we pose our ninth recommendation for design (V3): *Visualize future vehicle trajectories (e.g., through AR displays) to increase safety during automated driving.*

Augmentation of the drivers' view with potential hazards directs attention to the scene, which can create distractions during automated driving. We designed HUD warning strategies that adapt to the situation and the driver's gaze to reduce visual clutter. Users perceive the gaze-adaptivity of warning elements as confusing because the object highlight (bounding box) removal creates a switch of attention to the next highlight. Whereas constant warnings have a high variance in users' ratings, they perceive the on-demand warning strategy as safer, more helpful, and more acceptable. Further, they prefer on-demand warnings over the baseline. Based on these observations, we formulate our last recommendation for design (V4): *To increase acceptance and UX during automated driving, avoid constant visual augmentations of potential hazards yet provide them on-demand (e.g., during a TOR).*

11.2 Summary of Recommendations for Future Mobility Design

In the following, we summarize the previously posed design recommendations and point out their scope in terms of driving automation task (cf. Section 2.1.3) and challenge for design (cf. Section 2.5.1). Our design recommendations target four different areas of future mobility services.

The first area is the *design process* of future mobility itself: Designers should be sensitive to different abilities (P2) and attitudes (P1) of users. To remind them of the process, constant exposure through user consultation, personas, guidelines, etc., could help.

The second area is the *interior design*: During automated and autonomous driving and transitions, users perform activities like work or entertainment. Thus, vehicles should integrate possibilities to support these activities, and, at the same time, account for driving situations and possible transitions between driving modes (I1).

The third area is the *control design*: Designing interfaces that satisfy the need for control of users is an important aspect for acceptance of future mobility services. During automated or autonomous driving, control could be exerted on a higher level, such as configuring driving styles (C1), or on a lower level, such as exerting specific driving maneuvers (C2). In any case, the control interface has to be available in various contexts (see also I1) and, thus, be redundant in terms of modalities (C3).

The fourth and last area is the *visual design*: With AR technologies, Onboarding strategies for dealing with driving automation can be improved (V1). Communication of system states like the upcoming driving maneuvers via

#	Recommendation	Scope						
		Task			*Challenge*			
		Assisted Driving	Automated Driving	Autonomous Driving	Safety & Performance	Trust & Transparency	Competence & Control	Positive Experiences
	DESIGN PROCESS							
P1.	To increase the acceptability of autonomous mobility services, consider the diversity of potential user attitudes, e.g., through creating personas based on technology-openness, service- and social-orientation.	✓	✓	✓	✓	✓	✓	✓
P2.	To make future mobility services more inclusive, consider a broad range of users with potential impairments in the creation process as well as the journey context, mobility service, assistive technology interaction, and training.	✓	✓	✓	✓	✓	✓	✓
	INTERIOR DESIGN							
I1.	Include possibilities to integrate user devices seamlessly into the changing activity context and automation modes, e.g., for work or entertainment during automated and autonomous driving.			✓				✓
	CONTROL DESIGN							
C1.	To increase trust in and acceptance of autonomous mobility services, make driving styles adaptable for users.			✓		✓		✓
C2.	Provide a small voice-controllable maneuver set to users (e.g., left, right, start, stop) to keep them in control during automated or autonomous driving.		✓	✓		✓		✓
C3.	To ensure directability during automated or autonomous driving in different situations, provide redundant control modalities.		✓	✓			✓	
	VISUAL DESIGN							
V1.	To increase task performance, provide pleasant automation onboarding to users (e.g., through AR instructions).	✓	✓		✓	✓		✓
V2.	To increase UX during autonomous driving, visualize vehicle motion intentions.			✓		✓		✓
V3.	Visualize future vehicle trajectories (e.g., through AR displays) to increase safety during automated driving.		✓		✓	✓		
V4.	To increase acceptance and UX during automated driving, avoid constant visual augmentations of potential hazards yet provide them on-demand (e.g., during a TOR).		✓		✓	✓		✓

Table 11.1: Summary of recommendations for design.

virtual windshields, will help to increase users' experience and acceptance of future vehicles (V2). However, when the user has to take over from the automation during assisted or automated driving, displaying a concrete trajectory (V3) and being sparse with attention-drawing visualizations (V4) helps to prepare users for handovers.

Overall, our recommendations help to design the transition towards future autonomous mobility services that a variety of users can adopt and that are controllable and transparent in different situations.

11.3 Future Work

Throughout this thesis, we have taken an interaction-centered perspective on the driving activity transformation for vehicle users. However, we could only address a selected collection of challenges and possibilities in the scope. In the following, we present further design opportunities that future research could tackle, from which we discuss four: new control interfaces, the need for increasing studies' realism, adaptation, and accessibility. The discussion can help to inform future research on autonomous mobility services. Finally, we put our contributions into the bigger picture of the transforming mobility market.

11.3.1 Designing Control Interfaces with Different Abstraction for Different Situations

This thesis contributed to controlling the driving task in autonomous driving settings (cf. Part III). We concentrated on direct interventions in the driving process of a single user that uses a small set of atomic maneuvers with established interaction modalities, i.e., horizontal task sharing on the maneuver level. Nonetheless, direct, maneuver-based intervention is one of the multiple possibilities to provide control to users: Intervention could also happen through trajectory-based intervention, e.g., through joysticks or gaze, and in different situations, e.g., while executing NDRAs – exploring this design space and user preferences seems to be a meaningful step for future work. Besides the three direct and established input modalities we investigated, there is room for testing more implicit forms of cooperation, where the car recognizes the user and the driving situation and adapts its driving style accordingly.

11.3.2 Increasing the Ecological Validity in Automotive Research

Current research on autonomous mobility services is often limited to lab settings. Especially for studies on acceptability, UX, and trust in automated or autonomous driving, we see the need for real-world studies that go out of the lab. To archive increased ecological validity, we need 1) *realisitc study setups* that we 2) *repeat* over a long period.

Regarding the first aspect, we have to induce a high level of realism in our experiments and prototypes so that users have a realistic perception of autonomous mobility services. From our WoZ study (cf. Chapter 3), we have seen that users behave differently in a real-world setting from that what they suppose in online studies. However, we need to determine which kind of setup works best for which kind of phenomena of interest. For example, it would be interesting to see, given the same task, using a variety of experimental setups from videos in online questionnaires, driving simulators, VR simulations, AR setups, to real-world experiments (for a taxonomy, see Section 2.5.3), if the users respond to current measures of trust or UX differently. Starting with a literature review on long-term studies and their research methods could be a good starting point for future work.

The second aspect is especially relevant for studies on adaptive systems and psychological constructs such as trust, where users' evaluation or perception changes over time. For example, in our study on HUD warning, we found no performance degradation through repeated exposure through TORs but adverse effects on UX. Nevertheless, we assume that the annoying perception of the HUD warnings would influence performance over time. Thus, increasing the study duration might be required to observe such phenomena.

In addition, a combination of the first (setups) and second (repetition) aspect might be an interesting point for future work: The different types of study setups could influence the assessment of phenomena over time. One example is that a VR study might be novel and attractive for users who have never experienced such setups. In contrast, the same study in a real car might be perceived less attractive if the users are constant car users, and UX assessments could inherit this setup bias. Another example is that WoZ studies are hard to repeat because participants already know the simulated part of the setup during another repetition. Overall, examining the qualities of study setups from short- to long-term seems meaningful future work.

11.3.3 Seamless Adaptation and Integration of Interfaces

In some of our studies, users had quite ambiguous opinions on our presented design concepts. For example, users preferred different input styles for car control (cf. Chapter 7) or preferred other types of visualizations on the HUD (cf. Chapter 9, Chapter 10), or had a generally contrasting motivation to use the system Chapter 4). To include contrasting interface perceptions, vehicle manufacturers should adapt their systems to the users' preferences, e.g., driving style or trust. Adaptation requires detecting and combining features of interest, e.g., driver emotions, task engagement, and current traffic situation, to adapt the vehicle's interfaces.

We saw that in our WoZ study: The defensive, speed-limit matching driving style was appreciated at first, but later, after a few overtakes and honking cars, a participant wished for a slight increase of the speed (over the limit) to match the surrounding cars' speed. Investigating such ambiguous mixed traffic scenarios, where users expect the vehicle to bend the rules and where social norms and regulations collide that could negatively influence the UX over time, could be part of future work.

