



### Transparency Communication in Autonomous Driving through Uni- and Multimodal Feedback Modalities and its Effects on First-Time Passengers' User Experience, Understanding and Feeling of Safety and Control

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### **Preface**

Autonomous driving represents a paradigm shift within user experience design, necessitating innovative solutions that ensure passengers' understanding and overall well-being. This thesis emerges from a critical analysis of existing gaps in research emphasising transparency communication and its impacts on first-time users' user experience, perceived safety, and control.

The positionality of this research resides at the intersection of human-computer interaction, explainable artificial intelligence, and user-centred design. Throughout my academic journey, I recognised the critical need for more intuitive and transparent interactions between autonomous systems and human users, especially when traditional forms of control are absent. This insight has profoundly shaped the methodological approaches adopted in my research and guided the interpretation of findings, ensuring that outcomes genuinely address user-centric challenges. It was particularly important for me to integrate user perspectives deeply into each phase of the research, reflecting my commitment to placing user experience at the forefront of technological innovation in autonomous vehicles.

A series of empirical studies—conducted using virtual reality, physical simulators, and Wizard-of-Oz methodologies—provide the structural backbone of this work. These studies systematically explore the efficacy of uni- and multimodal feedback modalities, including light, auditory signals, augmented reality, textual information, and tactile cues. The experiments adopted rigorous mixed-method, between- and within-subjects designs, utilising robust measures such as the User Experience Questionnaire Short and the Autonomous Vehicle Acceptance Model. Statistical validity was ensured through controlled experimental designs, sufficient sample sizes, and methodological rigour, facilitating robust, replicable findings.

My contribution to the literature lies explicitly in clarifying how transparent multimodal communication enhances passengers' system understanding, perceived safety, control, and overall UX, in normal as well as failure conditions. Additionally, by developing the ADX.cards, a practical toolkit for interdisciplinary design applications, this thesis extends beyond academic discourse into tangible frameworks that practitioners can readily utilise. Thus, it contributes not only to theoretical knowledge but also to practical methodologies, promoting creativity and tailored UX solutions in the evolving landscape of autonomous mobility.

### Abstract

Autonomous Driving Experience (ADX) design is an emerging field of research and design that centres on enhancing the passengers' user experience in autonomous vehicles. The key is the provision of transparent communication regarding the perceptions and intentions of these autonomous vehicles. This thesis is grounded in the principles of experience design. It applies Human Computer Interaction research methods to investigate autonomous driving experiences. Specifically, it explores how using uni- and multimodal feedback modalities can positively influence passengers' user experience, their perceived feeling of safety and control, and their understanding of the autonomous driving system. These factors are crucial for the successful adoption of autonomous vehicles.

Autonomous driving relies heavily on artificial intelligence (AI) for reasoning and decision-making. However, passengers may feel uneasy and out of control without adequate explanations. This research addresses this issue by delving into Explainable AI and exploring how, when, and in what contexts specific aspects should be explained or visualised to enhance the passengers' experience.

The research unfolds in several stages. Initially, an extensive and systematic literature review reveals the need for a more human-centred approach to experience design in autonomous driving. Subsequently, four experiments were conducted. These experiments investigated the impact of different feedback modalities for transparent communication on the passengers' user experience, perceived feeling of safety and control, and system understanding. The first three experiments demonstrate their The fourth experiment, however, uncovers the limitations of positive influence. transparency communication in non-critical failure situations, necessitating alternative approaches. In the next phase, all recommendations and contributions generated throughout this comprehensive research endeavour were distilled and encapsulated within a card-based toolkit - the ADX cards. These cards serve as a valuable resource for the field, providing a tangible and accessible embodiment of the research's insights. To ensure the validity and practical utility of the ADX cards, the toolkit underwent an iterative design process, expert evaluations, and extensive workshop testing. Furthermore, the ADX cards were successfully applied in four distinct real-world case *ABSTRACT* iii

studies, further validating their effectiveness and relevance, as well as this thesis' research.

The main contributions of this research are twofold. Firstly, the experiments shed light on the critical role of transparency communication in enhancing the autonomous driving experience and establish a foundation to do so. Secondly, the knowledge acquired throughout this thesis has been distilled into a card-based toolkit, the ADX cards, making the research findings readily accessible and applicable to those interested in advancing the field of autonomous driving experience.

### List of Publications

- Increasing the User Experience in Autonomous Driving through different Feedback Modalities (Schneider et al., 2021)
- Explain Yourself! Transparency for Positive UX in Autonomous Driving (Schneider et al., 2021)
- Velocity Styles for Autonomous Vehicles affecting Control, Safety, and User Experience (Schneider et al., 2021)
- Don't fail me! The Level 5 Autonomous Driving Information Dilemma regarding Transparency and User Experience (Schneider et al., 2023)

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# List of Acronyms

ACC adaptive cruise control

ADAS advanced driver assistance systems

AI artificial intelligence

AR augmented reality

**AD** autonomous driving

**ADX** Autonomous Driving Experience

AV autonomous vehicle

AVAM Autonomous Vehicle Acceptance Model Questionnaire

BASt Bundesanstalt für Straßenwesen

CAD conditionally automated driving

CADS conditionally automated driving systems

**DARPA** Defense Advanced Research Projects Agency

**FSD** Full Self-Driving

**HCD** human-centred design

**HCI** Human Computer Interaction

**HCXAI** Human-Centred Explainable AI

**HMI** Human-Machine-Interface

**HOR** hand-over request

**HUD** head up display

**HQ** hedonic quality

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**OR** object recognition

PQ pragmatic quality

 $\mathbf{RQ}$  research question

SAE Society of Automotive Engineers

**SOTA** state-of-the-art

 $\mathbf{TOR}$  take-over request

UCD user-centred design

**UEQ** User Experience Questionnaire

 $\mathbf{UEQ\text{-}S}$  User Experience Questionnaire - Short

**UI** user Interface

UMD uni- and multimodal display

UX user experience

 $\mathbf{UXD}$  User Experience Design

VR virtual reality

**XAI** Explainable Artificial Intelligence

WoZ Wizard of Oz

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## Declaration

I, Tobias Schneider declare that the enclosed submission for the degree of Doctor of Philosophy meets the regulations stated in the handbook for the mode of submission selected and approved by the Research Degrees Sub-Committee. I declare that this submission is my own work, and has not been submitted for any other academic award.

## Contributory Statement

#### Disclaimer Experiment 2

Students of the Stuttgart Media University carried out the physical driving simulator build, the recording of the driving scenes and implementation of the designs during a semester project. The project was, among others, supervised by the author. He played a central role as the main idea giver and influencer of the project and provided guidance and specifications that formed the basis for the students' implementations. While the students executed the hands-on work, the author's ideas and influence shaped the project's direction and vision.

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#### Disclaimer Experiment 3

Students of the Stuttgart Media University carried out the adjustments of the physical driving simulator, the recording of the driving scenes and implementation of the designs during a semester project. The project was, among others, supervised by the author. He played a central role as the main idea giver and influencer of the project and provided guidance and specifications that formed the basis for the students' implementations. While the students executed the hands-on work, the author's ideas and influence shaped the project's direction and vision.

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#### Disclaimer Experiment 4

Students of the Stuttgart Media University carried out the recording of the driving scenes and implementation of the feedback modality during a semester project. The project was, among others, supervised by the author. He played a central role as the main idea giver and influencer of the project and provided guidance and specifications that formed the basis for the students' implementations. While the students executed

the hands-on work, the author's ideas and influence shaped the project's direction and vision.

The students in alphabetical order: Taro Altrichter, Max Audring, Selina Haas, Jacob Heinzelmann, Oliver Maicher, Ebony March, Cara Walter

# Chapter 1

Introduction

### 1.1 Motivation

With autonomous vehicles (AVs) slowly making their way towards the market (Rajasekhar and Jaswal, 2015), new challenges arise for first-time users. Compared to riding a Taxi, the passenger does not rely on a human driver anymore but an artificial intelligence (AI) to perform the driving task. This known yet new experience of driving is shown to raise concerns in regards of user experience (UX), anxiety and system understanding (Frison et al., 2019; Hartwich et al., 2020; Rödel et al., 2014; Tan et al., 2022) as well as feeling safe (American Automobile Association, 2016, 2017, 2018, 2019; Brennan and Sachon, 2022; Lloyd's Register Foundation, 2021) and in control (Howard and Dai, 2014; Jeon et al., 2018; Raue et al., 2019; Rödel et al., 2014). Thereby, positive experiences are needed for first-time passengers of AVs in order for them to not stop using a product (Hassenzahl and Tractinsky, 2006; Kahneman et al., 1999).

With the lack of a human driver, the area of Explainable Artificial Intelligence (XAI) becomes important to create an understanding of the AV's perception and actions and thus create transparency. Existing research has looked at the application of different feedback modalities, so-called uni- and multimodal displays (UMDs), to create transparency in automated driving systems (compare, for example, Geitner et al. (2019); Lewis et al. (2013); Politis et al. (2015a)), which will be referred to as transparency communication from here on out. Thereby, a big emphasis was put on reaction times, time to collision or take-over times for scenarios where people are still actively driving. With the increase of a system's autonomy, research shifted towards communicating the reliability of a currently active system (compare, for example, Beller et al. (2013); Kunze et al. (2018)).

While all these studies were centred around the driver, hence the user, they did not take their experience into consideration, revealing a gap in research regarding communication through UMDs. This thesis builds upon research and investigates how existing communication patterns can be applied to autonomous driving (AD) for providing information on the perception and intent of AVs through transparent communication, from now on called *transparency communication*. It looks at their influence on relevant metrics of AD, namely passengers' UX, perceived feeling of safety and control, and system understanding, the four main metrics of this thesis.

While a few studies on transparency communication in AD were available at the beginning of this thesis, looking at first implications through different modalities on some of the four main metrics, these were far from exhaustive (Beattie et al., 2014;

Fröhlich et al., 2019; Häuslschmid et al., 2017; Large et al., 2019; Wintersberger et al., 2017). Therefore, this thesis investigates using different feedback modalities for transparency communication in AD through four main experiments. The first three look at the influence on passengers of AVs and the four main metrics during regular driving, and the fourth experiment looks at the influence of non-critical failure situations on transparency communication and the potential need for different approaches.

Throughout this thesis, other researchers also added to the pool of knowledge of transparency communication in AD. However, there is no research available on how this generated knowledge on transparency communication in AD can easily be made available and applicable to design-based disciplines.

To address this second research gap, this thesis not only investigates transparency communication through empirical studies but also translates the gathered findings into a practical design tool. Therefore, a card-based toolkit called *ADX.cards* is developed. The ADX.cards aim to make the theories and insights on transparency communication in AD accessible and actionable for design-based disciplines, such as UX design, Human Computer Interaction (HCI), and automotive development. By offering structured guidance on understanding, safety, control, and system transparency, the toolkit supports users in creating, evaluating, and iterating transparency communication concepts, thereby operationalising the research for practical application.

### 1.2 Research Questions

This thesis addresses the following research questions (RQs):

- 1. How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?
- 2. How do failure situations affect the passengers' perception of transparency communication?
- 3. How can a framework be used to provide the research findings on transparency communication in autonomous driving to a broader, interdisciplinary audience for application in design-based disciplines?

#### 1.3 Thesis Outline

Chapter 2 thoroughly reviews literature relevant to transparency communication in AD. The chapter begins by introducing the concept of perceived feeling of safety and control, highlighting the factors influencing these needs and their connection to the human needs theory of UX design and their importance in AD. It then introduces the concept of UX, defining it and presenting two popular design frameworks. The chapter then explores the topic of XAI and its relevance to system understanding and transparency communication in AD, emphasising the importance of complete and interpretable explanations. Subsequently, the use of UMDs in manual, conditionally automated, and highly automated driving, as well as AD, is examined, analysing different feedback modalities and their combinations. The lack of research regarding UX and user-centred designs in transparency communication is highlighted here. The chapter concludes by discussing the application of UMDs for transparency communication in AD, including people's desire for more information, the need for safety and control, and the demand for research on transparency communication in AD. Overall, the literature review chapter inspires the first RQ of the thesis.

Chapter 3 provides an analysis of the current market availability of advanced driver assistance systems (ADAS), conditionally automated driving (CAD), and AD systems that utilise different feedback modalities for transparency and intent communication. The focus is on the implementation of UMDs by manufacturers such as Tesla, Mercedes-Benz, and Waymo. The analysis also highlights the challenges these systems face in transparency and intent communication, particularly when the vehicle's actions or route calculations may not be apparent to the passenger.

Chapter 4 presents the methodology of the thesis. It begins by defining the user-centred design (UCD) process, which serves as the basis for the approach taken in the thesis and informs the general procedure and experiments. The chapter then introduces three different types of simulators used in the experiments, discussing their advantages and disadvantages. Then, metrics utilised in the experiments are established. The implementation and analysis of the studies are described, outlining the process of conducting the experiments and the methods employed to analyse the results. Additionally, the involvement of participants in the experiments is discussed.

Chapter 5 presents and discusses the findings from focus groups and expert interviews. There is a correspondence between these and the literature review, highlighting the importance of designing for the perceived feeling of safety and control, XAI and UX in AVs. The chapter also explores the variability of information

transmission based on situational and contextual factors. Furthermore, experts present diverse opinions on the technology to be used for transparency communication. The analysis also acknowledges the significance of addressing failure situations and considering the communication of the AV's state and limitations, motivating the second RQ.

Chapter 6 discusses the four main experiments conducted as part of this thesis. Each experiment is introduced with background information and contextual details. The setup of each experiment is explained, including the methodology, materials used, and specific procedures followed. The findings from each experiment are analysed and discussed, identifying patterns and significant observations. Thereby, the first three experiments investigated the use of different feedback modalities for transparency communication in AD and their influence of the passengers' UX, perceived feeling of safety and control, and system understanding, answering RQ-1. The fourth experiment looked at the implications of non-critical failure situations in AD on transparency communication and discusses new challenges that arise through them, Additionally, the section explores the connections between the answering RQ-2. experiments, comparing and contrasting the results and conclusions with the current state of research. The chapter concludes with a comprehensive overview of the main experiments conducted, summarising the obtained results and highlighting the broader implications of the findings.

Chapter 7 introduces the main creative contribution of the thesis, a card-based toolkit called Autonomous Driving Experience (ADX) cards, which aim to convey research findings to designers and assist in creating and evaluating transparency communication in AD for first-time passengers. The toolkit has three main goals: providing necessary information, facilitating the creation of feedback modalities, and supporting users in developing evaluation strategies and data analysis. The chapter describes the creation process of the ADX cards, including theoretical concepts, design iterations, and validation through expert feedback and user workshops. The toolkit's potential usefulness is indicated, although further independent studies are recommended for deeper insights. Additionally, the chapter presents and discusses four case studies where the ADX cards were employed, highlighting the freedom in creating solutions and the content validity of the toolkit, answering RQ-3.

Finally, Chapter 8 presents the final discussion of the RQs, the thesis' contribution to knowledge and discusses limitations and possible future work.

### 1.4 Conclusion

In conclusion, this thesis looks at transparency communication in AD and its influence on passengers' UX, perceived feeling of safety and control, and system understanding. Therefore, existing knowledge is gathered and discussed through an exhaustive literature review, followed by a state-of-the-art (SOTA) analysis, expert interviews, and focus groups. This knowledge is used to create and examine different transparency communication solutions through uni- and multimodal feedback modalities in four main experiments that use various driving simulators. The obtained results of the four experiments and adjacent research are then made available through a card-based design toolkit, which aims to make the knowledge graspable and applicable for everyday use in design-based disciplines. The toolkit undergoes a first evaluation through experts, workshops and case studies.

# Chapter 2

Literature Review

In order to talk about the topic of this thesis, the (theoretical) foundations it is built upon have to be defined first. It is important to understand where this thesis comes from and how specific challenges and decisions came to be. This chapter reviews literature on all related topics of AI transparency in AD through UMDs.

First, the different automation levels of vehicles are introduced in section 2.1, and it is defined what this thesis refers to when talking about AD. Then, the perceived feeling of safety and control are discussed in section 2.2 and 2.3, and it is highlighted why both will be important for transparency communication in AD. As this communication is built for the passengers of AVs and will therefore be perceived subjectively, UX is defined in section 2.4. Then, literature on system understanding and transparency is reviewed, and XAI in general and for AD is defined in section 2.5. Finally, this chapter finishes with an extensive literature review on the use of UMDs in manual, conditionally automated and AD in section 2.6 and 2.7.

#### 2.1 Vehicle Automation Levels

As there is not just one level of vehicle automation, the Society of Automotive Engineers (SAE) came up with a classification system to help talk about different automation levels of vehicles (SAE On-Road Automated Vehicle Standards Committee, 2021b). They comprise six different levels. Ranging from SAE level 0 with no automation but only "warnings and momentary assistance" (SAE On-Road Automated Vehicle Standards Committee, 2021a) to level 5 where the vehicle is driven autonomously under all conditions and requires no supervision task by the user at all. Figure 2.1 shows a complete breakdown of the different levels.