During assisted or automated driving, it is essential to match the users' trust in and knowledge of the system with the actual capabilities in order to prevent overtrust and misuse. Here, we lack mechanisms that calibrate the users' trust to an adequate level. A computational model that monitors the drivers' trust, aiming at learned trust and behaviors (and overtrusting), could be a valuable extension to current approaches. Such a system could be based on inputs like eye-gaze patterns to assess trust and communicate critical outcomes of the current driving situation to the users.

In multiplication to adaptation mechanisms in the car, a key feature in autonomously driving vehicles will be integrating user devices into these mechanisms, e.g., the smartphone could work as an additional sensor device, provide information about the user, or work as a remote control for the vehicle. The seamless integration of user devices can change the whole journey experience. Thus, future work should look into designing potential use cases and concepts for co-controlling driving style, co-working, or entertainment.

11.3.4 Accessibility and UX for People with Different Abilities in Automotive Design and Research Processes

In Chapter 5, we have adopted the Universal Design process for the automotive domain. We covered the first two steps of identifying best practices and applications and characterizing user types. In the best case, designers and researchers would integrate users with different barriers to mobility in their concept and prototype generation and let them be part of the process to be aware of their needs and requirements. However, in practice, time or budget constraints hinder the integration. To address this, we can provide designers 1) guidelines and 2) user simulation tools that might help them to take the perspective of non-average users or to access potential needs or conflicts efficiently. To not start every process from scratch, we should learn from individual requirements and document them. For example, when we ask vision-impaired persons about their perceptions of the world and mobility-related mitigation strategies, this knowledge can be transferred to other individuals.

Generally, we could group user-specific requirements into generalized mobility service use-related problem/requirement areas and define design guidelines for which kind of service works best for which kind of problem areas, for example, which mode of transport and which kind of display to use for vision impaired users. In addition, pointing out potential conflicts between these problem areas can be helpful: Users with vision impairments need a high-contrast display that can trigger users in the autism spectrum that need a stimuli-reduced environment. Overall, handbooks or guides that remind of non-average user needs during the design would be a good starting point for future work.

In addition to design guides, building models that simulate user experiences beyond the norm could be a valuable contribution of future work. During the design process, user simulation models target either 1) the designer or 2) the artifact. Regarding the first target, the designer, we could use tools that help them empathize with non-average user needs, e.g., the age suite [Tim+20] for mobility impairments or the vision impairment simulations [Tig]. Regarding the second target, the artifact, similar to the RAMSIS [Sei97] simulation for vehicle interior ergonomics, providing designers with a tool that automatically tests common requirements of a non-average user, would be a game changer for inclusive mobility.

In sum, having mobility-specific inclusive design guidelines and user models as described will help to integrate non-average users' requirements better. However, these means will only cover the bare minimum, and future research and design should focus on creating pleasant user experiences for non-average users beyond just removing the access gap. To this end, it is necessary to include users directly in the design process. Here, tools that help improve communication between designers and end users are an interesting topic. For example, platforms that help designers find certain user groups, tools for remote collaboration, or tools that help them express their needs or build better prototypes.

11.4 Concluding Remarks

Through continuous technological progress (Electrification, Automation, V2X, AR, VR, etc.), we see that the field of mobility is rapidly transforming. Correspondingly, we have recently seen a shift in research on automotive user interfaces from manual and assisted to autonomous driving. Nonetheless, human interaction in and outside the car will radically change from what we know today. Not only will drivers become passengers, but the classical journey, e.g., visiting a friend in the next town, might start by foot and E-Bike, continue per train, and end with ordering an autonomous Robotaxi for the last mile. Given the service orientation of future mobility, the *journey experience* will be what users care for, and in that sense, the experience that fits their needs best.

Given the potential of radical changes in journey experiences through future mobility services compared to today's predominantly individual car transport, the contributions of this thesis help to understand the changing driving activity and how to transition to that next phase of mobility by providing insights into user needs and requirements of the services and how to build controllable and transparent vehicles. At the time same time, many of our contributions are of a temporary nature and might become complemented or substituted at the time the transition ends, e.g., when users start to use and build trust towards autonomous mobility services. Nevertheless, it is up to us as designers and researchers to continue to anticipate the future of mobility, design these services, and bring the future of mobility to the users so that we can better understand the consequences of taking one or another direction in mobility design and contribute to taking the better path.

VI

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VII

Appendix

List of Figures

List of Tables

List of Acronyms

ACD	Activity-Centered Design
AR	augmented reality
AV	automated vehicle
AVAM	Autonomous Vehicle Acceptance Model
ACC	adaptive cruise control
ADAC	Allgemeiner Deutscher Automobil-Club
ADAS	advanced driver assistance system
aLCA	active lane change assistant
aLKA	active lane keeping assistant
ANOVA	analysis of variances
APA	American Psychological Association
BASt	Bundesanstalt für Straßenwesen
CGI	computer generated imagery
CRPD	UN Convention on the Rights of Persons with Disabilities
CTAM	Car Technology Acceptance Model
CTML	Cognitive Theory of Multimedia Learning
DRA	driving related activity
GPS	Global Positioning System
GUI	graphical user interface
HAV	highly automated vehicle
HCI	Human-Computer Interaction
HD	high definition
HMI	Human-Machine Interface
HUD	head-up display
L3-AV	level 3 automated vehicle
LED	light-emitting diode
LKA	lane keeping assistant
LMEM	mixed-linear effects model
MBI	maneuver-based intervention
METUX	Motivation, Engagement, Thriving in User Experience
NHTSA	National Highway Traffic Safety Administration
NDRA	non-driving-related activity
NUI	Natural User Interface
ROSOG	remove object salience on gaze
SA	situational awareness
SAE	Society of Automotive Engineers
SDT	Self-Determination Theory
SOR	Stimulus-Organism-Response

TAM	Technology Acceptance Model
TOR	take-over request
UX	User Experience
UCD	User-Centered Design
UD	Universal Design
UTAUT	Unified Theory of Acceptance and Use of Technology
VR	virtual reality
VRU	vulnerable road user
V2X	Vehicle-to-X
WCAG	Web Content Accessibility Guidelines
WHO	World Health Organization
WoZ	Wizard of Oz
WSD	windshield display

ADDITIONAL DOCUMENTS

In the following, one can find these full-page attachments:

Workshop Materials

HRW HOCHSCHULE RUHR WEST UNIVERSITY OF APPLIED SCIENCES
WORKSHOP „BENUTZERSCHNITTSTELLEN FÜR MANÖVER-BASIERTES FAHREN" SEITE 1/3

Zusammenfassung des Manöver-basierten Fahrens unter SAE Level 4, nach dem Prinzip Conduct-By-Wire (CbW):

- Der Fahrer wird von der Fahrzeugstabilisierung entlastet
- Das Fahrzeug, einmal angefahren, folgt sicher einer Route oder einfach nur der aktuellen Fahrspur bis das Ziel erreicht ist oder die Spur endet
- Der Fahrer kann aktiv in den Fahrprozess eingreifen, z.B. um die gewünschte Fahrspur (Manöver) oder Geschwindigkeit (Parameter) anzupassen
- Der Fahrer beauftragt Fahrmanöver (z.B. Spurwechsel) über eine Manöverschnittstelle
- Man unterscheidet explizite (zu aktivierende Manöver, z.B. Abbiegen) und implizite Manöver (passive Manöver, die auf explizite Manöver folgen, z.B. Spur folgen nach Abbiegemanöver)
- Neben den Manövern gibt es Parameter zur Regelung des Fahrprozesses, die der Fahrer ebenfalls aktiv einstellen kann (z.B. Abstand zum vorausfahrenden Fahrzeug)
- Die Benutzerschnittstelle zeigt den aktuellen Zustand des Systems (aktive Manöver, eingestellte Parameter) und die aktuell verfügbaren Zustandsänderungen (verfügbare Manöver, einstellbare Parameter)

Persönliche Angaben:

Höchster Bildungsabschluss: ____________

Meine Erfahrung würde ich in den untenstehenden Themengebieten auf einer Skala von 1 (äußerst unerfahren) bis 10 (äußerst erfahren) wie folgt einschätzen (bitte Zahl eintragen) …

Informationstechnologie (allgemein): ___

Automobiltechnologie (allgemein): ___

Automobiltechnologie (Automatisiertes Fahren): ___

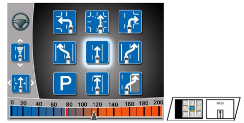
Design (User Interfaces): ___

Design (Gesten): ___

Design (Sprache): ___

Benutzerschnittstellen für Manöver-basiertes Fahren:

Abbildung 1 – **Taktiles Touchpad**



Die Schnittstelle ist für einen Touchscreen konzipiert. Die Eingabe erfolgt durch Berührung. Ein HUD zeigt das aktive Manöver vereinfacht.

Quelle:

Kauer, M., Schreiber, M., & Bruder, R. (2010, June). How to conduct a car? A design example for maneuver based driver-vehicle interaction. In *Intelligent Vehicles Symposium (IV), 2010 IEEE* (pp. 1214-1221). IEEE.

Abbildung 2 - **PieDrive**

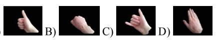
Die Schnittstelle ist für ein HUD konzipiert. Die Eingabe erfolgt durch Berührungsgesten über ein Multitouchpad nahe der Armlehne.

Quelle:

Franz, B. (2014). *Entwicklung und Evaluation eines Interaktionskonzepts zur manöverbasierten Führung von Fahrzeugen* (Doctoral dissertation, Technische Universität Darmstadt).

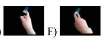
Freihandgesten: Die Ausführung von Freihandgesten kann zeitlich abgeschlossen oder kontinuierlich sein, eher dynamisch oder eher statisch. Für das Fahren kommen vor allem symbolische, deiktische und kinemimetische Gesten in Frage. Mimische Gesten hingegen sind oft zu komplex.

Symbolische Gesten: Haben eine bestimmte selbst-enthaltene Bedeutung, die erlernt werden muss.



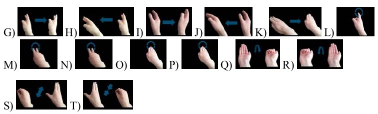
A) B) C) D)

Deiktische Gesten: Zeigegesten, die auf einen bestimmten Ort oder in eine bestimmte Richtung ausgerichtet sind. Sie sind oft sehr intuitiv.



E) F)

Kinemimetische Gesten: Imitieren eine Bewegungsrichtung. Bedeutung muss oft gelernt werden.



G) H) I) J) K) L) M) N) O) P) Q) R) S) T)

Quelle:

Zöller, I., Bechmann, R., & Abendroth, B. (2017). Possible applications for gestures while driving. *Automotive and Engine Technology*, 1-10.

Sprache: Bei der Spracheingabe kann man grundsätzlich zwei Arten von Dialogen unterscheiden. Der geführte Dialog gibt das System an Entscheidungspunkten Antwortmöglichkeiten vor und ist somit für das Manöver-basierte Fahren aus Sicht des Fahrers ungeeignet. Im *natürlich-sprachlichen Dialog* können jederzeit frei formulierbare Systemanfragen gestellt. Dabei sollte das Vokabular des Nutzers verwendet werden.

Im Auto könnte die Steuerung einer Klimaanlage wie folgt aussehen:

- "climate control driver's seat temperature down"
- "turn the driver's seat temperature to 60°"

Für die Verarbeitung Systemanfrage, müssen alle vom Fahrer geforderten Operationen aus der Anfrage extrahiert werden. Dies geschieht durch bestimmte Schlüsselphrasen (einzelne Wörter, zusammengesetzte Wörter, ganze Sätze). Ein Bespiel für die Zuordnung von Schlüsselphrasen zu Operationen:

Navigation Voice Commands	*Redirected to*
Home / Welcome / Maps / Main Page	Main page
Find by Name / Name	Find by Name page
Find by Abbreviation / Abbreviation	Find by Abbreviation page
Find by Category / Category	Find by Category page
Find within Distance / Within Distance	Find within Distance page
Get Directions / Directions	Directions tab
Browse Map / Browse	Browse page
Help	Help page
Overview	Overview page
Contact	Contact page
Go Back / Back	The previous page
Refresh / Reload	Refreshes the current page
Turn Off / Turn Off Voice	Same page with no voice interaction

Quelle:

Burgstaller, M., & Gmeiner, B. (2009). *Sprachbasierte Benutzerschnittstellen.*

i. Fahrmanöverkatalog

In diesem Aufgabenblatt geht es zunächst um die Gestaltung der einzelnen Fahrmanöver unter den im Kasten „Zusammenfassung“ vorgestellten Bedingungen. In der untenstehenden Tabelle ist für jedes Manöver eine Reihe angelegt und spaltenweise werden Deine Einschätzungen gewünscht. Sollten Fragen aufkommen, beispielweise zur Bedeutung einzelner Manöver oder zur Bearbeitung der Tabelle, können diese jederzeit mit dem Workshopleiter besprochen werden.

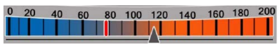
Erklärung zu den einzelnen Spalten:

I. Textuelle Beschreibung des Fahrmanövers(M)/-parameters(P), der CbW-Wechselschalter gehört in keine der beiden Kategorien, wird einmalig zum Aktivieren/Deaktivieren des CbW-Fahrmodus benötigt
II. Bildliche Darstellung des Fahrmanövers/-parameters (Symbol) – siehe Seite 1, Kasten „Benutzerschnittstellen für Manöver-basiertes Fahren“, Abbildung 1 (Gesamtsicht)
III. Falls Du Ideen hast, wie man eines der Symbole verbessern könnte, ist hier Platz für eine eigene Skizze des Manöver/-parametersymbols
IV. Hier soll ein passender Freihandgestenausdruck für die Manöver-/Parametereingabe überlegt werden und möglichst genau durch Skizzen und/oder Text beschrieben werden – eine Inspiration ist auf Seite 1 in dem Kasten „Freihandgesten“ zu finden (Ist hier bereits eine passende Geste bei, einfach den entsprechenden Buchstaben eintragen)
V. Hier soll ein passender sprachlicher Ausdruck für die Manöver-/Parametereingabe überlegt werden – Beispiele für Sprachbefehle sind auf Seite 1 in dem Kasten „Sprache“ zu finden
VI. Kommentar / Sonstiges: Alles was nicht die vorherigen Spalten passt.

I. Manöver / Parameter	II. Symbol	III. Eigene Skizze	IV. Eingabe mit Freihandgestenbefehl	V. Eingabe mit Sprachbefehl	VII. Kommentar / Sonstiges
1. Links abbiegen (M)					
2. Geradeaus fahren bei abknickender Vorfahrt (M)					
3. Rechts abbiegen (M)					
4. Spurwechsel links (M)					
5. Anfahren (M)					
6. Spurwechsel rechts (M)					
7. Parken (M)					
8. Zielbremsung am Haltestreifen (M)					

9. Halten am Seitenstreifen (M)					
10. CbW-Wechselschalter					
11. Abstand zum Vorausfahrenden (P)					
12. Exzentrizität auf der Spur (P)					
13. Geschwindigkeit Regulieren (P)	Siehe ii.	Skizze bitte im Feld „Kommentar“			

ii. Tachoanzeige

a) 

b) 

Ich bevorzuge Variante (a oder b): _________

iii. Aktivierung der Schnittstelle

Eine Aktivierung der Schnittstelle könnte in bestimmten Situationen sinnvoll sein, z.B. wenn Sprachbefehle während eines Gesprächs mit dem Beifahrer deaktiviert würden. Moderne Sprachassistenten wie Siri oder Alexa arbeiten mit Aktivierungsphrasen, um Fehleingaben zu vermeiden.

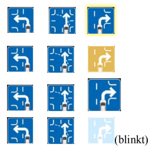
Als Aktivierungsphrase könnte ich mir vorstellen:

____

Als aktivierende Geste könnte ich mir vorstellen (bitte wie zuvor in der Tabelle beschreiben):

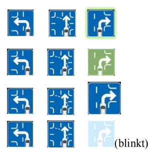
iv. Anzeige des Systemzustandes

Das Manöver „Rechts abbiegen“ soll als nächstes durchgeführt werden:

a) b) c) d) 

Ich bevorzuge Variante (a, b, c oder d): _________

Das Manöver „Rechts abbiegen“ ist im Moment aktiv:

a) b) c) d) 

Ich bevorzuge Variante (a, b, c oder d): _________

v. Akzeptanz

Die Interaktion mittels Sprache für Manöver-basiertes Fahren vorstellen könnte ich mir vorstellen:

[ ] ja [ ] nein [ ] eingeschränkt, Grund:_______________________

Die Interaktion mittels Freihandgesten für Manöver-basiertes Fahren vorstellen könnte ich mir vorstellen:

[ ] ja [ ] nein [ ] eingeschränkt, Grund:_______________________

vi. Herausforderungen

Die größten Herausforderungen für ein mögliches Interaktionskonzept durch Freihandgesten oder Sprache sind (max. 3 Nennungen)...