The SAE furthermore groups the first three levels into so-called *driver support* features and the last three into automated driving features. The first group requires the driver to supervise their vehicle all the time. In the second group, SAE level 3 requires the driver to take over when needed. In contrast, levels 4 and 5 require no takeover by the driver.

In 2022, Germany's Federal Highway Research Institute (Bundesanstalt für Straßenwesen, 2022) proposed an alternative to the six SAE automation levels. They define three modes of AD: assisted, automated, and autonomous. Figure 2.2 shows how they fit the three modes onto the SAE levels.

When this thesis is talking about AD, it is referring to the SAE level 5, where no driver takeover is needed or possible. CAD is referring to the SAE levels 1 to 4. Manual driving refers to level 0.

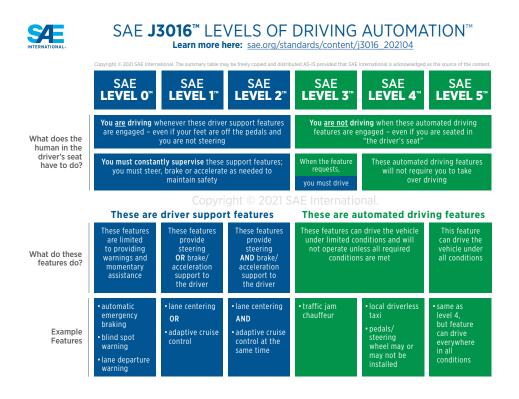


Figure 2.1: Different driving automation levels defined by the SAE On-Road Automated Vehicle Standards Committee (2021a).

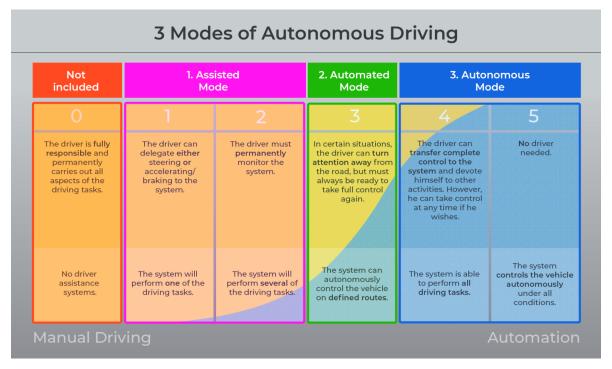


Figure 2.2: Different driving automation modes defined by the Bundesanstalt für Straßenwesen (2022).

### 2.2 Perceived Feeling of Safety

Studies and surveys have shown that feeling safe will be essential to accepting and using AVs. The Self Driving Car Consumer Survey by the American Automobile Association (2016) showed that 75% (N=1832) of Americans would not feel safe in a self-driving vehicle. With women and baby boomers being more afraid than men and younger generations. A year later, they reported similar results (N=1012) (American Automobile Association, 2017). In 2018, the number of Americans not feeling safe reduced to 63% (N=1004). Furthermore, they added that Generation X and baby boomers are more afraid of driving in AVs than younger drivers (American Automobile Association, 2018). One year later, the amount of Americans not feeling safe went back up to 71% (N=1008) (American Automobile Association, 2019). Fitting these findings, a survey by Brennan and Sachon (2022) revealed that 76% of Americans (N=1500) claim to feel less safe when operating or riding in vehicles equipped with self-driving technology.

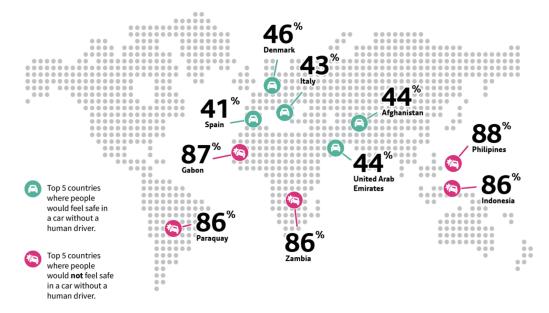


Figure 2.3: "Suppose that in the next few years we have cars that can drive themselves using a computer system in the car, without a human driving them. Would you feel safe being driven in a car without a human driver, or not?" (Lloyd's Register Foundation, 2021).

Widening the view from the US to the rest of the world, the World Risk Poll from Lloyd's Register Foundation (2021) (N>125000) shows that the feeling of safety in being driven autonomously varies across countries, see also Figure 2.3. It is further connected to people's education level and internet access availability, with higher education or better access equaling a higher feeling of safety. However, the majority of people say they would not feel safe in an AV regardless of country or background.

Thereby, an increase in autonomy is linked to a decrease of the perceived feeling of safety (Hewitt et al., 2019). A survey by DG CITIES (2022) from the United Kingdom (N=651) showed that the feeling of safety is tied to the driving environment, showing a difference between day and nighttime drives. Frison et al. (2019) showed similar findings regarding the driving environment; however, they were not connected to day and night but to urban and rural settings. In their study, participants (N=30) expressed a higher need for safety in urban environments compared to rural roads.

Having explored the varied studies highlighting public concerns about feeling safe in AVs, one must also understand what exactly the perceived feeling of safety is. The following subsection delves into the scientific definition of the perceived feeling of safety, describing its complexities and interconnections to understand better its impact and implications in the area of AD.

#### 2.2.1 Definition

This subsection defines what exactly the perceived feeling of safety is and how it entangles with the human needs theory of User Experience Design (UXD) in section 2.4.6.

According to the behavioural economic prospect theory of Kahneman and Tversky (1979), humans are loss-averse. The theory describes how people make decisions under uncertainty and suggests that people are more risk-averse when considering potential losses than when considering potential gains. Human's perception of safety thereby relates to avoiding losses which equals a state where they are protected from harm. Following the research of Eller and Frey (2019), one can express the core of feeling safe in a positive way by finding out humans' needs and how the response to their satisfaction looks like. They propose the concept of perceived safety, which they define as a stable state where the most important needs are satisfied. This overall concept shows a resemblance to the needs model of UXD discussed in section 2.4.6. However, while in UXD an unfulfilled human need may "only" lead to a bad UX, it may lead to actual harm when it comes to safety, as they are directly tied together (Baumeister, 2011). In the case of AD, this perceived feeling of safety might, for example, be related to the fear of getting into an accident and being harmed oneself. Eller and Frey (2019) claim that the perceived feeling of safety is not limited to physical integrity as proposed by Maslow (1943) but other needs that can have a social character. For example, pleasurable stimulation (Sheldon et al., 2001), appreciation and meaningfulness (Frey et al., 2011) or, as we will see in the next section, the concept of perceived control (Frey and Jonas, 2002). Eller and Frey (2019) believe

that this multitude of needs have an influence on feeling safe. Appreciation and meaningfulness might not be important to the safety perception of AVs. However, feeling in control and not being afraid of being harmed seem to be concepts worth pursuing when it comes to increasing the perceived feeling of safety in AVs.

To conclude, studies and surveys have shown that making passengers of AVs feel safe should be a priority, as people have expressed concerns regarding their feeling of safety. This attitude can vary depending on, among other things, age, gender, education or driving environment. Thereby, the concept of perceived safety is bound to actual harm and fulfilling different needs, showing a resemblance to the human needs theory of UXD discussed later in section 2.4.6. The apparent need for increasing the perceived feeling of safety is reflected in RQ-1 (How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?).

Transitioning from the discussion on the perceived feeling of safety in AD, another closely related but distinct aspect must be discussed: the perceived feeling of control. The following section will discuss how the sense of control - or the lack thereof - plays a crucial role in shaping the acceptance and UXs of AVs, thereby highlighting the complex construct that control is.

# 2.3 Perceived Feeling of Control

Next to the aforementioned perceived feeling of safety, the perceived feeling of control will play a part in accepting AVs and having a positive UX using them.

Howard and Dai (2014) (N=107) showed that the loss of control in AD is a point of concern for people. Thereby, women and individuals with lower incomes were more concerned about losing control than men and people with higher incomes. Furthermore, individuals who were driving alone during their commute and cyclists showed the most prominent concern regarding the loss of control in AD. In the same year, Rödel et al. (2014) came to a similar conclusion in their study. Participants (N=336) reported a decrease in their feeling of perceived control with rising autonomy levels. Women, young drivers in general and drivers with little experience reported the lowest results in regards to AVs. Jeon et al. (2018) came to a similar result when they conducted a survey with 866 people from Austria, Germany, South Korea, and the USA. They report that 83% of their participants stated the need to be able to take over control whenever they wish to. One year later, Raue et al. (2019) compared how people's (N=1484) attitudes about traditional driving affect their perceptions regarding AVs. They show that the risk and benefit perception inversely correlates with feelings of control and conclude that "Giving up control may, in fact, be one of the major barriers to the adoption of self-driving cars." (Raue et al., 2019, p.13). This general need for control is also reflected in the Self Driving Car Consumer Survey Fact Sheet of the American Automobile Association (2020). 2020 was the first year they added the topic of control to their survey. Furthermore, results also showed that feeling in control is linked to the perceived feeling of safety. 72\% of respondents (N=1301) said that being able take over control in case something goes wrong would increase their feeling of safety.

As with the perceived feeling of safety, having looked at various studies that emphasise public concerns regarding the feeling of control in AVs, it becomes necessary to understand what it is. The following subsection examines the scientific interpretation of the perceived feeling of control, discussing its complexities and interrelations to enhance the understanding of its significance and consequences within the context of AD.

### 2.3.1 Definition

Rotter (1966) is largely credited with introducing the term and concept of perceived control in 1966. It refers to an individual's perception of their ability to control their internal states, behaviours, and external environment (Langer and Saegert, 1977;

Lefcourt, 1966; Pearlin and Schooler, 1978; Wallston et al., 1987). The terms self-efficacy, mastery or locus of control have been used as well to describe the concept of perceived control (Keeton et al., 2008; Ledrich and Gana, 2013). Since then, over 50 years of research show that feeling to be in control has, for example, a positive influence on a person's well-being, health and anxiety (Alexander et al., 1989; Cheng et al., 2013; Haigh et al., 2011; Lachman and Weaver, 1998; Langer and Rodin, 1976; Pagnini and Phillips, 2015; Rodin and Langer, 1977). Thereby, perceived control seems to be more important to people living in western countries (Sastry and Ross, 1998).

Rothbaum et al. (1982) introduced the two-process model of perceived control. They state that people can have two different forms of control, primary and secondary. Primary control refers to attempts to change the world. In contrast, secondary control relates to attempts to alter oneself to fit in with the environment. According to Rothbaum et al., secondary control can be used when it is impossible to exert primary control. Having done so successfully is regarded as a state of acceptance.

Seven years later, Bryant (1989) introduced the four-factor model of perceived control, referring to the model of Rothbaum et al. (1982) and extending it to four types of control. (1) Primary-negative control, referred to as avoiding, is described as "the perceived ability to avoid negative outcomes" (Bryant, 1989, p.775). It is based on, among other things, a person's beliefs to be able to predict and avoid or have control over negative events. (2) Secondary-negative control, referred to as *coping*, is described as one's perceived ability to deal with negative results. Stemming from a variety of things, including coping strategies or the belief of being able to predict negative events and thereby prevent disappointment. (3) Primary-positive control, referred to as obtaining, is described as "the perceived ability to obtain positive outcomes" (Bryant, 1989, p.775). It is, for example, about a person's belief in being able to predict and obtain or have direct control over positive events. Secondary-positive control, referred to as savoring, describes one's perceived ability to appreciate and enjoy positive events. It results from, inter alia, one's beliefs about being able to enhance their well-being by recalling past positive events or using behavioural strategies to enjoy positive events longer.

### Illusion of Control

The term illusion of control was initially introduced by Langer (1975). It describes the phenomenon that people tend to overestimate their ability to exert control over events. She describes the illusion of control as confusion between situations based on

skill or chance. She says that one's judgment of their control is based on so-called *skill* cues. According to Langer, people tended to overestimate their control over situations with the introduction of elements of skill into situations based on chance.

Two decades later, Thompson et al. (1998) argued that the definition of Langer (1975) was not holistic enough to explain the many variations of the illusion of control effect. They state that a person's judgements about their availability of control are based on the concept of a control heuristic. The heuristic describes that one's judgement is based on two points. They must (1) want to create the result, and (2) there must be a connection between their action and the result. Perception of personal control is thereby increased if one can link their actions to the desired result. Furthermore, the illusion is more likely to happen in familiar settings or settings where the desired outcome is known and can be increased with feedback emphasising success rather than failure, which can have the opposite effect (Thompson, 1999).

McKenna (1993) also showed this illusion of control over situations in a self-reported behaviour study in 1993, where participants (N=93) were asked about perceived accident involvement. They rated their chance to be in an accident significantly lower when they were hypothesising to be the driver (high-control environment) rather than the passenger (low-control environment).

To conclude, the feeling of perceived control is a complex topic being researched for over 50 years in a multitude of different areas. It is about one's perception of their ability to exert control in different situations and can even lead to an illusion of control. Regarding AD, surveys have shown that people express a need for control in AVs. How strong this expression is, depends on factors like gender, income or type of commute. Furthermore, there is an indication that the feeling of control is linked to the feeling of safety. Therefore, the need for increasing the perceived feeling of control is reflected in RQ-1 (How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?).

Having defined the concept of the perceived feeling of safety and control in AD, the following section looks at a broader yet interconnected theme: UX. It will discuss the foundations of UXD and introduce two prominent UX design frameworks.

# 2.4 User Experience

This section looks at the topic of UX of interactive systems by analysing existing literature. It addresses the UX part of RQ-1 (How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?) and RQ-2 (How do failure situations affect the passengers' perception of transparency communication?). First, it is defined what an experience in itself is. Then, it is defined what UX is and how it differs from an experience, followed by the introduction of Usability and its influence on UX. Afterwards, two prominent design frameworks of UXD are introduced. Any research done on UX in this thesis will be built upon the introduced theories and the two design frameworks. The UX design process this thesis follows is later defined in Section 4.

## 2.4.1 Experience

In order to talk about the UXD of interactive systems, it is necessary to define an experience first. Kahneman et al. (1999) define an experience as a continuous commentary of the brain, evaluating the current situation as good or bad. Alben (1996) uses a more concrete definition and already takes a product into account. She refers to experience as "all the aspects of how people use a product [...]" (Alben, 1996, p.1), thus already referring to the holistic nature of UXD. As we will see in the following subsection, an experience is often described in the context of a product usage. However, compared to UX, an experience must not be bound to a product, for example going to a concert or visiting a museum (compare for example Law et al. (2009), and Section 2.4).

In his book *Emotional design: Why we love (or hate) everyday things* Norman (2004) defines three levels that influence a human's experiences (*visceral*, *behavioural*, and *reflective*). These levels form the basis for the emotional design theory that suggests positive experiences can stem from products that generate emotions.

- Visceral Level: This level concerns a user's initial raw emotional reaction to a product's visual appearance, sound, smell, and other sensory cues. The visceral level elicits a user's instinctive and aesthetic response to the product.
- Behavioural Level: The behavioural level focuses on the experience and usability of the product. It pertains to how a user responds emotionally to the ease of use or difficulty in using the product.

• Reflective Level: This level relates to users' experiences and feelings following their interaction with a product. It relates to how a user feels about using the product regarding, for example, pride, satisfaction, or regret. The reflective level evolves and becomes a user's lasting impression of the product.

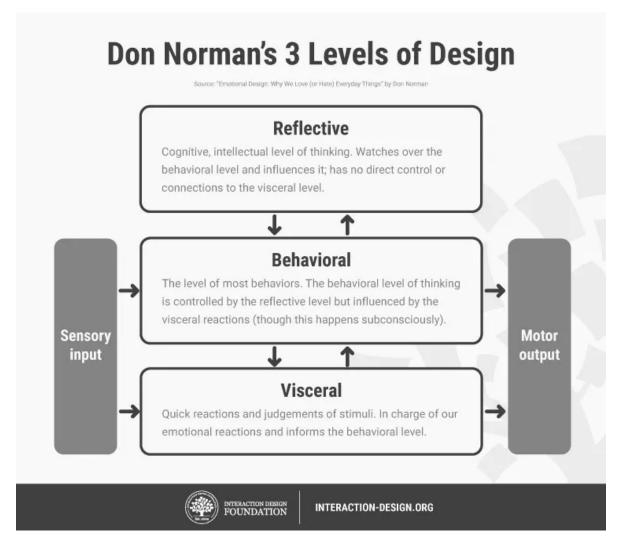


Figure 2.4: The three different levels of emotional design by Norman (2004) (image by Interaction Design Foundation (n.d.a)).

In the same year Forlizzi and Battarbee (2004) looked at experiences in interactive systems and products. They distinguish between three different types of experience (experience, an experience and co-experience).