1. ____
2. ____
3. ____

vii. Abschließende Gedanken

Consent Form

Aufklärung und Einwilligung

Probandenkennung: ___________________________

Sehr geehrte Damen und Herren,

vielen Dank für Ihr Interesse an unserer wissenschaftlichen Studie. Bitte lesen Sie sich die folgenden Informationen zunächst sorgfältig durch und entscheiden Sie dann über Ihre Teilnahme oder auch Nichtteilnahme an dieser Studie. Beides, Ihre *Teilnahme oder Nichtteilnahme stehen Ihnen frei*. Sie können Ihre freiwillige Teilnahme an der Studie *jederzeit* und *ohne Angabe von Gründen* abbrechen, ohne dass Ihnen daraus Nachteile entstehen. Auch die Studienleitung kann die Entscheidung treffen, die gesamte Studie abzubrechen oder Ihre Teilnahme vorzeitig zu beenden, wenn dies (etwa aus medizinischen Gründen) angezeigt sein sollte.

Es folgen Informationen zu unserer Studie:

- **Wer führt die Studie durch und wer hat Zugriff auf die erhobenen Daten?**

  [redacted]

  sowie der

  [redacted]

  und der

  [redacted]

  durchgeführt. Die genannten Partner verarbeiten Ihre Daten gemeinsam und haben Zugriff darauf.

- **Zweck der Studie:**

  Erforschung der Einstellungen und Reaktionen auf verschiedene Fahrstile eines automatisierten Fahrzeuges. Welche Fahrstile Sie dabei erleben werden ist zufällig.

- **Dauer und Vorgehen:**

  Die Studie beginnt mit einer Vorbefragung (Fragebogen und Interview, etwa 60 Minuten), dann folgen 6 Fahrten mit dem Fahrzeugprototypen (je max. 30 Minuten mit anschließendem Fragebogen, etwa 5 Minuten). Dazu erfragen wir von Ihnen 6 Fahrten (Start, Ziel, gewünschte Abholzeit, ggfs. Zusatzangaben) sowie Ihre Kontaktdaten, um Sie ggfs. über Änderungen informieren zu können. Zuletzt folgt die Abschlussbefragung (Fragebogen und Interview, etwa 45 Minuten). Die Gesamtdauer inkl. aller Fahrten beträgt etwas mehr als 5 Stunden.

- **Versuchsrisiken:**

  Während der Fahrt mit dem Versuchsfahrzeug sind Sie den üblichen Risiken im Straßenverkehr ausgesetzt. Ein Sicherheitsfahrer überwacht das System und übernimmt ggfs. in komplexen Situationen (Einparken, Ausparken, Mehrfacher Spurwechsel, Autobahnauffahrt, ...).

- **Voraussichtlicher Erkenntnisgewinn:**

  Aus den erhobenen Daten wollen wir Erkenntnisse zum komfortablen Gebrauch zukünftiger automatisierter Fahrzeugsystem gewinnen.

- **Welche Daten werden gesammelt:**

  Während der Studie sammeln wir folgende Daten:

  - Ihre unterschriebene Einverständniserklärung (wird getrennt von allen anderen Dokumenten aufbewahrt).
  - Informationen zum Ablauf der einzelnen Fahrten: Start, Ziel, gewünschte Abholzeit, Anzahl der Mitfahrer, ggfs. Zusatzinformationen.
  - Ihre Kontaktdaten: Name, E-Mail-Adresse, Telefonnummer (diese Daten werden nach Beendigung des Experiments gelöscht).
  - Die Unterhaltung während der Interviews (Audioaufzeichnung und Transkription)
  - Ihre Antworten aus den Fragebögen
    - Ihre allgemeinen demographischen Daten (Alter, Geschlecht, Ausbildung, Beruf)
    - Eine pseudonyme Kennung um die Antworten im Verlauf der Studie derselben Person zuordnen zu können (wir können diese aber nicht Ihnen persönlich zuordnen!)
    - Ihre spezifischen Antworten zu unseren Fragen (nicht personenbezogen)
  - Videoaufzeichnungen aus dem Fahrzeuginnenraum während der Fahrt.

- **Wie lange und wo werden Ihre Daten gespeichert?**

  Alle Daten, die während der Studie erhoben werden und die für die Auswertung notwendig sind, werden mindestens bis zum Ende des Projekts mitsamt seiner Auswertung und Publikation gespeichert. Gemäß den Grundlagen wissenschaftlicher Arbeit (siehe z.B. https://www.dfg.de/foerderung/antrag_gutachter_gremien/antragstellende/nachnutzung_forschungsdaten/index.html) ist darüber hinaus geplant, die Daten (Rohdaten und verarbeitete Daten) innerhalb der beteiligten Institutionen oder in einer fachlich einschlägigen, überregionalen Infrastruktur für mindestens 10 Jahre zu archivieren.

- **Gewährleistung der Vertraulichkeit bzw. Wahrung von Grenzen:**

  Alle Daten, die im Rahmen des Versuchs erhoben werden, d.h., die Antworten aus den Fragebögen, Ihre allgemeinen demographischen Daten, Interviewdaten, und Videodaten aus dem Fahrzeuginnenraum, werden streng vertraulich behandelt und lediglich in anonymisierter Form zu wissenschaftlichen Zwecken ausgewertet und publiziert. Digitale persönliche Daten werden verschlüsselt gespeichert, physikalische Dokumente werden z.B. in einem verschlossenen Schrank aufbewahrt. Die Freigabe von Bildmaterial für Anschauungszwecke im Rahmen wissenschaftlicher Veröffentlichungen ist optional und freiwillig.

Zusätzlich werden Sie hiermit über die in der DSGVO festgelegten Rechte informiert (Artikel 12 ff. DSGVO):

Rechtsgrundlage

Die Rechtsgrundlage zur Verarbeitung der Sie betreffenden personenbezogenen Daten bilden bei wissenschaftlichen Studien Ihre freiwillige schriftliche Einwilligung gemäß DSGVO. Zeitgleich mit der DSGVO tritt in Deutschland das überarbeitete Bundesdatenschutzgesetz (BDSG-neu) in Kraft.

Bezüglich Ihrer Daten haben Sie folgende Rechte (Artikel 13 ff. DSGVO, §§ 32 ff. BDSG-neu):

Recht auf Auskunft

Sie haben das Recht auf Auskunft über die Sie betreffenden personenbezogenen Daten, die im Rahmen der wissenschaftlichen Studie erhoben, verarbeitet oder ggf. an Dritte übermittelt werden (Aushändigen einer kostenfreien Kopie) (Artikel 15 DSGVO, §§34 und 57 BDSG-neu).

Recht auf Berichtigung

Sie haben das Recht, Sie betreffende unrichtige personenbezogene Daten berichtigen zu lassen (Artikel 16 und 19 DSGVO, § 58 BDSG-neu).

Recht auf Löschung

Sie haben das Recht auf Löschung Sie betreffender personenbezogener Daten, z. B. wenn diese Daten für den Zweck, für den sie erhoben wurden, nicht mehr notwendig sind (Artikel 17 und 19 DSGVO, §§ 35 und 58 BDSG-neu).

Recht auf Einschränkung der Verarbeitung

Unter bestimmten Voraussetzungen haben Sie das Recht, die Einschränkung der Verarbeitung zu verlangen, d.h. die Daten dürfen nur gespeichert, nicht verarbeitet werden. Dies müssen Sie beantragen. Wenden Sie sich hierzu bitte an ihren Prüfer oder an den Datenschutzbeauftragten des Prüfzentrums (Artikel 18 und 19 DSGVO, § 58 BDSG-neu).

Recht auf Datenübertragbarkeit

Sie haben das Recht, die sie betreffenden personenbezogenen Daten, die sie dem Verantwortlichen für die klinische Studie bereitgestellt haben, zu erhalten. Damit können Sie beantragen, dass diese Daten entweder Ihnen oder, soweit technisch möglich, einer anderen von Ihnen benannten Stelle übermittelt werden (Artikel 20 DSGVO).

Widerspruchsrecht

Sie haben das Recht, jederzeit gegen konkrete Entscheidungen oder Maßnahmen zur Verarbeitung der Sie betreffenden personenbezogenen Daten Widerspruch einzulegen (Art 21 DSGVO, § 36 BDSG-neu). Eine solche Verarbeitung findet anschließend grundsätzlich nicht mehr statt.

Einwilligung zur Verarbeitung personenbezogener Daten und Recht auf Widerruf dieser Einwilligung

Die Verarbeitung ihrer personenbezogenen Daten ist nur mit Ihrer Einwilligung rechtmäßig (Artikel 6 DSGVO, § 51 BDSG-neu).

Sie haben das Recht, ihre Einwilligung zur Verarbeitung personenbezogener Daten jederzeit zu widerrufen. Es dürfen jedoch die bis zu diesem Zeitpunkt erhobenen Daten durch die in der Studieninformation und Einwilligungserklärung zu der jeweiligen wissenschaftlichen Studie genannten Stellen verarbeitet werden (Artikel 7, Absatz 3 DSGVO, § 51 Absatz 3 BDSG-neu).

Möchten Sie eines dieser Rechte in Anspruch nehmen, wenden Sie sich bitte an Ihren Prüfer oder an den Datenschutzbeauftragten Ihres Prüfzentrums. Die Datenschutzbeauftragten der beteiligten Institutionen sind:

[redacted]	[redacted]	[redacted]

Außerdem haben Sie das Recht, Beschwerde bei der/den Aufsichtsbehörde/n einzulegen, wenn Sie der Ansicht sind, dass die Verarbeitung der Sie betreffenden personenbezogenen Daten gegen die DSGVO verstößt:

[redacted]

[redacted]

Falls Sie über diese Information hinaus noch weitere Fragen zur Studie haben sollten, beantworten wir Ihnen diese gern.

Einwilligung

Ich wurde mündlich und schriftlich über das Wesen, die Bedeutung, Tragweite und Risiken der wissenschaftlichen Studie informiert und hatte ausreichend Gelegenheit, meine Fragen hierzu in einem Gespräch mit der/dem Studienmitarbeiter/in zu klären.

Ich erkläre mich damit einverstanden, an der Studie teilzunehmen. Meine Teilnahme erfolgt freiwillig.

Mir ist bekannt, dass ich meine Einwilligung jederzeit ohne Angabe von Gründen mit Wirkung für die Zukunft widerrufen und der Weiterverarbeitung meiner Daten widersprechen kann. Zudem bin ich belehrt worden, dass von mir gespeicherte Daten gelöscht bzw. vernichtet werden.

Ich erkläre mich damit einverstanden, dass die im Rahmen dieser Studie erhobenen personenbezogenen Daten (ohne Klarnamen und Anschrift) in der in den Informationen für Teilnehmer/innen beschriebenen Weise zwischen den Projektpartnern übermittelt und auf elektronischen Datenträgern aufgezeichnet, verarbeitet, ausgewertet und in anonymisierter Form veröffentlicht werden.

Ich erkläre mich zudem damit einverstanden, dass die in der Studie erhobenen Daten auch über das Projektende hinaus für weitere Forschungszwecke verwendete werden dürfen (Artikel 3, Absatz 3 DSGVO).

Wenn Sie den Versuchsbedingungen zustimmen, möchten wir Sie bitten hier zu unterschreiben:

Datum, Unterschrift: _________________________________

(Proband)

Datum, Unterschrift: _________________________________

(Versuchsleiter)

Zusätzlich möchten wir von Ihnen wissen, ob wir in Veröffentlichungen zu dieser Studie (Wissenschaftliche Aufsätze und Präsentationen, Zeitungsberichte) Bildmaterial von Ihnen verwenden dürfen. Die Antwort hat keinerlei Konsequenzen für den weiteren Studienverlauf.

[ ] Ja, ich stimme der Veröffentlichung von Bildmaterial für die genannten Zwecke zu.

[ ] Nein, ich stimme der Veröffentlichung von Bildmaterial nicht zu.

Acceptance Questionnaire

Fragebogen (Abschluss)

Achtung: Dieser Fragebogen bezieht sich auf alle bisherigen Fahrten mit dem Fahrzeugprototypen!

1. Bitte geben Sie Ihre **Teilnehmerkennung** an.

Ihre persönliche Teilnehmerkennung besteht aus den letzten 4 Ziffern Ihrer Mobilfunknummer und dem zweiten und dritten Buchstaben Ihres Nachnamens (Großbuchstaben). Ein Beispiel: Max Mustermann hat die Mobilfunknummer 0170756432 – seine Kennung lautet 6432US.

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ablehnen. Entscheiden Sie dabei möglichst intuitiv.

	Stimme gar nicht zu						Stimme voll zu
Die Nutzung des Fahrzeugs würde mir erlauben schnell an mein Ziel zu kommen.	○	○	○	○	○	○	○
Die Nutzung des Fahrzeugs würde mir erlauben kostengünstig an mein Ziel zu kommen.	○	○	○	○	○	○	○
Die Nutzung des Fahrzeugs würde mir erlauben sicher an mein Ziel zu kommen.	○	○	○	○	○	○	○
Ich fände das Fahrzeug einfach zu nutzen.	○	○	○	○	○	○	○
Meine Interaktion mit dem Fahrzeug wäre klar und verständlich.	○	○	○	○	○	○	○
Es würde mir leicht fallen den Umgang mit dem Fahrzeug zu lernen.	○	○	○	○	○	○	○
Ich wäre stolz darauf das Fahrzeug Leuten zu zeigen, die mir nahestehen.	○	○	○	○	○	○	○
Ich wäre eher dazu geneigt das Fahrzeug zu nutzen, wenn viele andere es ebenfalls nutzen würden.	○	○	○	○	○	○	○
Ich würde das Fahrzeug eher nutzen, wenn andere Passagiere im Fahrzeug mitfahren würden.	○	○	○	○	○	○	○
Ich hätte angemessene Kontrolle über die Reise zu meinem Ziel.	○	○	○	○	○	○	○
Ich besitze das nötige Wissen für die Nutzung des Fahrzeugs.	○	○	○	○	○	○	○
Das Fahrzeug und Infrastruktur für die Nutzung des Fahrzeugs sind praktisch machbar.	○	○	○	○	○	○	○
Es wäre eine gute Idee das Fahrzeug zu nutzen.	○	○	○	○	○	○	○
Das Fahren würde durch das Fahrzeug interessanter werden.	○	○	○	○	○	○	○
Es würde Spaß machen das Fahrzeug zu nutzen.	○	○	○	○	○	○	○
Ich könnte mein Ziel mit dem Fahrzeug erreichen wenn ich nur die mitgelieferten Bedienungsanleitungen zur Hilfe hätte.	○	○	○	○	○	○	○
Ich könnte mein Ziel mit dem Fahrzeug erreichen wenn ich keine Hilfe hätte.	○	○	○	○	○	○	○
Ich könnte mein Ziel mit dem Fahrzeug erreichen wenn jemand da wäre, der mit helfen würde.	○	○	○	○	○	○	○
Ich hätte Bedenken das Fahrzeug zu nutzen.	○	○	○	○	○	○	○
Das Fahrzeug würde mir etwas Angst machen.	○	○	○	○	○	○	○
Ich hätte Angst das Fahrzeug nicht zu verstehen.	○	○	○	○	○	○	○
Angenommen ich hätte Zugang zu dem Fahrzeug, würde ich es voraussichtlich benutzen.	○	○	○	○	○	○	○
Wenn das Fahrzeug für mich verfügbar wird, plane ich es zu besitzen und zu nutzen.	○	○	○	○	○	○	○
Ich glaube, dass die Nutzung des Fahrzeugs gefährlich wäre.	○	○	○	○	○	○	○
Während der Nutzung des Fahrzeugs würde ich mich sicher fühlen.	○	○	○	○	○	○	○
Ich würde dem Fahrzeug vertrauen.	○	○	○	○	○	○	○

3. Nennen Sie bis zu 5 Dinge, die Sie während einer Fahrt mit einem autonomen Fahrzeug am ehesten tun würden.

Sie können private und/oder geschäftliche Dinge nennen.

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

4. Nennen Sie bis zu 5 Dinge, die Sie sinnvollerweise in einem autonomen Fahrzeug platzieren würden.
Sie können Dinge wie Möbel, Technik oder sonstige Gegenstände nennen, die Ihren Komfort erhöhen würden.