• They characterise experience as a "constant stream of "self-talk" that happens when we interact with products" (Forlizzi and Battarbee, 2004, p.263) similar to the definition of Kahneman et al. (1999). With everything we do we are experiencing. For example, riding a bike or showering.

- An experience is something that can be named or talked about, has a definite beginning and end and can animate users to emotional or behavioural change. For example playing a video-game or watching a TV show.
- A co-experience enables the creation of meaning and emotion through the joint use of products. For example playing a video-game with a friend or climbing together.

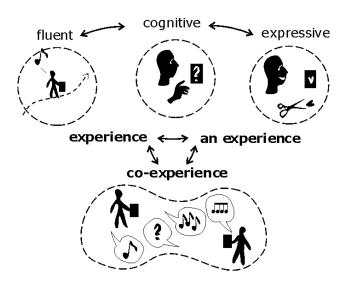


Figure 2.5: The three different types of an experience (Forlizzi and Battarbee, 2004).

According to Hassenzahl and Tractinsky (2006), an experience is a complex, subjective construct that consists, among other things, of the used product or interaction and internal parameters of the user. These are, for example, their current mood or goals. Due to its complexity, McCarthy and Wright (2004) emphasise that an experience must be examined in its entirety, including its context or specific scenario. Hassenzahl and Tractinsky (2006) thereby divide experience in three different, overlapping facets called beyond the instrumental, emotion and affect and the experiental, see Figure 2.6. Hassenzahl and Tractinsky are aware that three facets cannot fully present the complexity of an experience but rather offered different perspectives with it. Emphasising that positive HCI is more than focussing on usability problems.

Furthermore, all experiences are temporal, subjective and dynamic (Hassenzahl and Tractinsky, 2006). During an experience, emotions are created that influence if the user continues or stops their current activity (Kahneman et al., 1999). The goal of UXD is to create meaningful product interactions and possibly associated emotions (Forlizzi and Battarbee, 2004), yet, due to the subjectiveness of emotions, designers

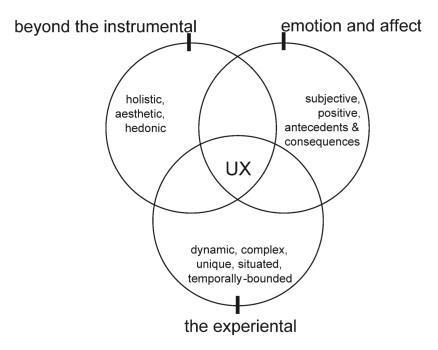


Figure 2.6: The three facets of user experience by Hassenzahl and Tractinsky (2006).

can only create the context for them to occur but never design for them directly (Hassenzahl and Tractinsky, 2006).

To summarise, experiences are the foundation to talk about UXD. There are multiple different definitions of what an experience is. It is, among others, defined as a complex, dynamic, subjective and holistic construct that is, for example, influenced by emotions or the context it occurs in. It involves a person and their environment and can encompass various sensory, cognitive, emotional, and behavioural components. It can be positive, negative, or neutral and can thereby vary in intensity and duration.

Building upon the understanding of an experience, the following subection looks at a more specific and pivotal aspect: UX. It delves into the definition of UXD and how it focuses on creating a more intuitive, engaging, and satisfying interaction between the user and a product. Furthermore, the Section shows the difference between an experience and a UX.

# 2.4.2 User Experience

The term UX was originally defined by Norman et al. (1995). In an interview with Adaptive Path the interviewer Peter Merholz quoted an email conversation with Don Norman, where he wrote: "I invented the term because I thought human interface and usability were too narrow. I wanted to cover all aspects of the person's experience with the system including industrial design graphics, the interface, the physical interaction

and the manual." (Merholz, 2007).

While the term UX can be interpreted differently (Law et al., 2009), even by experts, it has been defined in the ISO standard 9241-210 as a "person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service" (International Organization for Standardization, 2019). The difference to an experience is that UX is created through the bond of an experience to the usage of a product, system, service or object that is interacted with through a user Interface (UI) (Forlizzi and Battarbee, 2004; Law et al., 2009), see Figure 2.7. Without that interaction there is no UX. The product itself only offers the potential

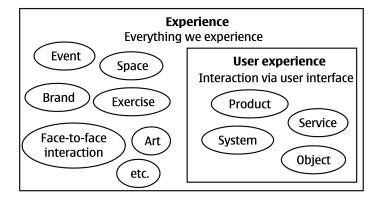


Figure 2.7: The separation between experience and UX (Law et al., 2009).

for an experience (Hassenzahl, 2007). Hassenzahl (2007) explains it using the example of a convertible. By standing in the garage, the convertible offers the potential for an experience. However, only by driving it on a nice day, hence interacting with the product, a UX is created. A UX is thereby always something individual. It is of course possible for a group of people to experience something together, however, each person will still have their own individual experience (Law et al., 2009). The group of people is just one of many contextual factors in UX. Despite being subjective, these individual experiences are furthermore dynamic as well as context-dependent. Thereby, a UX is not something linear. It may have peaks or turn from something positive into something negative. A new smartphone might be an exciting experience until the camera app crashes right at the moment when you want to take an important picture. Furthermore, the subjective context of every person experiencing plays a relevant role. Someone who has just been broken up with will probably have a different UX with the same product than someone who just got into a relationship.

In conclusion, UX describes a subject's experience when using a UI to interact with a product, system, service or object. This is what sets it apart from experience. The interaction enables the UX, with the product only offering the potential for it. It is thereby individual and dependent on the subjective context of every individual.

Having defined what a UX is and how it differentiates from an experience, the following subsection focuses on a more specific yet crucial component of HCI: Usability. It defines the term and presents fundamental factors of usability, such as learnability, accessibility, and efficiency. Understanding usability is key to ensuring that a UX is not only enjoyable but also functional and effective in real-world scenarios.

# 2.4.3 Usability

In the journey towards a good UXD, usability is the initial gateway to a positive overall UX. It addresses fundamental issues that may arise when using a system, paving the way for more advanced experiences. Usability ensures a product is easy to use, focusing on the user's initial interaction rather than the complete UX. Providing users with effortless access to a product is an essential step towards delivering a positive experience.

Usability is defined by its own ISO norm as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (International Organization for Standardization, 1998).

Nielsen (2012b) summarises usability in five so-called quality components: learnability, efficiency, memorability, errors and satisfaction.

- Learnability: How quickly can users complete basic tasks when they first encounter the design?
- Efficiency: After users have become familiar with the design, how efficiently can they complete tasks?
- *Memorability*: When users revisit the design after a period of inactivity, how quickly can they regain proficiency?
- *Errors*: What is the frequency and severity of errors made by users, and how easily can they recover from them?
- Satisfaction: How enjoyable is the experience of using the design?

Nielsen mentions satisfaction as the fifth quality component, showing the direction usability aims in: UX. Or, as he also states it: "[...] leaving is the first line of defense

when users encounter a difficulty" (Nielsen, 2012b). Therefore, usability serves two purposes: firstly, it directly enhances the product experience and contributes to the overall UX. Secondly, it sets the foundation for more comprehensive and user-centred design approaches to build upon. This is why it is considered the fundamental aspect of successful UXD.

To summarise, usability refers to the ease and efficiency users can interact with a product or system to achieve their goals. It involves designing interfaces that are intuitive, user-friendly, and accessible, allowing users to navigate, understand, and use the product effectively. It thereby forms a basis for positive UXs.

Progressing from discussing the tangible aspects of usability, which focus on the practicality and efficiency of user interactions, the following subsection looks at mental models. It explores the cognitive framework users form around using a system – how they understand, perceive, and anticipate its functioning. Defining mental models is crucial for aligning technology design with user expectations and enhancing the overall effectiveness and UX.

### 2.4.4 Mental Model

One influential factor on people's UX when interacting with products are mental models. They are cognitive representations of the external world that allow them to comprehend and interact with their environment (Craik, 1944; Johnson-Laird, 1989; Norman, 1983) and were initially defined by Craik (1944). These models are built through people's experiences and interactions with the world around them, and they are constantly evolving as new information is learned. Mental models are used to explain and predict the workings of objects, systems, or processes in people's environment, and they guide their future interactions with them (Johnson-Laird, 1989; Nielsen, 2010). Individuals have different experiences and backgrounds, and as a result, they develop individual mental models of a system during their interaction. These mental models are often simplified versions of the actual system workings. However, they are sufficient if they allow users to understand and predict the majority of observed system behaviour (Norman, 1983). For example, users do not need to understand the complex workings of a car to start it successfully.

Working with, enhancing or changing mental models can pose several challenges. Their persistence distinguishes them, as they can be resistant to alteration even if they clash with the actual behaviour of the product (Moray, 1987). Changing an individual's mental model can thereby be a time-consuming task. Moreover, mental models are incomplete representations of a system's functions. They are based on an

individual's subjective understanding of how the product works. This subjectiveness also makes mental models unstable over time, as users tend to forget details (Norman, 1983).

If mental models are wrong, which they can be as they are subjective (Craik, 1944; Johnson-Laird, 1989), or do not adequately reflect the complexity of a system, users may experience difficulty in predicting and explaining the system's behaviour. This can lead to usability problems and may indicate areas where the system needs to be improved (Nielsen, 2010). The bigger the gap between the designer's conceptual and the user's mental model, the bigger the chance for usability problems; see Figure 2.8. The designers' expertise can lead them to form comprehensive mental models, causing them to perceive each feature as easy to understand. However, users' mental models may be less developed, leading to an increased likelihood of errors and difficulty using the design.



Figure 2.8: Conceptual versus mental model.

To conclude, mental models are people's internal representations of a system or process based on their prior knowledge, experiences, and beliefs. They are incomplete, subjective, and can be resistant to change, making them challenging to work with and enhance. Adhering to the users' mental model is integral to designing UX.

Having looked at mental models and how users conceptualise and interact with systems, the following section focuses on personas. It will define personas and their use in UXD by understanding the users' goals, needs, and behaviours.

### 2.4.5 Personas

A commonly used design method in UX design are personas invented by Cooper (1999). They are fictional characters that represent the target users of a product or service and are used to understand and empathise with the potential users (Cooper, 1999; Cooper et al., 2007). Thereby, personas are given attributes like a name, image, detailed background or list of pain points to help teams familiarise themselves with their potential customers. Instead of talking about an abstract group of customers,

teams can now refer to concrete personas and their name.

Personas are crucial in enhancing the design process by bringing several benefits (Cooper, 1999; Cooper et al., 2007; Grudin and Pruitt, 2002; Pruitt and Adlin, 2010). They improve empathy and understanding of users' perspectives, allowing designers to better grasp their needs and desires. This leads to a more user-centred approach, resulting in design decisions that are supposed to align more closely with user needs and goals. Additionally, personas facilitate communication and collaboration among design teams, ensuring a shared understanding among team members about the target users. Furthermore, personas help reduce subjective biases and assumptions in the design process, enabling designers to make more objective and informed decisions. Thereby, personas are used to contribute to creating user-centred and -friendly designs.

In conclusion, personas are a valuable tool in UX design, enabling designers to empathise with users and make informed design decisions. By understanding target users' goals, needs, and behaviours, personas help create user-centred experiences. Through research, creation, validation, and utilisation, personas aim to contribute to improved usability and user satisfaction in the design process.

Transitioning from personas, the following subsection discusses the needs model of UXD. It defines how this model can help to systematically address and fulfil the varying needs and expectations of users identified through, among others, Personas. By applying the needs model, one can create a more user-centred design approach, ensuring that the UX is not just functional but also profoundly resonant and satisfying.

### 2.4.6 The Needs Model

One aspect of the creation process of experiences are the aforementioned emotions, which are linked to actions and thoughts (Carver and Scheier, 2001; Kaptelinin and Nardi, 2006). According to McCarthy and Wright (2004), emotions and experience cannot be separated. Based on Nussbaum (2003), they state that our actions are fulfilled by values, needs, desires and goals (McCarthy and Wright, 2004).

Hassenzahl et al. (2010) argued that McCarthy and Wright (2004) never described what they meant by *needs* and proposed that it is possible to categorise experiences even though they are subjective and different every time. Based on initial research of Sheldon et al. (2001), they suggest categorising experiences by basic psychological needs, such as competence or stimulation, and that their fulfilment is the source of positive experiences when interacting with interactive products. With their

need-oriented experience model, they understand experiences "as clusters of particular situations, actions and feelings, revolving around a particular need, which "colours" the entire experience" (Hassenzahl et al., 2010, p.358). Focussing on human needs fulfilment should thereby create a positive experience that is personally meaningful (Hassenzahl et al., 2013). The higher the need fulfilment, the greater the positive effect (Hassenzahl et al., 2015). With the focus on interactive products, Hassenzahl et al. (2010) reduced the initial ten needs of Sheldon et al. (2001) to six: autonomy, competence, relatedness, popularity, stimulation and security, see Figure 2.9. It is thereby not necessary or possible that an experience fulfils all of the aforementioned needs (Hassenzahl and Diefenbach, 2012). Oftentimes, there is one salient need that forms a positive experience. However, Hassenzahl et al. (2013) themselves emphasise that the list of needs is not immutable and that needs can be added or removed from the list when designing for experiences. These needs allow for the categorisation of experiences, for example, relatedness experiences (Hassenzahl and Diefenbach, 2012). And are furthermore used as guides in the design process and to create inspiration (Hassenzahl, 2010). Which needs are salient and should be fulfilled depends on the undertaken activity (Hassenzahl et al., 2015).

Need	Description		
Autonomy	Feeling that you are the cause of your own actions rather than feeling that external forces or pressure are the cause of your action.		
Competence	Feeling that you are very capable and effective in your actions rather than feeling incompetent or ineffective.		
Relatedness	Feeling that you have regular intimate contact with people who care about you rather than feeling lonely and uncared for.		
Popularity	Feeling that you are liked, respected, and have influence over others rather than feeling like a person whose advice or opinion nobody is interested in.		
Stimulation	Feeling that you get plenty of enjoyment and pleasure rather than feeling bored and understimulated by life.		
Security	Feeling safe and in control of your life rather than feeling uncertain and threatened by your circumstances.		

Figure 2.9: The Needs Model of Hassenzahl et al. (2010).

In conclusion, the human needs model of UXD focuses on identifying and fulfilling the needs of individuals in the context of their interactions with a product. It is based on the promise that people have fundamental psychological needs and that addressing them leads to better UXs. Furthermore, the model allows categorising experiences by their salient experience.

Building upon the theory of universal psychological needs, the following subsection looks at the model of pragmatic and hedonic qualities. It discusses how these two distinct yet interconnected aspects - pragmatic (usability and functionality) and hedonic (pleasure and emotional satisfaction) - play a vital role in shaping the UX. The subsection thereby shows how the model can help to evaluate the subjectiveness of UX.

## 2.4.7 The Model of Pragmatic and Hedonic Qualities

The model of pragmatic hedonic qualities is a framework for evaluating UX. It seeks to capture the subjective nature of UX by using questionnaires and by consolidating multiple experiences into meta-experiences, which are then analysed in terms of their pragmatic and hedonic dimensions (Hassenzahl, 2007). Thereby, Hassenzahl (2003) follows the approach that humans experience products on two different dimensions – the pragmatic quality (PQ) and the hedonic quality (HQ).

The pragmatic dimension concerns how well the product or service functions and how easily users can achieve their goals while interacting with it (Hassenzahl, 2007). Hassenzahl (2003) refers to this as do-goals. The PQ concerns the usability side of products and how efficiently and effectively they work. Thereby, humans focusing on their goals in a product interaction put a higher focus on the PQ (Hassenzahl et al., 2002). The hedonic dimension focuses on the emotional and experiential aspects of the interaction, such as how enjoyable a product is to use and how well it aligns with users' values and aspirations (Hassenzahl, 2007). Hassenzahl (2003) refers to this as be-goals.

The model is based on the theory of universal psychological needs (compare section 2.4.6), which suggests that people have basic needs that influence their satisfaction with an experience. By considering both the pragmatic and hedonic dimensions of UX, designers can create products that are not only functional but could also provide a satisfying and engaging experience for users. Thereby, the model looks at four different ways of experiencing things (Hassenzahl, 2007).

- 1. Actual experiences influence product perceptions and measures of hedonics and pragmatics reflect a summary of these actual experiences.
- 2. Perceptions can be probed repeatedly during experiences to observe changes

over time, as hedonic perceptions may decrease and pragmatic perceptions may increase due to habituation and learning (compare for example Hassenzahl (2001); von Wilamowitz-Moellendorff et al. (2006)).

- 3. The model clearly distinguishes between perception and overall evaluation. It considers the hierarchy of needs situation-dependent, with varying degrees of goal and need relevance. Delimiting itself from classic, fixed models like the pyramid of functionality, usability and pleasure of Jordan (2000).
- 4. Two distinct usage modes are defined to take into account the user's overall state: goal-mode, where obtaining particular objectives is the focus, and action-mode, where actions are the focus producing volatile goals.