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

Trust Questionnaire

Fragebogen
(Fahrt 1)

Achtung: Dieser Fragebogen bezieht sich nur auf das Fahrerlebnis eben gerade und nicht auf vorherige Fahrten!

1. Bitte geben Sie Ihre **Teilnehmerkennung** an.

Ihre persönliche Teilnehmerkennung besteht aus den letzten 4 Ziffern Ihrer Mobilfunknummer und dem zweiten und dritten Buchstaben Ihres Nachnamens (Großbuchstaben). Ein Beispiel: Max Mustermann hat die Mobilfunknummer 0170756432 – seine Kennung lautet 6432US.

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2. Bitte bewerten Sie das Fahrzeugsystem.

Es folgen Bewertungskategorien des Fahrzeugssystems. Geben Sie an, wie gut Sie das System in den einzelnen Kategorien bewerten. Abstufungen zwischen völliger Unzufriedenheit und völliger Zufriedenheit sind durch Kreise dargestellt. Durch Ankreuzen eines dieser Kreise können Sie die jeweilige Kategorie bewerten.

	sehr unzufrieden						sehr zufrieden
Fahrstil	○	○	○	○	○	○	○
Sicherheit	○	○	○	○	○	○	○
Komfort	○	○	○	○	○	○	○
Gesamtzufriedenheit	○	○	○	○	○	○	○

3. Bitte bewerten Sie Ihr Erlebnis mit dem Fahrzeugsystem.

Es folgen Aussagen über das Fahrzeugsystem. Geben Sie an, inwieweit Sie mit den Aussagen übereinstimmen. Abstufungen zwischen völliger Zustimmung und völliger Ablehnung sind durch Kreise dargestellt. Durch Ankreuzen eines dieser Kreise können Sie Ihren Grad der Übereinstimmung mit einer Aussage äußern.

	trifft gar nicht zu						trifft völlig zu
Ich bin misstrauisch den Entscheidungen des Systems.	○	○	○	○	○	○	○
Das System bietet Sicherheit.	○	○	○	○	○	○	○
Das System arbeitet tadellos.	○	○	○	○	○	○	○
Ich kann dem System vertrauen.	○	○	○	○	○	○	○
Das System ist vertrauenswürdig.	○	○	○	○	○	○	○
Ich muss vorsichtig im Umgang mit dem System sein.	○	○	○	○	○	○	○
Die Handlungen des Systems haben negative Auswirkungen zur Folge.	○	○	○	○	○	○	○
Das System ist verlässlich.	○	○	○	○	○	○	○
Ich bin sicher im Umgang mit dem System.	○	○	○	○	○	○	○
Das System verhält sich undurchsichtig.	○	○	○	○	○	○	○
Das System ist irreführend.	○	○	○	○	○	○	○
Ich kenne mich mit dem System aus.	○	○	○	○	○	○	○

4. Haben Sie Anmerkungen bezüglich der Fahrt oder des Fahrzeugsystems? (optional)

Bitte stichpunktartig antworten. Bei Platzmangel die Rückseite verwenden.

NASA-TLX Questionnaire

soSci
oFb - der onlineFragebogen

estore-old → conditions 21.11.2022, 18:56

Seite 01

IDS

1. Probandennummer

Dies übernimmt der*die Versuchsleiter*in für Sie. Melden Sie sich bitte bei ihr*ihm, sofern nicht bereits geschehen.

[Bitte auswählen]

2. Versuchsbedingung

Dies übernimmt der*die Versuchsleiter*in für Sie. Melden Sie sich bitte bei ihr*ihm, sofern nicht bereits geschehen.

[Bitte auswählen]

Seite 02

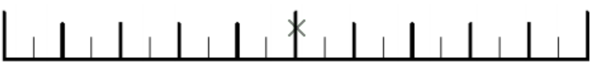
DAL

Beantworten Sie die folgenden Fragen bitte möglichst spontan.

3. Aufwand an Aufmerksamkeit

Bewertung der Aufmerksamkeit, die die Fahrt erfordert – z.B. um zu denken, zu entscheiden, zu wählen, suchen und so weiter.

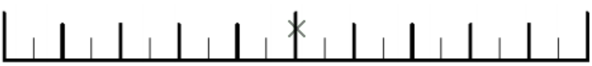
Bitte auf die Skala klicken und das Kreuz so platzieren, dass es Ihre Einschätzung den Aufwand an Aufmerksamkeit während der Fahrt widerspiegelt.

gering  hoch

4. Visuelle Anforderung

Bewertung der visuellen Anforderung, die für die Fahrt erforderlich ist.

Bitte auf die Skala klicken und das Kreuz so platzieren, dass es Ihre Einschätzung die visuelle Anforderung während der Fahrt widerspiegelt.

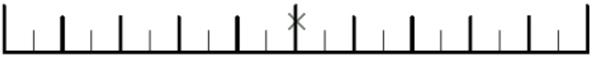
gering  hoch

5. Auditive Anforderung

Bewertung der auditiven Anforderung, die für die Fahrt erforderlich ist.

Bitte auf die Skala klicken und das Kreuz so platzieren, dass es Ihre Einschätzung die auditive Anforderung während der Fahrt widerspiegelt.

gering



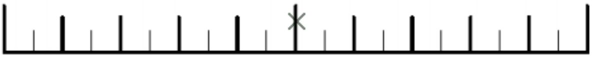
hoch

6. Zeitliche Anforderung

Bewertung der konkreten Belastung aufgrund der zeitlichen Anforderung während der Fahrt.

Bitte auf die Skala klicken und das Kreuz so platzieren, dass es Ihre Einschätzung die zeitliche Anforderung während der Fahrt widerspiegelt.

gering



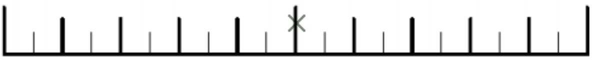
hoch

7. Situativer Stress

Beurteilung des Grades der Belastungen/Stress bei der Durchführung der Fahrt wie Müdigkeit, Unsicherheitsgefühl, Gereiztheit, Entmutigung, und so weiter.

Bitte auf die Skala klicken und das Kreuz so platzieren, dass es Ihre Einschätzung des situativen Stresses während der Fahrt widerspiegelt.

gering



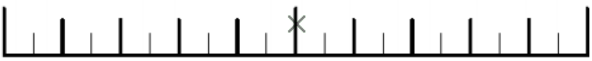
hoch

8. Störung

Beurteilung der eventuellen Störung der Fahrt durch den Wechsel von Fahraufgabe und Gedächtnisaufgabe.

Bitte auf die Skala klicken und das Kreuz so platzieren, dass es Ihre Einschätzung die Störung während der Fahrt widerspiegelt.

gering



hoch

Seite 03
HUD

9. Bitte bewerten Sie das Head-Up Display (HUD) während der Fahrt.
Geben Sie an, in wie weit Sie den folgenden Aussagen zustimmen.

	Stimme gar nicht zu 1	2	3	4	5	6	Stimme voll und ganz zu 7
Das HUD hat mich von der Nebenaufgabe abgelenkt.	○	○	○	○	○	○	○
Das HUD hat mir geholfen, den Übernahmeaufforderungen nachzukommen.	○	○	○	○	○	○	○
Das HUD hat mir geholfen, die Fahrumgebung wahrzunehmen.	○	○	○	○	○	○	○
Das HUD hat mir geholfen, die Fahrumgebung zu verstehen.	○	○	○	○	○	○	○
Das HUD hat mir geholfen, die Fahrumgebung vorauszusehen.	○	○	○	○	○	○	○
Das HUD hat mir geholfen, zu wissen was das Fahrzeug weiß.	○	○	○	○	○	○	○
Ich konnte dem HUD vertrauen.	○	○	○	○	○	○	○
Das HUD gab mir ein Gefühl der Sicherheit.	○	○	○	○	○	○	○
Ich würde das HUD nutzen.	○	○	○	○	○	○	○

Seite 04
UX

10. Wie positiv bzw. negativ würden Sie die Fahrt bewerten?
Geben Sie an, inwieweit Sie den folgenden Aussagen zustimmen.

Ich empfand die Fahrt als...	Stimme gar nicht zu 1	2	3	4	5	6	Stimme voll und ganz zu 7
...positiv	○	○	○	○	○	○	○
...negativ	○	○	○	○	○	○	○

Interview Guide

Englisch version below (p. 4 ff.)

==
German Version
==

Einzelinterviews - Leitfaden

Begrüßung und Instruktion (5min)

Guten Tag Herr/Frau XYZ,

vielen Dank, dass Sie sich die Zeit genommen haben, an dieser Interview-Studie im Rahmen eines vom Europäischen Fonds für regionale Entwicklung geförderten Projekts zur automatisierten Mobilität teilzunehmen. Mein Name ist Henrik Detjen und ich arbeite an der Hochschule Ruhr West im Bereich Mensch-Technik Interaktion. Für den Erfolg des Projektes ist es wichtig, Sie als Experten zu befragen, um Bedenken, Wünsche und Ihre Einstellung zum Wandel der Mobilität zu erfahren. Deswegen haben wir Sie zu dem heutigen Interviewtermin eingeladen.
Wichtig ist mir zu betonen, dass ich an Ihrer Meinung interessiert bin. D.h. es gibt auf die Fragen, die ich Ihnen stellen werde, keine richtigen oder falschen Antworten. Bitte beantworten Sie die Fragen offen und ehrlich. Keine Sorge, Ihre Angaben werden anonymisiert ausgewertet, sodass keine Rückschlüsse auf ihre Person möglich sind. Damit mir keine Informationen entgehen, werde ich die Interviews video- und audioaufzeichnen, um sie anschließend bestmöglich auswerten zu können. Die Teilnahme an der Untersuchung ist selbstverständlich freiwillig und jederzeit ohne Angabe von Gründen widerrufbar.
Nachdem Sie nun alle nötigen Informationen erhalten haben, können Sie frei entscheiden, ob Sie an der Studie teilnehmen oder nicht. Bitte lesen Sie sich hierzu diese Einverständniserklärung ([redacted])[Link über Chat zusenden] durch und unterschreiben Sie diese, falls Sie an dem Interview teilnehmen möchten. Vielen Dank für Ihre Unterstützung. Falls Sie Fragen haben, können Sie mir diese jederzeit gerne stellen.

Themenkomplex: Warm-up - Arbeit und Umfeld (5min)

Da es in unserem Projekt um Behinderteneinrichtungen geht, würde ich als erstes gerne etwas über Sie und Ihr Arbeitsumfeld erfahren:

- In Ihrer Einrichtung… Welche Aufgaben erledigen Sie?
- Was machen Ihre Betreuten an einem typischen Arbeitstag?
- Was macht Ihnen an der Arbeit besonders Spaß?
- Welche Probleme treten dabei auf?
- Wofür würden Sie sich mehr Zeit wünschen?

Vereinfachte Version:

In unserem Projekt möchten wir etwas über Dich, Deine und Deine Arbeit erfahren.

- Was hast Du heute so gemacht?
- Was hat dabei besonders viel Spaß gemacht?
- Was hat dabei keinen Spaß gemacht?

Themenkomplex: Aktuelle Mobilitätsmuster (10min)

Jetzt würde ich gern etwas genauer auf das Thema Mobilität in Ihrem Arbeitsalltag und mit den Betreuten eingehen, dabei möchte ich den Fokus auf Menschen mit kognitiven Schwächen bzw. Einschränkungen legen:

- Was macht kognitiv Eingeschränkten das Reisen besonders attraktiv?
- Welche besonderen Herausforderungen stellen sich für kognitiv Eingeschränkte bei der Nutzung von Mobilitätsangeboten:
    - Zu Fuß, Mit dem Rad, Auto, ÖPNV
- Beschreiben Sie den letzten Ausflug mit Ihren Clienten...
- Wann und unter welchen Umständen ist eine Begleitung durch eine weitere Person nötig/sinnvoll?
- Gibt es technische Unterstützung bei der Nutzung von Mobilitätsangeboten für kognitiv Eingeschränkte?
- Was könnte bei der Nutzung von Mobilitätsangeboten für kognitiv Eingeschränkte besser sein?
- Und was für Sie als [insert Job]?

Vereinfachte Version:

Jetzt würde ich gerne mit Dir über deinen Arbeitsweg, Reisen und Ausflüge reden.

- Wie kommst Du zur Arbeit / nach Hause? Und wie kommst Du zum Einkaufen?
    - Zu Fuß, mit dem Rad, oder mit dem Auto (Wer fährt?)?
    - Wie lang ist der Arbeitsweg zirka?
    - Gibt es Dinge, die Dich nerven, wenn Du dorthin unterwegs bist?
- Und wie kommst Du zu Freunden oder bekannten die weiter weg wohnen?
    - Wo wohnen die? Zu Fuß, mit dem Rad, oder mit dem Auto (Wer fährt?)?
    - Gibt es Dinge, die Dich nerven, wenn Du unterwegs länger bist?

Themenkomplex: Automatisierte Mobilität (10min)

Nehmen wir nun einmal an, wir seien in das Jahr 2050 gereist. Computersysteme sind in der Lage komplexe Fahraufgaben zu übernehmen. Der Mensch reist als Passagier in autonomen Fahrzeugen mit, z.B. in einem fahrerlosen Bus.

- Was wären Ihre Erwartungen und Bedenken, wenn Sie mit einem autonomen Fahrzeug unterwegs wären?
    - Wie denken Sie über diesen Punkt…
        - Sicherheits- und Kommunikationsmechanismen im Fahrzeug
        - Nutzung der freien Zeit

Abschlussfragen:

- Was ist abschließend aus Ihrer Sicht der wichtigste Punkt, damit Sie ein autonomes Fahrzeug für kognitiv eingeschränkte Personen in der Einrichtung nutzen würden?
- Was würde Sie davon abhalten, ein autonomes Fahrzeug für kognitiv eingeschränkte Personen in der Einrichtung zu nutzen?

Vereinfachte Version:

Stell Dir vor, dass wir weit in die Zukunft gereist sind. In dieser Zukunft könnten Autos und Busse ohne Fahrer fahren.

- Würdest Du z.B. einen Bus ohne Fahrer benutzen?
    - Ja/Nein: Warum?
    - Nein: Hättest Du Angst vor irgendetwas?
- Würdest Du unterwegs die Möglichkeit haben wollen, mit jemandem zu sprechen?
    - Ja/Nein: Warum?

Vielen Dank für das Gespräch!

===
English Version
===

Individual interviews - guide

Greeting and instruction (5min)

Good afternoon Mr./Mrs. XYZ,

Thank you for taking the time to participate in this interview study as part of a project on automated mobility funded by the European Regional Development Fund. My name is Henrik Detjen and I work at the Ruhr West University of Applied Sciences in the field of human-technology interaction. For the success of the project, it is important to interview you as experts to find out about concerns, wishes and your attitude towards the change in mobility. That is why we have invited you to today's interview.
It is important for me to emphasize that I am interested in your opinion. That means there are no right or wrong answers to the questions I will ask you. Please answer the questions openly and honestly. Don't worry, your information will be evaluated anonymously, so that no conclusions can be drawn about your person. To make sure that I don't miss any information, I will video- and audio-record the interviews so that I can evaluate them in the best possible way afterwards. Participation in the study is of course voluntary and can be revoked at any time without giving reasons.
Now that you have received all the necessary information, you are free to decide whether or not to participate in the study. Please read through this consent form (https://forms.gle/xEEsS3rwQxsoYvs37) [send link via chat] and sign it if you would like to participate in the interview. Thank you very much for your assistance. If you have any questions, please feel free to ask me at any time.

Topic: Warm-up - work and environment (5min)

Since our project is about assisted work and living facilities, I would like to know is about you and your work environment first:

- In your facility… For what tasks are you responsible?
- What do your clients do on a typical work day?
- What does a typical workday look like?
- What is especially fun about your work?
- What problems do you encounter?
- What would you like more time to do?

Simplified version:
In our project we would like to learn about you, your and your work.

- What did you do today?
- What was especially fun about it?

- What was not fun about it?

Topic: Current mobility patterns (10min)

Now I would like to go into more detail about the topic of mobility in your everyday work and with the people you care for, focusing on people with cognitive weaknesses or limitations:

- What makes travelling for cognitively impaired clients attractive?
- What special challenges do cognitively impaired people face when using mobility services?
    - On foot, By bike, By car, Public transport?
- Describe the last trip you made with your clients…
- When and under what circumstances is it necessary/meaningful to have another person accompany you?
- Are there technologies that support the use of mobility services for the cognitively impaired?
- What could be better in the use of mobility services for the cognitively impaired?
- And what for you as [insert job]?