To summarise, the model of pragmatic and hedonic qualities is a reductionist framework used for evaluating the subjectiveness of UX. It is based on the theory of need fulfilment. Pragmatic (do-goal) and hedonic (be-goal) aspects are thereby influenced by actual experiences and can change over time.

### 2.4.8 Conclusion

This section has presented the topic and essential concepts of UX by analysing existing literature. After defining what an experience is and highlighting the differences between UX and an experience, two prominent design frameworks (needs model and model of pragmatic and hedonic qualities) were discussed. The general theory and the two frameworks form the basis for any research conducted regarding UX in this thesis.

The experiments described later in section 6 follow the theory of Hassenzahl et al. (2013) regarding the mutability of needs in UXD resulting in the categorisation of experiences (Hassenzahl and Diefenbach, 2012). They base parts of their research on the needs of perceived safety and control, and transparency and evaluate if their fulfilment leads to a better UX in AD.

# 2.5 System Understanding and Transparency: Explainable Artificial Intelligence

This section looks at the topic of XAI by reviewing existing literature. It addresses the transparency communication part of RQ-1 (How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?) and RQ-2 (How do failure situations affect the passengers' perception of transparency communication?). First, it is defined what XAI is. Then, literature regarding what makes a good explanation is discussed, followed by the definition of user-centric XAI and the specific use and requirements of XAI in AD.

XAI aims to increase transparency and accountability in AI systems by using various techniques to clarify how an AI algorithm arrives at a particular outcome (Adadi and Berrada, 2018; Colley, Eder, Rixen and Rukzio, 2021; Phillips et al., 2020). As early as 1984, expert systems tackled the topic of XAI (Buchanan and Shortliffe, 1984; Hasling et al., 1984). Back then, explanations were primarily seen as system-generated reasoning paths providing technical explanations for experts. Hasling et al. thereby defined an explanation as "the ability of a program to discuss what it is doing in some understandable way" (Hasling et al., 1984, p.1). Eight years later, Wick and Thompson (1992) already suggested taking the user and their preferences into account, adapting the explanations of an expert system to their mental model to provide them with appropriate reasoning steps.

The ability to explain why an AI algorithm makes a particular prediction is becoming increasingly important, especially as AI systems are being used in critical applications such as healthcare, finance, and AVs. Thereby, an increase in system autonomy is linked to a decrease in the user's system understanding (Hewitt et al., 2019), highlighting the need to design for the understanding of AI systems. However, designing effective explanations for end-users remains a challenge, as different users may have different levels of technical knowledge and require different types of explanations (Liao and Varshney, 2021; Samek and Müller, 2019). The technical explanations that an AI system can provide may not always be enough or useful for what the end-users require in a particular situation (Wolf, 2019). This is further connected to users' mental models, which are generally resistant to alternations (Moray, 1987). However, providing them with explanations of how a system works can improve their mental model of it and even their perceived feeling of control (Kulesza et al., 2012, 2010) whereas not explaining a system has the opposite effect on

their mental model (Norman, 1983). As a result, creating XAI applications necessitates human-centric methodologies that prioritise people's need for explainability and measure success by their experience (Liao and Varshney, 2021).

Having introduced the concept of XAI, highlighting the importance of transparency to make complex AI models more understandable, the following subsection looks at what makes a good explanation. It explores different approaches to distinguishing a mere explanation from a good, effective one in AI. It further reveals that research is still divided on what constitutes a good explanation.

## 2.5.1 What is a Good Explanation?

In order to increase a system's transparency and make it better understandable to its users, explanations of the system and its doings are needed. However, it remains unclear what even constitutes a good explanation (Guidotti et al., 2018; Hoffman et al., 2018; Lim et al., 2009; Lombrozo, 2016; Miller, 2019). This subsection gives an overview of different approaches.

Lim et al. (2009) performed a study (N=211) that evaluated the effectiveness of different types of explanations in comprehending a system's operation. The study utilised a system representing an intelligent system underlying a context-aware application and an interface that enabled users to learn about the application. Participants were shown examples of the system's operation along with various automatically generated explanations and then tested on their understanding of the system. The study was divided into four parts. (1) Learning - allow participants to learn how the system works. (2) Fill-in-the-Blanks Test and (3) Reasoning Test to examine the participants' understanding of the application. (4) Survey - asking users to explain how they think the application works. The findings of Lim et al. indicate that explanations that describe why the system behaved in a certain way were more effective in promoting comprehension and trust. In contrast, explanations that describe why the system did not behave in a certain way were effective in achieving acceptable performance despite lower understanding on the participants' side. The study further revealed that providing why and why not explanations were more effective and important than how to and what if explanations. Lim et al. highlight that participants with prior knowledge about such systems formed mental models of the system that were less precise and accurate, which is consistent with the findings of Moray (1987) about mental models being resistant to alternations.

Lombrozo (2016) looked at the role of explanations in learning and inference, and how people have strong intuitions about what constitutes a good explanation. He also discussed how people favour simple and broad explanations, and how engaging in explanation can shape learning and inference. He ends his review with multiple unanswered thoughts regarding explanations, two of which fit the domain of XAI in AD.

- To what degree do people's preferences for simple and general explanations differ depending on the domain and the individual? Are there certain domains where people have a greater inclination towards simplicity? How do variations in people's explanatory preferences relate to other factors like culture and expertise?
- In real-life situations, explanations may have multiple qualities that compete with each other. The simplest explanation may not always be the most comprehensive. This raises questions about how different qualities of explanations are balanced to determine overall preferences.

These two thoughts perfectly fit the complex environment an AV operates, raising a wide possibility of follow-up questions. For example: Do passengers of AVs prefer simple explanations? Is their preference the same for different driving situations? What is needed to provide comprehensive explanations in AD? How should these explanations be conveyed?

Hoffman et al. (2018) created a Goodness Checklist that can be used to design for good explanations or examine if an AI system is providing them. However, they highlight that for evaluation, the checklist should not be used by the researchers who created the XAI system but by independent ones. They defined seven questions that can be answered, yes or no, to evaluate how good an explanation is. Hoffman et al. then continue and differentiate that an objectively good explanation does not necessarily have to be satisfying for the targeted users highlighting the need for user-centric design. They define explanation satisfaction as a concept based on context and "the degree to which users feel that they understand the AI system or process being explained to them" (Hoffman et al., 2018, p.5). Deriving seven essential characteristics of explanations: (1) understandability, (2) feeling of satisfaction, (3) sufficiency of detail, (4) completeness, (5) usefulness, (6) accuracy, and (7) trustworthiness.

In 2019, Miller (2019) conducted an extensive survey on the requirements for system explanations for humans, highlighting humans' subjective nature and the challenges for XAI. He summarised his results in four findings.

- When people want to know why something happened, they might compare it to what could have happened instead. This is known as foils and has social and computational consequences for XAI.
- People select one or two causes from an infinite number of causes to be *the* explanation, but cognitive biases influence this selection.
- Referring to probabilities or statistical relationships in an explanation is not as
  effective as referring to causes, and the most likely explanation is not always the
  best.
- Explanations are a transfer of knowledge. How someone explains something depends on what they think the other party already knows and what they want to know.

The four points discussed by Miller all support the idea that explanations are not just about showing causes. They also depend on the context and the beliefs of the person being explained to, showing a direct relation to the subjectiveness of UX and the UCD method (see section 4.1). Combining XAI with human reasoning is believed to improve how humans and AI systems interact with each other (Phillips et al., 2020; Wang et al., 2019). It is thereby emphasised that one must understand the needs of stakeholders and their social and user-centric aspects to provide explanations that are tailored to their requirements (Holzinger et al., 2019; Miller et al., 2017; Wang et al., 2019). Or, to put it more simply: "Understanding people informs Explaining AI" (Wang et al., 2019, p.1), see Figure 2.10.

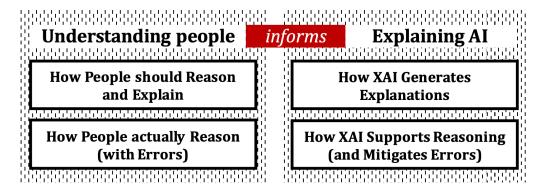


Figure 2.10: Conceptional framework of Wang et al. (2019).

To summarise, there are different approaches to what makes a good explanation in XAI systems. Studies have shown that explanations that describe why the system behaved in a certain way can be more effective in promoting comprehension and trust. Further, people seem to favour simple and broad explanations. Hoffman et al. (2018)

provide seven characteristics of good explanations partly contradicting the simple approach of Lombrozo (2016): understandability, feeling of satisfaction, sufficiency of detail, completeness, usefulness, accuracy, and trustworthiness. Lastly, there is a common understanding that explanations are subjective and depend on the context and beliefs of the person being explained to, leading to the next subsection: user-centric XAI. It discusses different approaches for tailoring these explanations to meet the specific needs and understanding of various users.

## 2.5.2 User-Centric Explainable AI

As discussed in the introduction, XAI applications have a need for user-centric methodologies and should prioritise the users' experience and their need for explainability (Liao and Varshney, 2021). This subsection elaborates on existing user-centric approaches.

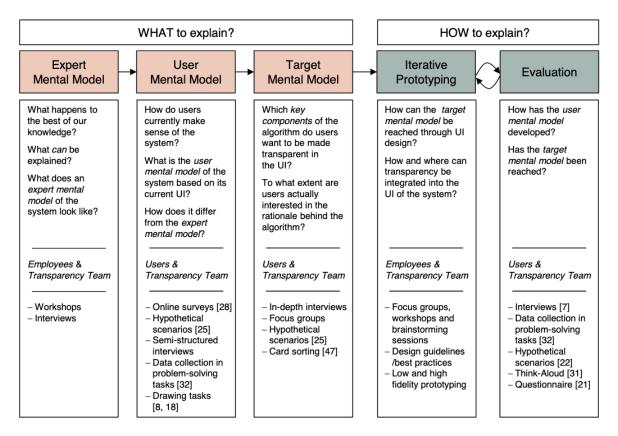


Figure 2.11: Stage-based, participatory design process for user-centric XAI by Eiband et al. (2018).

Eiband et al. (2018) developed a stage-based, user-centric design process that uses a holistic and iterative approach to design for XAI focusing on improving the users' mental model, see Figure 2.11. The process was developed with XAI for UIs in mind.

They follow an, as they call it, pragmatic approach to transparency with two main questions. (1) What to explain? and (2) How to explain?. The first question consists of three consecutive steps, the second of two iterative ones. Each step is supported by guiding questions, possible stakeholders and exemplary methods. Thereby, in its structure, the stage-based design process of Eiband et al. shows a resemblance to the UCD process, see section 4.1.

- Expert Mental Model: Gather knowledge from experts and extract all important components needed for an expert mental model.
- *User Mental Model*: Gather knowledge from users and extract all important components needed for a user mental model. Compare the users' mental model to the experts' mental model and identify any discrepancies or similarities between them.
- Target Mental Model: Forming the targeted mental model by regarding which important components need to be made transparent for the user and how deep the users' interest in the algorithm's functionality is.
- *Iterative Prototyping*: Iteratively designing a prototype that considers the target mental model.
- Evaluation: Measuring the effectiveness of the developed prototype in user tests by comparing the target mental model with the user mental model. The fewer the differences in mental models, the more effective the XAI solution.

Regarding user-centric XAI, Ehsan and Riedl (2020) introduced a new term - Human-Centred Explainable AI (HCXAI). They describe it as a methodology that puts the human user in the centre of designing technology for XAI, highlighting their emphasis on building a holistic understanding of the user and who they are. To design user-centred XAI applications, they recommend taking a sociotechnical approach, combining the fact that XAI is influenced by social factors and context and its technological surroundings. This approach should enable the creation of technology that considers the values of designers and users. They further show inspiration from the UCD process, see section 4.1, highlighting the need for user studies in XAI applications to get a full picture of the users and their socially situated nature with XAI systems. They then emphasise that creating designs that consider sociotechnical dynamics requires comprehending the complex and contextual human experience where individuals derive meaning through their interactions with technology, showing a strong reference to UXD. Ehsan and Riedl continue by highlighting that they believe designing for HCXAI should be viewed through the lens of Critical Technical

Practice (Agre and Agre, 1997) to provide the foundation for reflectiveness. Thereby, Critical Technical Practice promotes questioning a field's fundamental beliefs and symbols, thoughtfully analysing them to resolve obstacles, and creating fresh inquiries and suppositions. Ehsan and Riedl identify four main steps: (1) Recognise the fundamental metaphors and assumptions of the field. (2) Observe which elements are neglected when operating within those assumptions. (3) Highlight the ignored components. (4) Create technology and methods to integrate the previously neglected aspects as alternative technology. They state that following this approach (1) allows the human-centred side of XAI to be at the centre, which can lead to new design ideas, (2) encourages designers to think differently about human factors and gives users more control over technology and (3) helps us better understand humans in HCXAI. Ehsan and Riedl then conclude by recommending to use of proven methodologies from the area of HCI such as participatory design, value-sensitive design or ludic design (Bodker, 2021; Friedman et al., 2013; Gaver et al., 2004). Thereby, reflective HCXAI does not favour one design tradition over another, nor does it substitute one with the other. Instead, it combines and merges knowledge and techniques from relevant fields without taking a normative position.

Langer et al. (2021) propose a model for XAI that is inspired by UXD, the human needs model and the UCD process emphasising the importance of understanding stakeholders' specific interests, goals, needs, and demands in different contexts, which they call desiderata, see Figure 2.12. According to Langer et al., the success of explainability approaches depends on how well they satisfy these stakeholder The model highlights the main concepts and their relations of how desiderata. explainability approaches are supposed to lead to their satisfaction and how human understanding is a mediator between explainability approaches and the satisfaction of desiderata. The model motivates a process that includes explainability approaches, explanatory information, and stakeholders' understanding. As an outcome, the adjusted understanding of the stakeholders then affects how much their interests and needs are satisfied. Langer et al. suggest that the model can guide evaluating, adjusting, choosing, and developing explainability approaches and can be useful in detecting where input from disciplines outside of computer science is crucial. Furthermore, they differentiate between two scenarios for evaluating explainability approaches. (1) In the evaluation scenario, the goal is to determine if a specific approach was effective and, if not, how to improve it. (2) In the discovery scenario, the goal is to find an appropriate approach that satisfies stakeholders' needs.

To conclude, user-centric XAI is a relatively new topic for which a first set of

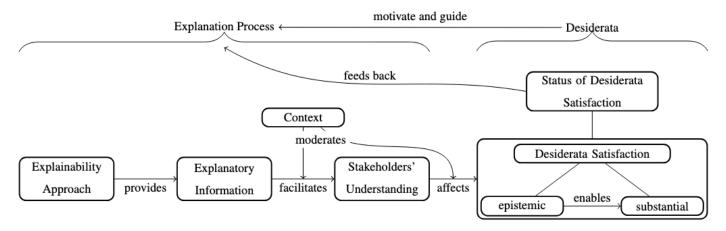


Figure 2.12: Conceptual explainability model by Langer et al. (2021).

different approaches has been researched. These approaches show similarities to the user-centric approach of UXD and focus on holistically understanding the target user. Ehsan and Riedl (2020) even introduced a new term for it: HCXAI. Eiband et al. (2018) propose a stage-based design process, inspired by the iterative UCD process, see section 4.1. Langer et al. (2021) propose a conceptual explainability model that puts the stakeholders' goals, needs and demands at its centre.

Having defined why a user-focused perspective is important in making AI understandable and beneficial for the users, and since research activities all propose generalised approaches to designing XAI, the following subsection examines how these principles are applied in the specific, rapidly evolving field of AD and reveals peculiarities of XAI in AD.

# 2.5.3 Explainable AI in Autonomous Driving

This subsection will explore the current state of XAI in AD, discussing AD-specific classifications of terms, dimensions and user requirements.

Wiegand et al. (2020) performed a driving simulator experiment to discover people's explanation needs and when they request explanations in AD. Participants (N=26) experienced 17 real-life inspired driving situations that were based on reports of AV users. During the study, the think-aloud method was used. Participants were asked to press a button if they hypothetically wanted an explanation from the vehicle regarding the driving situation. Wiegand et al. then defined a codebook with different coding categories for the participants' statements, see Table 2.1. Their different categories for XAI in AD are (1) Emotion and Evaluation, (2) Interpretation and Reason, (3) Capability of the Car, (4) Interaction and (5) Prediction. In their study, more than a third of the statements referred to the Emotion and Evaluation category

Definition	Count	Example		
Emotion and Evaluation				
Dissatisfaction with driving behaviour	265	"This is totally unnecessary."		
Desire for explanation	138	"I would like an explanation for that."		
Irritation / confusion	131	"[] for no real reason."		
Annoyance	122	"That's kind of frustrating already."		
Feeling of safety	116	"I think it is totally dangerous."		
Interpretation and Reason				
Looking for reason in the		"It might have slowed down because of the		
environment / other traffic	252	kid. It could also be that we simply reached		
participants		the destination."		
Cluelessness	131	"It's absolutely impossible to understand		
Cruelessiless		why we are standing here."		
Vehicle status	100	"There is no car visible far and wide. It feels to me like there's been a mistake."		
Capability of the Car				
Comparison to own driving behaviour	180	"I would do that completely different."		
Mental model autonomous system / driving	163	"[] but I do not think [the car] saw that, at least I did not."		
Interaction				
Desire to interact / change	154	"I would really like to step in and get on		
driving behaviour		the gas right now."		
Prediction				
Confusion of future driving	60	"We will overtake this time. I suppose. But		
manoeuvres		don't drive faster. Or do we?"		
Expectation of future		"No oncoming traffic. Then I would say		
driving manoeuvre /	50	now, we drive left, before another car		
behaviour		comes."		