Simplified version:
Now I'd like to talk to you about your commute, travel, and outings.

- How do you get to work / home? And how do you get to the grocery store?
    - On foot, by bike, or by car (Who drives?)?
    - How long is your commute to work?
- Are there things that annoy you when you travel there?
- And how do you get to friends or acquaintances who live further away?
    - Where do they live? By foot, by bike, or by car (who drives?)?
- Are there things that annoy you when you are on the road for a longer time?

Topic: Automated mobility (10min)

Let's assume we have traveled to the year 2050. Computer systems are able to take over complex driving tasks. Humans travel as passengers in autonomous vehicles, e.g., in a driver free bus.

- What are your expectations and concerns about travelling in an autonomous vehicle?
    - What would you think about this point…
        - safety or communication mechanisms
        - time gained

Concluding questions:

- In conclusion, from your perspective, what is the most important point that would make you use an autonomous vehicle for cognitively impaired individuals in the facility?
- What would prevent you from using an autonomous vehicle for cognitively impaired individuals in the facility?

Simplified version:
Imagine that we have traveled far into the future. In this future, cars and buses could run without drivers.

- For example, would you use a bus without a driver?
    - Yes/No: Why?
    - No: Would you be afraid of anything?
- Would you want to be able to talk to someone on the road?
    - Yes/No: Why?

Thank you very much for the interview!

Individual Contributions

For pointing out the individual contributions of this thesis, we use the CRediT author contribution taxonomy since major journal publishers use it, like Elsevier, PLOS ONE, or Nature. The CRediT taxonomy consists of the following author roles from which every publication author can fill several. We removed the categories validation, data curation, resources, supervision, and funding acquisition since these categories do not fit in the scope of this thesis. The remaining categories are used to describe better the co-author roles in the following.

Contributor Role	**Role Definition**
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims.
Methodology	Development or design of methodology; creation of models.
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components.
Formal Analysis	Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data.
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.
Writing – Original Draft Preparation	Creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation).
Writing – Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation.
Project Administration	Management and coordination responsibility for the research activity planning and execution.

Table 2: Applicable author contribution roles as defined within the CRediT taxonomy [NIS22].

	Publication	Contributor*	Contribution Roles**								
			Conceptualization	*Methodology*	*Software*	*Formal Analysis*	*Investigation*	*Writing – Draft*	*Writing – Review & Editing*	*Visualization*	*Project Administration*
[Det+21b]	*“How to Increase Automated Vehicles’ Acceptance through In-Vehicle Interaction Design: A Review”* Detjen, Faltaous, Pfleging, Geisler, and Schneegass	A	✓	✓	NA	NA	✓	✓	✓	✓	✓
		CoA	✓	✓	NA	NA	-	-	✓	-	-
[DSG19]	*“Maneuver-based Driving for Intervention in Autonomous Cars”* Detjen, Schneegass, and Geisler	A	✓	NA	NA	NA	✓	✓	✓	✓	NA
		CoA	✓	NA	NA	NA	NA	✓	✓	-	NA
[DPS20]	*“A Wizard of Oz Field Study to Understand Non-Driving-Related Activities, Trust, and Acceptance of Automated Vehicles”* Detjen, Pfleging, and Schneegass	A	✓	✓	NA	✓	✓	✓	✓	✓	✓
		CoA	✓	✓	NA	-	-	-	✓	-	✓
[DNG21]	*“Attitudes Towards Autonomous Public Transportation”* Detjen, Nurhas, and Geisler	A	✓	✓	-	✓	✓	✓	✓	✓	✓
		CoA	✓	✓	✓	✓	✓	✓	✓	✓	✓
[Det+22b]	*“An Emergent Design Framework for Accessible and Inclusive Future Mobility”* Detjen, Schneegass, Geisler, Kun, and Sundar	A	✓	✓	NA	✓	✓	✓	✓	✓	✓
		CoA	✓	✓	NA	-	-	-	✓	-	-
[Det+19]	*“User-Defined Voice and Mid-Air Gesture Commands for Maneuver-based Interventions in Automated Vehicles”* Detjen, Faltaous, Geisler, and Schneegass	A	✓	✓	✓	✓	✓	✓	✓	✓	✓
		CoA	-	-	-	-	-	✓	✓	-	-
[DGS20]	*“Maneuver-based Control Interventions During Automated Driving: Comparing Touch, Voice, and Mid-Air Gestures as Input Modalities”* Detjen, Geisler, and Schneegass	A	✓	✓	✓	✓	✓	✓	✓	✓	✓
		CoA	-	-	-	-	-	-	✓	-	-
[DGS21]	*“Driving as Side Task: Exploring Intuitive Input Modalities for Multitasking in Automated Vehicles”* Detjen, Geisler, and Schneegass	A	✓	✓	✓	✓	✓	✓	✓	✓	✓
		CoA	-	-	-	-	-	-	✓	-	-
[Det+21a]	*“Supporting User Onboarding in Automated Vehicles through Multimodal Augmented Reality Tutorials”* Detjen, Degenhart, Schneegass, and Geisler	A	✓	✓	-	✓	✓	✓	✓	✓	✓
		CoA	✓	✓	✓	✓	✓	-	✓	-	✓
[Det+21d]	*“Towards Transparent Behavior of Automated Vehicles: Design and Evaluation of HUD Concepts to Support System Predictability Through Motion Intent Communication”* Detjen, Salini, Kronenberger, Geisler, and Schneegass	A	✓	✓	✓	✓	✓	✓	✓	✓	✓
		CoA	✓	✓	✓	✓	✓	-	✓	-	-
[Det+22a]	*“Investigating the Influence of Gaze- and Context-Adaptive Head-up Displays on Take-Over Requests”* Detjen, Faltaous, Keppel, Prochazka, Gruenefeld, Sadeghian, and Schneegass	A	✓	✓	-	✓	✓	✓	✓	✓	✓
		CoA	✓	✓	✓	-	✓	✓	✓	✓	✓

Table 3: Individual contributions of this thesis author for each related publication; * *A = Author of this thesis, CoA = Publications’ Co-Authors*; ** *✓= Contributed, - = No contribution, NA = Not applicable*.

DECLARATION

Ich gebe folgende eidesstattliche Erklärungen ab:

Ich erkläre hiermit, dass ich in keinem laufenden oder früheren Promotionsverfahren zum Erwerb desselben Grades „Dr. rer. nat.“ endgültig gescheitert bin.

Die Gelegenheit zum vorliegenden Promotionsverfahren ist mir nicht kommerziell vermittelt worden. Insbesondere habe ich keine Organisation eingeschaltet, die gegen Entgelt Betreuerinnen und Betreuer für die Anfertigung von Dissertationen sucht oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt. Hilfe Dritter wurde bis jetzt und wird auch künftig nur in wissenschaftlich vertretbarem und prüfungsrechtlich zulässigem Ausmaß in Anspruch genommen. Mir ist bekannt, dass Unwahrheiten hinsichtlich der vorstehenden Erklärung die Zulassung zur Promotion ausschließen bzw. später zum Verfahrensabbruch oder zur Rücknahme des Titels führen können.

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Essen, den 20.10.2023

Henrik Detjen

With constantly growing automation capabilities in vehicles, the way we interact with them has already begun to change. Whereas automotive design has been based on technical considerations (speed, handling, etc.) for a long time, the non-involvement of the human in the driving task, creates new requirements while being mobile. Not only will drivers become passengers, the classical journey, e.g., visiting a friend in the next town, might start by foot and E-Bike, continue per train, and end with ordering an autonomous Robotaxi for the last mile. Given the service orientation of future mobility, the *journey experience* will be what users care for, and in that sense, the experience that fits their needs best.

In this thesis, we provide answers to the question of how users' needs and goals will change in future autonomous mobility services compared to today's individual transport. Thereby, we focus on in-vehicle interaction between users and vehicle automation. Further, we look at how to improve the users' safety and overall experience during automated and autonomous driving modes. In particular, we aim to bridge the gulfs of evaluation and execution of automated driving. We design and evaluate interfaces that are based on user needs and goals and provide them with maneuver-based control to intervene in the driving process and augmented reality interfaces that help understand and predict the vehicle's driving process. From these design studies, we derive lessons learned and design recommendations for future automated vehicles.