Table 2.1: Overview of the Wiegand et al. (2020) codebook with the different categories and the most counted definitions.

highlighting the importance of participants' emotions in AD, with negative emotions prevailing (83%). Another important area concerns passengers trying to find a reason for the AV's driving behaviour or simply not understanding its actions. This is extended with the passengers' comparing the AV's action to their own driving behaviour and mental model of how autonomous systems should work. Furthermore, many participants expressed their need to exercise control, being in line with the findings about perceived feeling of control in section 2.3. As an interesting finding Wiegand et al. highlight that participants mostly requested explanations during the ride and not afterwards.

Omeiza et al. (2021) defined six different dimensions of explanations for AD. They can be categorised into two groups: technological and human-centred. This thesis will focus on the human-centred dimensions of explanations in XAI.

### **Human-centred dimensions:**

- Causal Filters: They are explanations that use specific causes to help understand something based on what we already know. These explanations can come from questions like "why," "why not," "how to," and "what if." They can be factual (why), contrasting (why not), or hypothetical (what if).
- *Interactivity*: Refers to the ability of a passenger to ask additional questions to request more explanations.

### Technological dimensions:

- Explanation Style: The way explanations are given can be grouped into different styles based on the type of information used and how it is presented. The styles are Input Influence, which lists input variables and how they affect decisions; Sensitivity, which shows how much an input variable needs to change to affect the output; Case-based, which finds a similar example from the model's training data to explain the decision; and Demographic, which provides statistics on previous outcomes for people of the same demographics.
- Model Dependence: Refers to whether an explanation method can be used for any type of autonomous driving model or if it is specific to only one model. If it can be used for any model, it is called model agnostic.
- Scope: Refers to the extent of the explanation. Global explanation explains the overall decision-making process of a model, while local explanation explains a single prediction. In the case of AD, global explanation refers to explaining the entire behaviour of an AV. In contrast, local explanation only explains a subset of the AV's behaviour.
- System Type: Refers to the type of system an explanation technique is designed for. It can be either a data-driven system, which explains the output of a machine learning model, or a goal-driven system, which explains the behaviour of an autonomous agent based on (change of) plans and goals.

It could be argued that the *System Type* dimension could fit into both groups. While it does describe a technical aspect of the explanation technique, it also has implications for how humans can interact with and understand the explanations.

However, for the purposes of grouping definitions, it is placed under the technological group since it is primarily focused on the technical aspects of the explanation technique.

In their survey on vision-based self-driving systems, Zablocki et al. (2022) created a taxonomy of terms related to explainability and their meaning, see Figure 2.13. Thereby, explainability is understood as the combination of interpretability and completeness. Interpretability refers to being understandable by humans (as discussed above (Holzinger et al., 2019; Miller et al., 2017; Wang et al., 2019)). Completeness refers to the explanation's thoroughness. Zablocki et al. further distinguish two approaches that allow for interpretability: transparency and post-hoc interpretability. Transparency thereby refers to whether the system has transparency built into its design. An intrinsically transparent system would be one that is designed to be transparent from the beginning rather than having transparency added as an afterthought. In contrast, post-hoc interpretability uses retrospective methods that justify decisions made by any opaque system after the fact. Furthermore, Zablocki et al. defined four basic "W" questions that should be answered when designing for XAI in AD. (1) Who needs an explanation? (2) Why is an explanation needed? (3) What kind of explanation is needed? (4) When is the explanation needed?

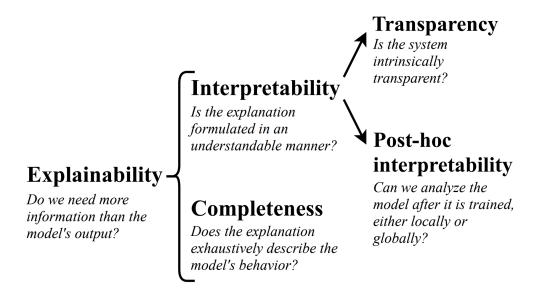


Figure 2.13: Classification of terms related to explainability by Zablocki et al. (2022).

In conclusion, for XAI in AD, passengers' emotions seem salient. Furthermore, passengers try to find reasons for driving behaviour in the environment or other traffic participants and want to exercise control. They also tend to compare the AV's driving

actions with their mental models. Explainability in AD is thereby the combination of completeness (explanation thoroughness) and interpretability (understandable by humans). Interpretability is the combination of transparency (built in from the start) and post-hoc interpretability (providing retrospective explanations). Furthermore, two dimensions that can help to design XAI for AD are causal filters (for example "why", "why not", and "how to") and interactivity, allowing the passenger to request more information if needed.

### 2.5.4 Conclusion

This section discussed different aspects of XAI. After a general introduction to the topic, the importance of good explanations in XAI systems was emphasised, and different approaches were discussed. Furthermore, it has been shown that there is a need for a user-centric approach to XAI, which involves understanding the target user and their needs showing resemblance to UXD and its models like the UCD process or the human needs model. Lastly, this section discussed XAI in the context of AD, highlighting the importance of completeness and interpretability in explanations, the salience of human emotions and the importance of the users' mental models.

Overall, it demonstrates the diverse, complex and evolving nature of XAI research. In terms of AD Omeiza et al. (2021) have summarised the role of XAI well:

"AVs should be able to explain what they have 'seen', done, and might do in environments in which they operate." (Omeiza et al., 2021, p.1)

# 2.6 The Use of Uni- and Multimodal Displays in Manual and (Conditionally) Automated Driving

UMDs are an essential component of modern automobile design. Recent research has investigated their influence in manual and CAD regarding, among other things, driver warnings, take-over requests (TORs) and uncertainty communication. This thesis looks at the application of UMDs in the context of SAE level 5 AD. Due to the different nature of being the passenger in a level 5 AV compared to (partially) driving oneself, the use cases of UMDs might deviate from the discussed literature in this section. However, to understand how their application in this thesis' research has come to be, one must understand where their use in driving is originally coming from.

UMDs are increasingly present within cars, creating a multisensory experience (Ho and Spence, 2008). Regarding manual driving, distractions or driver inattention have motivated the design of uni- and multimodal warnings for the driver, using, for example, visual, tactile and auditive modalities. With the development of ADAS that allow the driver to take their hands off the steering wheel for a limited time, new use cases for UMDs emerged: TORs and uncertainty communication. The following subsections analyses the different use cases in greater detail.

# 2.6.1 Driver Warnings

Before the integration of UMDs into CAD, these displays were already being employed in manual driving. One of the main use cases being driver warnings, providing critical alerts to drivers in real-time to prevent potential accidents or hazards on the road.

Already in 1997 Dingus et al. (1997) examined the use of uni- and multimodal auditory and visual cues for driver warnings. They conducted three on-road studies using visual, auditory and audiovisual cues to present collision warnings to drivers (N=108) and, additionally, to see how false alarms changed the drivers' attitude towards system reliability and their driving behaviour. The visual cues consisted of three different presentations: a car icon indicating headway, multiple coloured bars indicating safe distance and continuously blinking blocks if the headway was too low. Auditory cues consisted of the verbal statements "Look ahead." and "Brake!" (Dingus et al., 1997, p.224) depending on the headway. According to their study, prominent visual cues led to increased headways. In comparison, auditory warnings were less effective regarding headway, yet, they may be a useful warning addition regarding the time to deceleration. Last but not least, if too many false warnings occurred (>60%), younger drivers seemed to lose trust in the system by decreasing their headways and

maintaining a self-chosen distance to the car ahead.

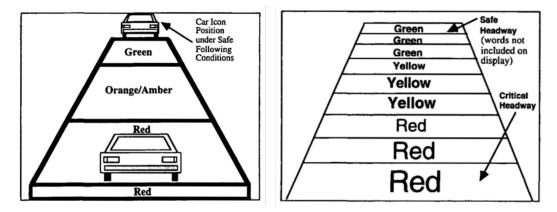


Figure 2.14: Visual cues by Dingus et al. (1997).

Ben-Yaacov et al. (2002) performed a real-life experiment where participants (N=30) took part in four drives using a collision avoidance system. The first three drives occurred on the same day, and the fourth drive six months later. Ben-Yaacov et al. put drivers in three different groups with different system reliability rates (95%, 80% and 60%) and measured their distance to lead vehicles throughout longer highway drives (between 20 and 70 km). Their system sounded auditory warning signals as long as drivers were under a certain headway threshold. Ben-Yaacov et al. concluded that a warning system using auditory cues educated drivers on safer headways and led to participants maintaining them for at least six months. Contrary to Dingus et al. (1997), they could not show significant differences for different system failure rates.

In the same year, Lee et al. (2002) looked at the multimodal combination of visual and auditory cues to warn drivers about rear-end collisions. In a driving simulator, participants (N=120) drove on a rural highway. A lead vehicle would brake abruptly at the end of two drives (city, motorway access). The warning cues were transmitted early or late. They consisted of four sound bursts at 2500Hz and an icon above the instrument cluster showing a vehicle collision. Participants were engaged in a secondary task from time to time, watching numbers in the rearview mirror. In a second experiment, participants (N=20) experienced two drives without a secondary task. Lee et al. concluded that multimodal warnings helped distracted and undistracted drivers react more quickly alike. Furthermore, drivers who received warnings decelerated less abruptly. Early warnings thereby provided better results than late or no warnings.

Two years later, Lee et al. (2004) added a third, vibrotactile modality to their

multimodal feedback modality system. In two driving simulator experiments, participants (N=40, N=20) were engaged in a secondary task reading emails and informed about braking events via visual (collision warning icon), auditory (warning sound) and vibrotactile (seat vibration imitating warning sound) stimuli. Thereby, Lee et al. differentiated between significant, moderate, and insignificant braking situations. They compared graded warnings (warning strength related to situation severity) with single-stage warnings (triggering only in significant braking situations). They concluded that graded warnings increased safety distance and reduced improper reactions to insignificant braking events. Furthermore, with graded alerts, vibrotactile notifications were considered less irritating and more suitable than single-stage warnings.

In a driving simulator study, Ho et al. (2005) used spatial vibrotactile cues to direct the driver's attention to the front or the rear in emergency situations. Ho et al. warned the driver if they were approaching a car in front too fast or if a car from behind was approaching them too fast. Participants (N=32) were presented with 24 driving scenarios, 20 critical and 4 non-critical. Ho et al. found out that vibrotactile stimuli increased the participants' reaction times in critical driving events, regardless of whether the stimuli came from the direction of the thread (front or rear) or the same direction.

Two years later, Ho et al. (2007) added the second modality audio to their driving simulator. Examining auditory, vibrotactile and audio-tactile warning designs for potential collision events with the vehicle in front. Participants (N=15) experienced a drive on a two-lane road through a neighbourhood. Vibrotactile cues were transmitted through a belt around the participants' waists. The auditory cue was the sound of a car horn. The uni- and multimodal cues were presented when the lead vehicle suddenly decelerated. The results of Ho et al. show that multimodal stimuli led to participants braking significantly earlier than using unimodal stimuli.

Fitch et al. (2007) looked at using uni- and multimodal auditory and vibrotactile cues in the same year. They performed an on-road study where participants (N=32) drove a car and were tasked to report the alert direction. The auditory cue used a broadband alert sound for directional warning (Edworthy, 1996). The vibrotactile cues (100 to 140 Hz) were presented via multiple motors in the seat cushion, creating different vibration areas. Roughly one alert was presented per minute. Fitch et al. concluded that warnings containing vibrotactile cues led to the fastest response times, increased directional localisation, and are useful for informing about crash threat

locations. However, other than Ho et al. (2005), who concluded that directional feedback is not important, they have tested only directional vibrotactile cues.

One year later, Scott and Gray (2008) added a third modality: visualisation. In their driving simulator study, they looked at visual, auditory and vibrotactile stimuli to warn drivers of rear-end collisions. However, they did not combine the modalities but only used them unimodally. Participants (N=16) were instructed to follow a car on a two-lane main road which randomly changed speeds and performed 11 unexpected full stops. The warnings either consisted of LEDs forming a red warning triangle in the dashboard, a 2000Hz tone or vibrotactile stimuli around the waist, similar to Ho et al. (2007). Scott and Gray concluded that vibrotactile warnings led to the fastest response times, were significantly better than visual-based warnings and were most suited for rear-end collision warning compared to the other modalities or no feedback at all.

Chang et al. (2008) added a new feedback modality: voice. In their driving simulator study, they compared the unimodal use of audio and voice modalities in two different driving situations. Participants (N=30) were driving on a straight, two-lane roadway and experience two different emergency situations. (1) A vehicle overtook them and cut in front of them. Later, it performed an emergency braking. (2) At an intersection, a vehicle randomly rushed through it, not being expected by participants. Warnings either consisted out of a beep sound at 2kHz or a speech message. However, Chang et al. never stated what the message said exactly. They concluded, depending on the driving event, which modality performed better. The beep sound led to better results with emergency braking of the vehicle in front. The speech message performed better at the intersection where drivers were unaware of the direction of the vehicle.

Cao et al. (2010) used unimodal vibrotactile and auditive cues for driver warnings with different priorities and referred to them as informative interruption cues. They defined five different task scenarios: an easy driving situation, a difficult driving situation, driving and listening to the radio, driving and talking with a passenger, and driving under noisy conditions (loud road surface). While investigating driving situations, their experiment did not use a driving simulator. Instead, they asked participants (N=30) to use a mouse to follow a square on a screen. They justified their experimental setup with driving being a task mainly requiring visual attention. The participants quickly learned the vibrotactile and auditory cues. The vibrotactile stimuli were less disruptive to the driving task and identified with higher accuracy than the auditory ones. However, auditory cues led to faster response times, contrary

to Scott and Gray (2008), and participants reported higher physical comfort.

In their on-road study, Fitch et al. (2011) examined whether multiple warning types (for example forward collision or not staying in the lane) can be communicated through different vibrotactile patterns in the driver seat. Participants (N=24) were driving a car on a test track and exposed to different amounts of types of warnings (1, 3 or 7 types). Fitch et al. found out that too many different types of warnings can lead to decreased response times and confusion. Unique locations for every type of alert can help to counteract this problem. They recommended communicating three different types of alerts through vibrotactile cues when accurate responses are required, and no other feedback modalities are present.

Chun et al. (2012) examined vibrotactile cues for forward vehicle collisions in their driving simulator study, see Figure 2.15. Participants (N=24) drove behind a vehicle and were engaged in a secondary task (entering numbers). The lead vehicle randomly decreased its speed, and participants were presented with vibrotactile alerts in the steering wheel or the seatbelt. Chun et al. concluded that vibrotactile warnings led to faster response times and reduced collisions.



Figure 2.15: Experimental setup of Chun et al. (2012).

One year later, Lewis et al. (2013) used the bimodal combination of auditory, visual and vibrotactile cues to warn drivers and compared them to their unimodal

counterparts. In their experiment, they distinguished between low- and high-urgency situations. Participants (N=22) were driving a simulated vehicle. They were instructed to react as soon as possible to any alert received. Visual warnings consisted of a box displaying "warning" with a coloured background in green (low urgency) or red (high urgency). Auditory and vibrotactile (on participants' left wrist) warnings consisted of longer inter-pulse intervals (low urgency) or shorter ones (high urgency). Lewis et al. found that high-urgency bimodal cues led to faster response times compared to low-urgency unimodal cues. Furthermore, bimodal cues were missed less often by participants. They concluded that high signal urgency and multimodal cues could be used for effective driver warnings.

In the same year, Politis et al. (2013) also examined these three warning modalities in a driving simulator study and combined them into one multimodal feedback (N=20). They were looking at their influence on recognition time during driving, focussing on three different levels of urgency. As in the study of Lewis et al. (2013), high-urgency multimodal warnings led to faster and more precise responses than medium and low-urgency warnings. They further confirmed their results in another driving simulator study (N=15) the following year where the car in front was braking (Politis et al., 2014). Warnings with higher urgency led to a better driver response. Moreover, multimodal feedback increased the response times compared to unimodal feedback. The year after, they examined visual and auditory warnings (N=20) in critical driving situations (lead car braking) and non-critical situations (lead car not braking) (Politis et al., 2015b). Visual warnings produced shorter response times in non-critical situations. In contrast, response times were quicker in critical situations with warnings that included auditory feedback.





Figure 2.16: Experimental setup of Politis et al. (2014).

To conclude, multiple studies have shown the usefulness of auditive, visual, vibrotactile and spoken UMDs for driver warnings. High urgency, multimodal

warnings seem to provide the best results regarding driver performance. Including vibrotactile or auditive stimuli in the warning design has proven to be a successful way of warning drivers. Vibrotactile cues can also be used to convey different types of warnings. However, research deviates from which modality provides faster reaction times and if certain system failure rates are disadvantageous or not. Furthermore, it seems to depend on the driving situation or its criticality. For example, visual warnings seem to be beneficial for non-critical driving situations and auditory warnings seem to be beneficial for critical situations. Whereas spoken warnings worked better than auditory warnings at intersections.

While in level 5 AD passenger reaction times will not play a role, it is still essential to understand the early operational purposes of UMDs in driving. It will be interesting to see if any counterparts in AD will have similar effects as when used for warnings, for example, multimodal feedback leading to better results than unimodal. Furthermore, as one will also see in the following subsections, even though the studies focussed on the driver, none of them took their subjective experience into play. This will be further discussed in this section's conclusion.

## 2.6.2 Take-Over Requests

The previous section looked at research regarding the use of UMDs for driver warnings. With the rise of CAD systems, for example SAE level 3 with traffic jam assistance (SAE On-Road Automated Vehicle Standards Committee, 2021b), new requirements for driver-car-communication arise. Now, drivers might not be in full control of the vehicle at all times. Through automation, the driver can be taken out of the loop, resulting in worsened driving reactions (compare, for example, Brookhuis et al. (2001); Endsley (1995a); Endsley and Kaber (1999); Neubauer et al. (2012)). However, at this level, driving situations are still occurring that require the driver to take over control soon or as quickly as possible, due to, for example, system limitations or automation failures. This control hand-over is realised by using so-called TORs. The need for communicating TORs is mostly based on the users' lack of situational awareness when taking back control is due (Endsley, 1995b). After a TOR, drivers still need time to comprehend the current driving situation to properly being able to control the vehicle.

Gold et al. (2013) examined how much time is needed after a TOR for the driver to be in control again and hence how soon the driver's attention needs to be redirected to driving. They provided the TOR information by using an audiovisual modality (sinusoidal tone and icon) in a driving simulator study. They came to the

conclusion that a shorter time to take-over increases the drivers' (N=32) reaction times at the cost of reducing their driving quality (e.g. reduced shoulder checks and increased brake use).

Naujoks et al. (2014) used the same audiovisual, multimodal TOR communication as Gold et al. (2013) in their driving simulator study. However, they were also looking at the unimodal modalities. Additionally, their warning icon was flashing (5Hz). Participants (N=16) faced multiple takeover situations. Naujoks et al. concluded that multimodal TORs lead to faster takeover times than unimodal, visual ones. This effect was especially present in takeover situations with greater difficulty. It must be mentioned that they did not compare unimodal auditory feedback but only audiovisual and visual.

Zeeb et al. (2015) used the same multimodal feedback modalities as Gold et al. (2013) and Naujoks et al. (2014), but focussed on gaze behaviour during a secondary task. Through a driving simulator study, they were able to show that their testers (N=89) could be divided into high-, medium- and low-risk drivers. High-risk drivers had slower, worsened reactions to TORs. In their model, they argue that the time to takeover is not influenced by motor factors but cognitive ones.

In the same year, Melcher et al. (2015) added two more stimuli for the TOR. In addition to the audiovisual presentation, the driving simulator vehicle used brake jerks as a way of communication as well as presenting the TOR directly on the testers' (N=44) mobile phone on which they were playing a mobile game during the drive as a secondary task. They came to the conclusion that it is irrelevant how and where a TOR is communicated as long as drivers have enough time for the take-over. However, they found out that presenting the TOR on the mobile phone led to an increase of the users' perceived safety.





Figure 2.17: Driving simulator of Melcher et al. (2015).

Politis et al. (2015a) used auditory, visual and tactile unimodal stimuli and their multimodal combination to investigate how effectively they inform distracted drivers (N=21) playing a game on a tablet of a handover. They created six types of speech messages and different levels of warning urgency. In their driving simulator study, they looked at two different situations: critical (lead-car braking with immediate take-over required) and non-critical (a weak GPS signal where take-over was requested). The unimodal, visual warning led to low driving performance. High-urgency unimodal auditory and multimodal auditory-tactile warnings led to faster hand-over transitions. Participants perceived the unimodal stimuli as less annoying. However, they were also perceived as less effective than their multimodal counterpart.

In the same year, Walch et al. (2015) confirmed the usefulness of multimodal stimuli for TORs. In their driving simulator study (N=30), they used audiovisual feedback to communicate required take-overs for participants that were distracted with a secondary task for different situations with varying time-to-take-over and amount of information provided. They displayed an icon in the display paired with the reason (e.g. "Caution: Fog" or "Caution: Take over the wheel" (Walch et al., 2015, p 12)) combined with abstract earcons (Brewster et al., 1993) and a voice reading out loud the visual message. Their results showed that multimodal feedback for TORs can effectively counteract the system limitations of AVs. Furthermore, multimodal feedback that provided a reason for the TOR was favoured by participants. This coincides with the findings of Koo et al. (2015) discussed in section 2.6.4.



Figure 2.18: Experimental setup of Walch et al. (2015).

Borojeni et al. (2016) added light as a communication channel for TORs and combined it with auditory feedback in a driving simulator study. They installed a light bar behind the steering wheel that always illuminated in red, but with different patterns. Static red: upcoming take-over, left or right half is red: upcoming take-over and location of obstacle, left or right half is red with moving light: upcoming take-over, location of obstacle and indication of suggested steering direction. The parallel, auditory cue was a 1000Hz sine wave tone. Participants were distracted with a secondary task. The multimodal presentation of the TOR reduced the participants'

(N=21) reaction times and increased the times to collision by keeping a consistent workload.



Figure 2.19: Driving simulator setup with light bar of Borojeni et al. (2016).

As discussed before, Melcher et al. (2015) presented the TOR for the participants, among other things, directly on the smartphone which they used to play a mobile game. Two years later, Politis et al. (2017) used auditory, vibrotactile and colour-based visual cues to inform about a take-over displayed on the driving simulator screen. Additionally, they directly displayed the TOR on the tablet on which testers (N=20) played a game as a distractor task, yet they never mentioned the study of Melcher et al. (2015) in their research. They distinguished between abstract (earcons, coloured circle, vibration patterns) and language-based (coloured text, spoken text) cues. While Melcher et al. (2015) came to the conclusion that it is irrelevant how and where the TOR is displayed, yet displaying it on the user's phone increased the perceived safety, Politis et al. (2017) found out that abstract and language-based feedback led to equally improved handovers when displayed on the tablet. When displayed on the screen of the driving simulator, only abstract cues led to improved handovers.

Telpaz et al. (2017) used auditory, textual and vibrotactile stimuli for TORs. Next to a double beep and a message on the screen informing about the upcoming take-over, the main modality was a vibrotactile driver seat. The seat was able to provide the user with spatial information of vehicles that were approaching them by vibrating different areas of the seat. Depending on the approaching vehicle's lane (left, same, right) the according side of the seat vibrated. The vehicle's distance to the driver (long - short) was conveyed on the vertical vibration axis of the chair

(bottom - top). In their experiment, participants (N=26) experienced six different take-over situations. They reported that the vibrotactile stimuli lowered the participants time-to-take-over and increased their efficiency. Testers found the vibrotactile feedback alerting but not annoying.

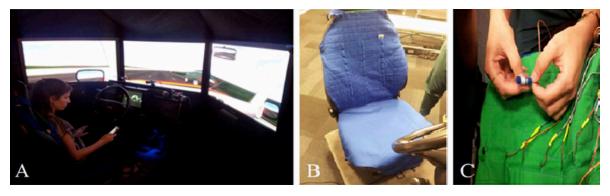


Figure 2.20: Driving simulator setup with vibrotactile seat of Telpaz et al. (2017).

Petermeijer et al. (2017) also engaged in research regarding spatial cues for TORs. In their study they used auditory and vibrotactile cues and their multimodal combination to inform about a TOR due to an upcoming head-on collision that had to be bypassed by testers (N=24) changing lanes. Unlike Telpaz et al. (2017) who only used vibrotactile feedback for spatial communication, they used both modalities. Auditory feedback consisted of two 2700Hz beeps lasting 240ms each. Vibrotactile feedback was presented using a vibrotactile driver seat with a 60Hz vibration frequency and the same pattern as the auditory cues. TORs were presented directional (the lane drivers had to change to in order to avoid the collision) and non-directional. Compared to their unimodal counterparts, multimodal cues led to faster take-overs. However, they did not improve brake or lane change times. Furthermore, testers experienced the unimodal auditory cue as less satisfying and useful.

In 2019, Geitner et al. (2019) used tactile, auditory and auditory-tactile warnings to communicate TORs. Participants (N=45) were engaged in different secondary tasks with comparable workload and had to press the brake to avoid a collision with a lead-car braking once they were presented with the uni- or multimodal warning. In regards to emergency braking, Geitner et al. found out that unimodal tactile feedback resulted in significantly worsened brake times than auditory or auditory-tactile warnings.

Huang et al. (2019) analysed the effect of auditory, visual and vibrotactile cues in

uni, bi- and trimodal combinations. The auditory feedback consisted of six 400Hz bursts. Visual feedback was given in the form of a small red circle shown on the center monitor. Vibrotactile cues were transmitted over a belt on to the lower back with 250 Hz. Regarding the time-to-takeover, participants (N=16) were the fastest when presented with the trimodal combination in critical driving situations (they were asked to quickly press the brake). When the testers were occupied with a secondary task their response times worsened and the perceived workload increased.

Jarosch and Bengler (2019) compared the effect of different automated driving durations on TORs. Participants (study 1 N=56, study 2 N=73) were engaged in two secondary tasks and experienced the same highway drive at two different lengths. They used visual (red steering wheel with hands), textual ("please drive manually" (Jarosch and Bengler, 2019, p.517)) and auditory (earcon) cues to inform participants that they needed to take over control due to an accident on their lane. They concluded that takeover performance varied between participants and that the duration of the automated drive, the longer, the worse, seemed to have a greater impact on the performance than the secondary tasks.

Salminen et al. (2019) used unimodal abstract auditory, visual and vibrotactile cues and their multimodal combinations to communicate TORs with participants (N=12) that were partially engaged in a secondary task by playing a mobile game on a smartphone. The cues consisted of beeps, a red light bar at the bottom of the screen blinking and vibrotactile feedback through a haptic seat sending feedback to the testers' thighs. As in the study of Huang et al. (2019), being engaged in a secondary task reduced the participants' reaction times to take over. Unimodal cues led to slower reactions compared to multimodal feedback, with unimodal audio cues creating the slowest reaction times.

In 2021, similar to Melcher et al. (2015) and Politis et al. (2017), Li et al. (2021) examined on-device cues for TORs. Furthermore, they also used a head up display (HUD) for communication. Participants (N=46) were engaged in a secondary task (select and watch an episode of a TV show). They experienced three different automated highway rides in a driving simulator and had to take over control when exiting the highway. Li et al. used multimodal cues (auditory, visual and textual) in the form of beeps and a countdown starting at ten, framed in red. Other than in the study of Politis et al. (2017), the HUD resulted in faster takeovers than the mobile phone. The result was thereby also contradicting with the statement of Melcher et al. (2015) about the irrelevance where a TOR is displayed as long as there is enough time

to take over. Furthermore, the HUD reduced participants' cognitive workload compared to not providing a feedback modality.

The use of augmented reality (AR) in driving has already been examined for uncertainty communication in 2018 (Kunze et al., 2018), see section 2.6.3. Riegler et al. (2022); Riegler, Weigl, Riener and Holzmann (2020) looked at the application of the AR modality in the windshield for TORs. Both studies used a virtual reality (VR) driving simulator (highway drive) to display information on the windshield. The takeover request was displayed on a red background with an icon and text and a beep sound. They stated that participants (N=23) showed faster takeover times when positioning information within the three-dimensional space of the world (for example, on a truck in front) rather than sticking it to the windshield (Riegler, Weigl, Riener and Holzmann, 2020). However, their reported results did not report significant differences. Furthermore, the TOR was always displayed on the windshield and not within the world. In their second study, participants (N=24) reported significantly faster takeover times when content was presented in one single window compared to multiple content-specific ones (Riegler et al., 2022). The TOR was presented in the same way as in the first study.

In conclusion, UMDs have proven to be a valid way to communicate TORs in CAD. Multiple studies have examined the use of visual, auditory, vibrotactile, textual, light and on-device cues. In some studies, multimodal displays led to better takeover performance and felt more effective to the participants than their unimodal counterparts. According to the study of Walch et al. (2015), presenting a reason in the communication between the user and the vehicle seems to be a useful solution as it was favoured by participants, confirming principles of XAI (see section 2.5). Furthermore, according to Melcher et al. (2015), presenting a TOR on the users' device leads to an increased perceived feeling of safety. Regarding takeover performance, Melcher et al. (2015), Politis et al. (2017) and Li et al. (2021) reported different results regarding on-device cues. However, this form of communication might be interesting for SAE level 5 AD, where taking back control is not possible anymore and feeling safe might be an important variable.

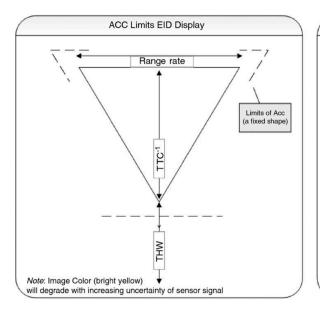
All the studies discussed above focussed on the driver, hence the user. Nonetheless, similar to the driver warnings research, they show the same gap in knowledge regarding the driver's UX. Melcher et al. (2015) took a first look at perceived safety, and only as late as 2020 did a more user-centred approach find its way into TOR research (Riegler et al., 2022; Riegler, Weigl, Riener and Holzmann, 2020). This gap is further present

in other research areas of CAD, as this thesis will discuss in the next section about uncertainty and reliability communication.

## 2.6.3 Uncertainty / Reliability Communication

Another approach for communicating TORs in CAD is uncertainty or reliability communication. Instead of providing the driver with a message when a handover is due, the system continuously communicates its uncertainties regarding the automation to give the driver more time to prepare for taking over control.

The first research of uncertainty communication in the driving context was published by Seppelt and Lee (2007) and dealt with a failing adaptive cruise control (ACC) in their driving simulator study. They used an abstract visualisation to represent the system's uncertainty, see Figure 2.21. Participants (N=24) experienced four drives, two manual ones and two with ACC available. 44 ACC failures of different severity occurred during the drives. Participants were engaged in a secondary task not related to the drive. While their results were insignificant, Seppelt and Lee assumed that informing drivers rather than warning them may be better.



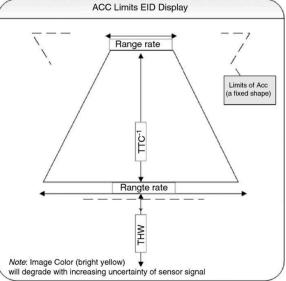


Figure 2.21: Abstract uncertainty visualisation of Seppelt and Lee (2007). Ecological Interface Design display showing (a) triangle/yield shape that appears when approaching or matching lead vehicle speed, and (b) trapezoid shape when lead vehicle is moving faster. Shapes visualize Time Headway (vertical position), inverse Time to Collision (height), and range rate (width). Dashed lines indicate Adaptive Cruise Control braking limits and minimum safe following distance.

Beller et al. (2013) performed a driving simulator study communicating

automation uncertainty in the form of an uncertainty symbol, see Figure 2.22. Participants (N=28) drove on a foggy two-lane highway using an ACC. From time to time, a car appeared in front of their vehicle. Sometimes, the automation failed in terms of braking when inappropriate or not braking when it should. These situations required the participants to take over control. The uncertainty symbol was displayed in the instrument cluster. Beller et al. found out that communicating uncertainty helped to prevent the false understanding that automation cannot fail. In case of an automation failure, it led to a significantly increased time to collision. Furthermore, participants trusted and accepted the automation more than without the uncertainty presentation.

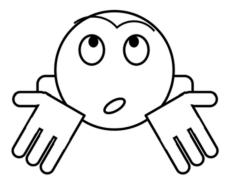


Figure 2.22: Uncertainty symbol of Beller et al. (2013).

Helldin et al. (2013) concluded that providing users (N=59) with an uncertainty representation reduced their time to take over. However, contrary to the results of Beller et al. (2013), it also reduced their trust in the system compared to not showing it. Participants drove an automated vehicle on a traffic-less two-lane country road in winter weather with varying intensity of snowing. When the visibility reached a certain threshold, the automation would fail. Participants then had to take over control. Unlike Beller et al. (2013), they did not use an uncertainty symbol in their driving simulator study but a visual 7-step scale (very high ability to no ability), see Figure 2.23.

Noah et al. (2017) extended uncertainty communication research by comparing the communication of the system's reliability with the communication of the driver's needed engagement. They created and compared 12 visualisations for reliability and 12 for needed engagement. However, it must be noted that their study did not involve participants (N=36) driving. They only showed the different visualisations on a screen. Noah et al. concluded that the system's automation reliability is superior to reporting the driver's needed engagement.



Figure 2.23: Driving simulator setup and uncertainty representation by Helldin et al. (2013).

As with other uncertainty communication research from the military and aviation sector (see, for example: Dzindolet et al. (2003); Finger and Bisantz (2002); McGuirl and Sarter (2006); Wang et al. (2009)), up to this point, only visual, unimodal communication in the instrument cluster was investigated. Kunze et al. (2018) introduced AR as a new modality for uncertainty communication in driving. However, they referred to it as urgency instead of uncertainty since pilot studies had shown that testers (N=46) had problems understanding the concept of system uncertainty. They tested 66 variations for communicating low, medium and high system urgencies. They found out that colour- and animation-based forms and symbols were preferred by testers and communicated urgency well. As with Noah et al. (2017), it must be mentioned that their participants did not experience the experiment in a driving simulator but rated different interface layouts in front of a laboratory computer screen.

In the same year, Faltaous et al. (2018) used the feedback modality light, in the form of a light bar, to communicate the system's reliability in a driving simulator study, see Figure 2.24. Participants (N=20) experienced a drive on a straight two-lane road. Occasionally, a lead vehicle appeared, and the simulator vehicle would automatically overtake. If another vehicle were in the other lane, it would wait for it to pass. Thereby, participants could experience two types of failures. First, the automation sometimes did not detect the vehicle in front and, therefore not overtake it. Second, it could detect a vehicle in front when there was none. In both scenarios, participants were able to take over control. Faltaous et al. concluded that offering too many steps for reliability communication may not be needed nor comprehended in full detail by users as testers could not perceive all the different levels of reliability. They confirmed previous research that testers preferred unimodal feedback for reliability communication.



Figure 2.24: Driving simulator setup and uncertainty representation by Faltaous et al. (2018).

One year later, Seppelt and Lee (2019) investigated visual and auditory cues and their multimodal combination for uncertainty communication, referred to by them as continuous feedback. In their simulator study, participants (N=48) experienced 12 automated drives using ACC on urban and highway roads with limited visibility (rainy and foggy). Seppelt and Lee compared continuous feedback with discrete warnings, only appearing when the automation was about to fail. The driving conditions led to ACC failures or near-failures, prompting users to take over. Discrete warnings consisted of a yellow triangle and a beep. Continuous feedback consisted of a visualisation similar to the one by Seppelt and Lee (2007), see Figure 2.21, and continuous sound streams complementing the visual feedback modality. Participants who were given uninterrupted feedback relied more suitably on their ACC system when compared to those who received discrete warnings. This constant feedback also led to a higher rate of proactive response to automation malfunctions and better system comprehension. The multimodal feedback combination led to the best results.

In the same year, Kunze et al. (2019) took an anthropomorphic approach to uncertainty communication using a visualised heartbeat in the instrument cluster in a multimodal combination with textual information showing the beats per minute. In their simulator study, Kunze et al. related a higher heartbeat to an increased stress level equaling a higher uncertainty level. In case of a heartbeat increase, the instrument cluster display turned red. Participants (N=34) drove on a two-lane highway for 20 minutes using an ACC system under varying fog conditions. In case of an automation failure, participants, who were engaged in a secondary task (a visual

search task), had to take over control. Kunze et al. concluded that an anthropomorphic uncertainty communication led to better takeover performance. However, it also increased drivers' cognitive workload, worsening performance in secondary tasks.

Shull et al. (2022) also used a light bar to express automation confidence in their driving simulator study in a rural road scenario. Participants (N=60) were engaged in a secondary task. They faced six situations where the lane-centring automation failed, requiring a takeover. The TOR was signalled through a red steering wheel icon in the instrument cluster and an auditory beep. The confidence bar consisted of three steps from confident (green) to somewhat confident (yellow) to not confident (red). Their results indicate that a multimodal audiovisual modality leads to better takeover performance than a unimodal visual modality or a no-feedback baseline. However, for the uncertainty communication, only visual feedback was used. The auditory cue was only relevant for the TOR.

To summarise, multiple studies have examined the use of UMDs in the CAD context to communicate the systems' uncertainty or reliability to the driver. They mostly relied on visualisations in the instrument cluster. Newer studies also introduced light and AR as a way of communication. Compared to warning or TOR research, they did not use vibrotactile stimuli for reliability communication but only relied on visual ones. Auditory stimuli were only used for the takeover warning associated with the uncertainty representation. Studies showed that in CAD, informing about the system's status is better than a warning and helps drivers increase their understanding of the system. Furthermore, using feedback modalities for uncertainty communication led to varying results regarding participants' trust. However, all studies agreed that they led to increased takeover performance. Generally speaking, visual communication seems to work well for communicating system uncertainty as long as it is not presented in a complicated way but uncertainty communication can also lead to an increased cognitive workload.

Staying consistent with the research gap of the previous subsections, research on uncertainty or reliability communication lacks focus on the UX of the drivers, or their perceived feeling of safety or control, even though they are the centre of the research. In regards to AD, it must be said that all studies assumed that there was still a driver who was in control of the car or could take control of it. Regarding SAE level 5 AD, the passenger will not be able to take over control. Therefore, communicating, for example, uncertainty might not be a viable option anymore. Nonetheless, it is still

relevant to see what types of UMDs were used by researchers to convey information for later research.

### 2.6.4 General Communication using UMD

While the subsections before looked at very precise usage areas for UMDs there has also been research looking at more general ways of driver-vehicle communication in manual an CAD.

Liu (2001) used uni- and multimodal auditory and visual cues for general communication in driving. In their driving simulator study, participants (N=32) experienced multiple drives with feedback shown on a display above the instrument cluster or communicated via audio using voice and chime sounds. Drivers were asked to complete a predefined driving course as quickly as possible while obeying all traffic rules and avoiding driving mistakes. Furthermore, they were instructed to identify different feedback types (vehicle or road hazard) through a push-button task. Liu concluded that the multimodal feedback cues led to the best response times, driver navigation, and the lowest reported workload on participants. Unimodal visual feedback lead to a higher workload and reduced driving safety. Furthermore, multimodal cues increased the performance of older drivers.

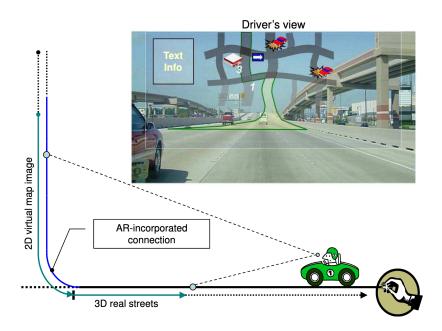


Figure 2.25: AR feedback modality setup of Kim and Dey (2009).



Figure 2.26: Driving simulator setup of Koo et al. (2015).

Kim and Dey (2009) looked at the application of AR for displaying navigation-relevant information directly into the viewport of elderly drivers, see Figure 2.25. In their driving simulator study, participants (N=24) experienced four different drives (two with AR navigation, two with classical navigation in the centre console). Kim and Dey concluded that displaying driving navigation relevant information using AR in the driver's viewport significantly reduced navigation errors and distractions.

Koo et al. (2015) looked at how different ways of presenting information about the semi-autonomous car automatically braking changed the perception of the drivers (N=64). They presented the information in a driving simulator study via an auditory voice alert, divided into how-information ("the car is braking"), why-information ("obstacle ahead") and a combination of both how- and why-messages. Only describing the car's actions (how) resulted in worsened driving performance. Describing the reason behind an action (why) increased the driving performance similar to the study of Walch et al. (2015) where feedback containing a reason was preferred by testers (see section 2.6.2. The combination of both led to the best driving performance, however, it also led to testers having negative feelings.

Häuslschmid et al. (2016) conducted an experiment where they tried to find out where participants (N=21) prefer different types of content displayed via an AR modality in the windshield. They created different areas of content within the windshield area. 1) Notification area containing urgent driver warnings, 2) ambient

area containing low-priority information like the time, 3) reading area containing longer texts like SMS, 4) vehicular area containing vehicle-related information, 5) personal area containing driver-related information like entertainment controls and 6) environmental area containing information related to the driving environment like the distance to the lead-vehicle. Participants experienced augmented driving videos on a Google Cardboard headset. Häuslschmid et al. concluded that participants were mostly divided on where certain types of information should be placed. However, there was a stronger agreement regarding the location of urgent warnings and vehicular information, see Figure 2.27.

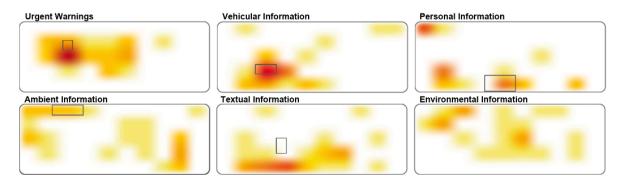


Figure 2.27: Heatmap of preferred areas for different types of content by Häuslschmid et al. (2016).

In conclusion, UMDs have also been used for more general applications in manual and CAD. Multimodal audiovisual feedback cues were reported to increase driving performance and reaction times compared to their unimodal counterparts. Voice feedback explaining driving situations worked best for driving performance when including how and why information with the side effect possibility of introducing negative feelings. Being presented with a reason for driving actions was generally preferred. Furthermore, the application of AR provided positive results when used for navigation, urgent warnings and vehicular information.

Falling in line with the conclusions of the previous subsections, research once again focussed on the user but lacked focus on their UX or perceived feeling of safety and control.

#### 2.6.5 Conclusion

This section discussed existing literature regarding the use of UMDs in manual and CAD. Thereby different areas of application have been presented. Next to general use cases, UMDs have been used for driver warnings, TORs and uncertainty or reliability communication. Thereby a multitude of different feedback modalities and their

multimodal combinations have been employed. A summary of the used feedback modalities can be seen in Figure 2.28. The Figure's colour coding reveals that visual, auditory and tactile modalities have gotten more research attention than the others. Especially the areas of warning and TOR design, where the driver is actively controlling the vehicle, have put much emphasis on these cues. Tactile feedback modalities have even only been used for areas where drivers are still in control. Regarding multimodal combinations of feedback modalities, see Figure 2.29, visual-auditory, visual-tactile and visual-auditory-tactile are the most prominent combinations. Thereby, mostly warnings and TORs made use of multimodal displays.

Modlity - Purpose	Visual	Auditory	Light	Textual	Tactile	Voice	On-Device	AR
Warnings	6	11			10			
TORs	12	14						
Uncertainty	7							1
General	1							2

Figure 2.28: Table showing the different feedback modalities used for different purposes. The number and intensity of the colour represent the amount of literature review studies that discussed the modality.

Modlity - Purpose	Visual Auditory	Visual Tactile	Visual Textual	Visual On-Device	Auditory Tactile	Auditory Voice	Visual Auditory Textual	Visual Auditory Tactile	Auditory Textual Tactile	Visual Auditory Break Jerks On-Device
Warnings	3							3		
TORs	4							4		1
Uncertainty	2									
General	1									

Figure 2.29: Table showing the different multimodal feedback modality combinations used for different purposes. The number and intensity of the colour represent the amount of literature review studies that discussed the modality.

Interestingly, even though the discussed studies above all focused on the driver, hence the user, almost none took any UCD theories into account. While there was a great focus on takeover times or system understanding, UX was not a part of it, even though they all designed for the user. Melcher et al. (2015) reported first results

regarding the perceived safety of participants. However, only in 2020 did research begin to focus on UX and the perceived feeling of safety and control in CAD (Riegler et al., 2022; Riegler, Weigl, Riener and Holzmann, 2020). Especially in regards to level 5 AD, where it is not about reactions and takeover times, focussing the research on the experience side could help widen knowledge about UMD modalities and their influence on the people who are in contact with them. This user-centric approach is reflected in RQ-1 (How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?).

Now that it has been defined where the use of UMDs in driving originated, the following section will look at their current application state in level 5 AD. This will provide an overall picture of UMDs and help understand their application in different levels of driving automation.

# 2.7 State of UMDs, Safety and Control, Explanations and User Experience in Autonomous Driving

With the main topics of this thesis defined (feeling of perceived safety and control, XAI and UX), this subsection will give an overview of the current state of the literature regarding these topics in level 5 AD. As discussed in the subsections before, research of manual and CAD has nearly given any attention to these topics and only recently started to focus on them. This section shows that research regarding SAE level 5 AD is still in its early stages. As such, there is limited knowledge and understanding of how passengers will interact with and experience AVs. Extensive research will be needed to understand passengers' expectations regarding AD and how they behave, and how to design for their needs. This will involve understanding the technical aspects of AD and the human factors involved. More importantly, putting the user at the centre of these experiences will be inevitable.

In a study with 336 participants, Rödel et al. (2014) revealed why UXD regarding AVs will be essential. They have shown that the UX of different autonomy levels in vehicles is the highest in currently deployed levels. They reason that an increase in the level of autonomy is linked to a non-linear decrease of the UX and the perceived feeling of control. As discussed in section 2.4.1, positive experiences are needed if people are not to stop using a product (Kahneman et al., 1999). However, it must be said that their study asked participants to rate different vehicles and their automation using imagination. They did not actually get to experience the different levels. Kyriakidis et al. (2015) found similar, though less extensive, results, concluding that people (N=5000) enjoy manual driving most.

Beattie et al. (2014) compared unimodal spatialised auditory cues in manual driving to SAE level 5 autonomous driving. They conducted a driving simulator experiment where participants (N=15) were presented with different spatialised vehicle sounds that are well-known to drivers of manual vehicles, for example, indicator sounds, acceleration or gear changes. Beattie et al. wanted to find out how the spatialisation of these auditory driving cues influences drivers of AVs. For the manual experiment condition, participants drove through a city. They were presented with videos of autonomous driving sequences for the autonomous condition. Beattie et al. concluded that the spatialised presentation of auditory driving cues could better inform passengers of AVs of intended driving actions. Furthermore, participants reported a significantly increased perceived feeling of control and a reduced workload compared to manual driving.

Three years later, Häuslschmid et al. (2017) conducted a driving simulator study with 30 participants on three different visualisation modalities communicating car actions and situations that are important or connected to safety, see Figure 2.30. Their world in a miniature visualisation was inspired by the one of Tesla<sup>1</sup> and displayed a reduced and simplified version of the world around the vehicle. The chauffeur avatar was an anthropomorphic visualisation that reacted in a friendly way with the passengers. While these two modalities dynamically adjusted to the environment around the vehicle, the third modality, car turn signals, did not behave dynamically and was used as a baseline, only providing information about planned directional changes. Both the world in a miniature and chauffeur avatar increased the trust in the autonomous vehicle. However, only the world in a miniature modality led to the strongest UX and perceived feeling of safety.

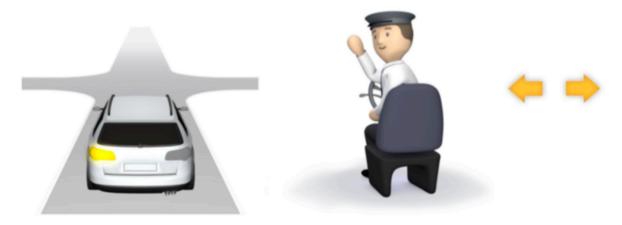


Figure 2.30: The three visualisations of Häuslschmid et al. (2017): world in a miniature, chauffeur avatar and car indicators as baseline.

In the same year, Wintersberger et al. (2017) examined the use of AR in a driving simulator study. Participants (N=26) experienced two autonomous drives during fog. One with an AR feedback modality highlighting oncoming cars green if overtaking was possible and red if not, and another without the feedback modality, see Figure 2.31. Furthermore, the vehicle drove slightly faster than appropriate for the foggy condition. Results indicate that participants' acceptance of the system increased with the AR modality. Furthermore, they said that the modality supported them in understanding the driving situation. Wintersberger et al. conclude by saying that for presenting how and why information (compare Koo et al. (2015) in section 2.6.4) in AD, it might be

<sup>&</sup>lt;sup>1</sup>https://www.tesla.com/de DE/autopilot (Accessed: March, 2023)

sufficient to highlight objects relevant to follow-up driving actions. They assume that passengers would be familiar with potential subsequent driving actions.



Figure 2.31: The AR visualisations of Wintersberger et al. (2017).

Gang et al. (2018) looked at the application of abstract auditory icons in a driving simulator study to communicate the AV's perception of relevant driving events. Participants (N=24) either experienced a drive with or without the auditory feedback modality. Furthermore, they were engaged in a reading task, see Figure 2.32. In total, six different driving events happened during the study. (1) and (2) change in traffic density, (3) obstacle in the lane of the participant's vehicle, (4) tailgating, (5) another vehicle in the blindspot, and (6) making way for an emergency vehicle. Gang et al. concluded that participants preferred synthesised sounds and that the auditory icons increased their awareness of driving-relevant events.

Oliveira et al. (2018) conducted a real-world study with 20 participants in a self-driving pod, see Figure 2.33. The pod autonomously drove through a lab in which an urban-looking scenario was built. Oliveira et al. examined three different ways of controlling (select the destination and spontaneously interrupt the ride) the AV. (1) A pre-installed tablet for interaction combined with an additional screen above the windshield permanently displaying drive-relevant information (destination, ETA, current time and weather). (2) A smartphone (personal device) combined with an additional screen. And (3) a smartphone (personal device) only, with no additional screen. Their findings indicate that participants want to keep an eye on the state of the AV and view information regarding the trip, such as a route map and relevant details. The pre-installed tablet, in combination with the additional screen, was preferred over a smartphone-based interface.

Large et al. (2019) used the same self-driving pod of Oliveira et al. (2018) in a study with 34 participants. Large et al. focused on the three different use-cases



Figure 2.32: The simulator setup of Gang et al. (2018).

system notifications, scheduling work tasks and entertainment. In their study, participants were provided three different ways of interaction: an anthropomorphic, conversational voice agent, an interface controlled by voice-commands and a touchscreen interface. They conclude that the anthropomorphic, conversational voice agent led to the highest increase in UX and perceived feeling of control.

Fröhlich et al. (2019) conducted a real-life experiment with an autonomous shuttle bus (N=56) and an imaginary ride study in a stationary bus examining different cues for the AV communicating its awareness and intent (N=77). They compared textual, icon-based and AR modalities for information transmission, see Figure 2.34. The autonomous bus ride was used to derive participants' awareness and intent



Figure 2.33: Study environment of Oliveira et al. (2018).



Figure 2.34: Different feedback modalities used by Fröhlich et al. (2019) (textual, iconbased, AR).

communication needs. Fröhlich et al. concluded that passengers may have a general need for XAI in AD communicated via screens. In the imaginary ride study, they found out that participants reported a greater need for communicating potential hazards than general driving information, like route changes. Furthermore, they recommend using the different feedback modalities in a multimodal combination.

Löcken et al. (2020) used light bars to communicate potential conflicts on the AV's route to participants (N=18); see Figure 2.35. They created two designs and compared them to a no-feedback baseline. The first design highlighted the direction of the obstacle in red. The second design further added the AV's planned trajectory as feedback. In case of an emergency situation, all light bars turn red. In their driving simulator study, Löcken et al. found that light feedback increases passengers' UX compared to the no-feedback baseline. Thereby, the second design, including the planned trajectory, lead to a significantly better UX.



Figure 2.35: Feedback setup of Löcken et al. (2020).

Schraagen et al. (2020) presented participants (N=32) three different textual explanation styles. (1) causal ("I slow down because of the person on the left side" (Schraagen et al., 2020, p.340)), (2) intentional ("I slow down because I believe the woman wants to cross the street" (Schraagen et al., 2020, p.340)) and (3) mixed ("I slow down because there is a person on the left side and I believe she wants to cross the street" (Schraagen et al., 2020, p.340)). Participants were presented with ten different driving situations (7 urban, 2 rural, 1 highway), which consisted of multiple Google Street View images and their explanations. Schraagen et al. concluded that intentional explanations led to the best levels of trust. Furthermore, mixed explanations led to the best system understanding of the AV.

Detjen et al. (2020) conducted a Wizard of Oz (WoZ) study (N=12) where they repeatedly drove participants around in an actual vehicle mimicking an AV. Therefore, they separated the driver from the passengers by installing a wall. They hung a display on the wall that showed the road in front of the vehicle through a camera, acting as a windshield, creating the illusion of not having a driver, see Figure 2.36. They told participants that a human driver was present but only as a safety driver, not driving the vehicle. Light bars to the left and right of the screen indicated driving direction changes. Detjen et al. concluded that the participants' acceptance only slightly changed over time and that they highlighted feeling safe as the main factor for acceptance.

In a driving simulator study, Hartwich et al. (2020) compared the influence of the presence and non-presence of a human driver for the same prerecorded drive. Participants (N=50) experienced a 7km long urban and country road drive. One group was told a researcher drove them. The other group was driven autonomously. When in reality, both groups were driven autonomously. The drive included different traffic situations like lane changes or traffic lights. Hartwich et al. reported that participants rated all points of their driving experience (comfort, enjoyment, system acceptance) worse when being driven autonomously. They further concluded that displaying information about the AV's drive via a display modality is a promising way



Figure 2.36: WoZ vehicle setup of Detjen et al. (2020).

to increase participants' experience. The most requested types of information were speed (limit), next driving manoeuvre, detection of the leading vehicle, distance to the leading vehicle, detection of oncoming vehicles and informing about obstacles ahead, see Figure 2.37.

Colley, Eder, Rixen and Rukzio (2021) performed two simulator studies to look at object highlighting in AD using visual screen-based and AR feedback modalities, see Figure 2.38. In their first study, participants (N=32) experienced object highlighting in a pre-recorded 3D simulation via a screen in the centre console or an AR-highlight in the windshield. Colley, Eder, Rixen and Rukzio reported that the AR object highlighting was rated better than the screen-visualisation. In their second experiment, participants (N=41) watched a recording of a real drive that was augmented with object highlighting, simulating AR. They concluded that highlighting drive-relevant objects using AR led to an increase in participants' situation awareness and kept their cognitive load at a low level.

In another VR simulator study, Colley, Krauss, Lanzer and Rukzio (2021) looked at the unimodal use of AR, light and HUD feedback modalities for XAI communication in AD, see Figure 2.39. Participants (N=20) experienced three different critical driving situations in an AV in VR. (1) A child running into the street, (2) a dog running into the street, (3) a blind person walking into the street. The HUD displayed a warning icon and an explanatory text. The AR modality circled the object of concern in blue and displayed an explanatory text next to it. The lightbar lit up at the person's position, following it along. They further tested a mode where the object of concern is highlighted depending on its priority to the driving situation. For example, it was colouring the blind person red to show its relevance to

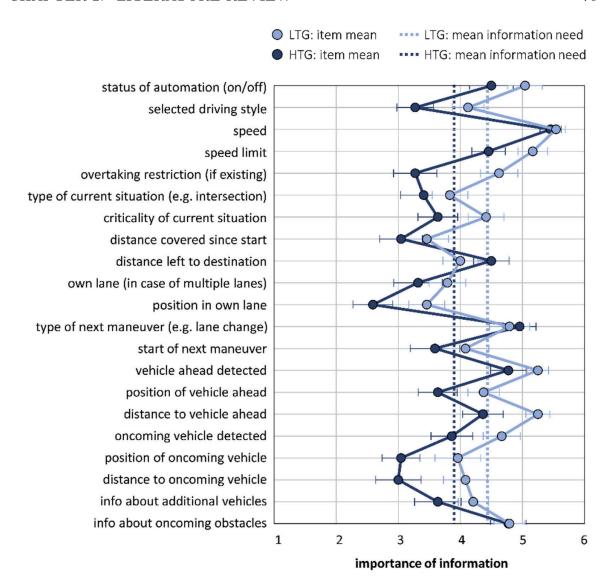


Figure 2.37: Derived information needs of participants in the study of Hartwich et al. (2020). LTG = lower trust group, HTG = higher trust group.

the driving situation. Colley, Krauss, Lanzer and Rukzio could not find a significant difference between the different feedback modalities. However, they concluded that, compared to not presenting feedback, they increased the perceived feeling of safety, perceived intelligence of the AV and acceptance.

Detjen, Salini, Kronenberger, Geisler and Schneegass (2021) performed a driving simulator experiment (N=27) to analyse the effect of AV behaviour transparency on the passengers' UX. They used a HUD showing icons and an AR display, both placed in the windshield, to increase transparency (see Figure 2.40). Participants were told that the vehicle in the simulator was driving autonomously. Both feedback modalities led to positive UX measurements, with the AR display ranking higher than the HUD.

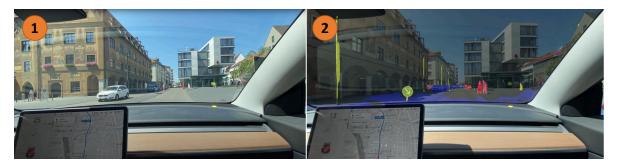


Figure 2.38: AR object highlighting of Colley, Eder, Rixen and Rukzio (2021).

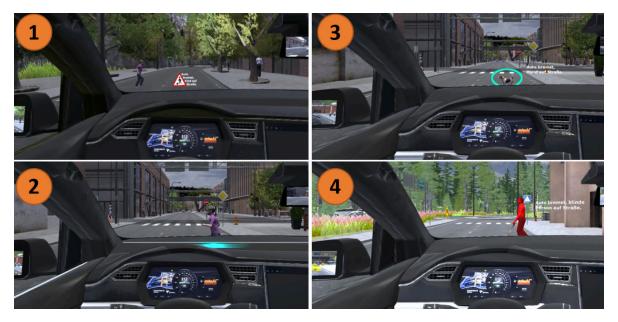


Figure 2.39: Different feedback modalities of Colley, Krauss, Lanzer and Rukzio (2021): 1) HUD, 2) light, 3) AR, 4) priority.

They contribute the recommendation of presenting the vehicle's intentions and its behaviour in order to increase the passengers' UX of the ride.

One year later, Dandekar et al. (2022) compared two different feedback modalities for explainability of AD in a simulator study (N=18). They augmented real-life city driving videos with a vehicle cockpit. The first modality used a coloured light bar reacting dynamically to the drive. The second modality displayed drive-relevant text and symbols on the windshield. Their modalities were examined in regular driving situations (for example, reacting to traffic lights or vehicles in front) and emergency situations (pedestrian walking into the street). They found out that the light bar modality's more implicit way of communication led to a better UX for the participants.





Figure 2.40: Icon based HUD and AR display of Detjen, Salini, Kronenberger, Geisler and Schneegass (2021).

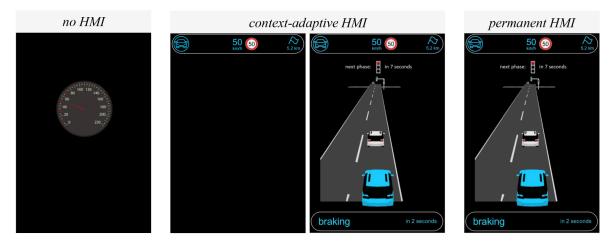


Figure 2.41: Different feedback ways of Hollander et al. (2022).

In the same year, Hollander et al. (2022) conducted a driving simulator study, where participants (N=50) were provided with three types of transparency communication via a display in the centre console. (1) no-feedback baseline displaying a speedometer. (2) Contextual driving information consisting of basic driving information like current and allowed speed and distance to the target destination, which was shown all the time. And context-dependent, detailed information showing a world in miniature visualisation combined with textual information in important driving situations. (3) Permanent driving information shown through the world in miniature visualisation and textual information; see Figure 2.42. Hollander et al. concluded that displaying context-dependent information rather than permanently showing information was preferred by passengers and significantly increased two sub-scales of their UX (User Experience Questionnaire (UEQ): dependability and perspicuity).

Flohr et al. (2023) performed a real-life Wizard of Oz experiment with participants (N=30) seated in the back of a van. They used a similar setup like Detjen et al.

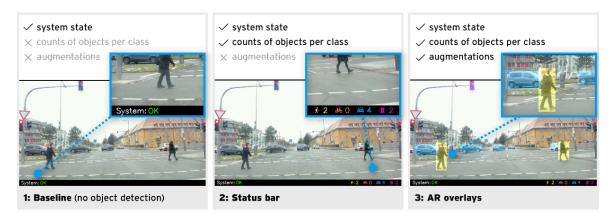


Figure 2.42: Info bar and AR object highlighting of Flohr et al. (2023).

(2020), where the driver compartment was walled-off, and a monitor was put on the wall, showing the road in front of the vehicle, simulating an autonomous ride. Participants were driven through a city, and different feedback modalities were used. (1) a no-feedback baseline, only showing that the system is working. (2) An icon- and text-based info bar at the bottom of the screen showing the count of recognised entities. (3) An AR object highlighting of relevant entities. Flohr et al. concluded that the AR object highlighting significantly increased passengers's HQ of their UX compared to the other two variants.

#### 2.7.1 Conclusion

Level 5 AD will encounter novel challenges optimising the passengers' UX. As previously indicated in the earlier subsections, individuals have repeatedly emphasised their desire for safety and control, along with comprehending the AV's capabilities and actions. As shown in this subsection, the findings of the subsections above have been confirmed by research regarding level 5 AD. Researchers have examined several communication strategies and interaction designs, providing first insights for UXD, UCD or XAI in AD and, at the same time, highlighting that research regarding this topic is just in its infancy. Figure 2.43 shows the researched feedback modalities and their influence on different metrics.

With people enjoying manual driving over AD and a link between the decrease of UX and the increase of autonomy levels, a strong need for research regarding the topics mentioned above has been shown for AD. People have expressed a general need for information about the autonomous drive, with a higher communication requirement regarding potential hazards than general driving information. Thereby,

requesting information during the ride seems to be preferred to requesting information after the ride. Furthermore, passengers' need for perceived safety and to take over control has been shown once again.

Modality - Influence	Visual	Auditory	Light	Textual	Convers. Voice Agent	AR
UX						
Safety						
Control						
Understanding						
Awareness						

Figure 2.43: Table showing which feedback modalities positively influences different metrics in AD research.

Various metrics have been positively influenced by different feedback modalities, as shown in Figure 2.43. Most of the six modalities increased the UX (5). Followed by the awareness (4) and perceived feeling of safety (3). Less research is available regarding the perceived feeling of control (2) and the understanding of the system (2). Interestingly, there was no investigation into how the different metrics correlate. Looking at intercorrelations between the different metrics could potentially help further understand the communication using UMDs in AD and their implications on the passenger.

More generally speaking, presenting the intentions of the AV seems beneficial for increasing the UX, understanding, and perceived safety and control of the ride. Unlike manual and CAD research, level 5 AD research did not explicitly focus on vibrotactile feedback modalities. Therefore, generally more emphasis was placed on the actual user. More intensive research is needed to understand the interplay of transparency, understanding, safety and control with UX in level 5 AD communicated through UMDs.

## 2.8 Conclusion

This chapter has reviewed, presented and discussed literature relevant to this thesis' topic of transparency communication in AD and is used to inspire the research questions of this thesis.

Section 2.2 and 2.3 presented the perceived feeling of safety and control. It has been shown that people express a strong need for both of them in AD. Regarding safety, the importance people assign to it can differ based on factors such as age, gender, education, or driving conditions. The idea of safety perception is linked to actual harm and meeting various needs, showing a solid connection to the human needs theory of UXD. In terms of perceived feeling of control, similar to the perceived feeling of safety, the intensity of people's need for it relies on variables such as gender, income, or mode of transportation. It is about how an individual perceives their capability to control various circumstances and may even result in a false sense of control, a so-called illusion of control.

Even though the amount of safety and control needed depends on influential factors like age or gender, the general need for both was always present in studies.

Section 2.4 introduced the topic of UX by analysing existing literature. The concepts of experience and the differences between UX and an experience were defined. Two design frameworks, the needs model and the model of pragmatic and hedonic qualities, were discussed and will form the basis for any research conducted regarding UX in this thesis.

As this thesis focuses on transparency communication in AD, and thereby system understanding, the topic of XAI was introduced in section 2.5. It was shown that it is still uncertain what qualifies as a good explanation and that XAI shows a resemblance to the UCD process and the human needs model as research highlighted a need for a user-centric approach, understanding the users and their needs. Lastly, the significance of providing complete and interpretable explanations in the context of AD was discussed. The relevance of human emotions and the users' mental models were emphasised.

In Section 2.6, literature discussing the use of UMDs in manual and CAD has been reviewed. The section divided various applications into four groups: driver warnings, TORs, uncertainty or reliability communication and general communication. Per group, the researched feedback modalities and their multimodal combinations have been analysed and summarised. It has been shown that visual, auditory, and tactile

modalities received the most research attention. Multimodal combinations of feedback modalities in the form of visual-auditory, visual-tactile, and visual-auditory-tactile were also prominent. Even though the discussed literature looked at the driver, user-centred theories were hardly considered. Only as late as 2020 did research focus on user-centric attributes like perceived feeling of safety and control or the UX. This user-centric approach is also supported by the XAI literature. It should help improve UMDs for their use as transparency communication for passengers in AD.

Section 2.7 then looked at the current state of research regarding the application of UMDs for transparency communication in AD. In general, people want more information about the autonomous drive, especially when it comes to potential dangers. They prefer to ask for information during the ride rather than after and, confirming the previous research, still want to feel safe and have the option to take over control themselves. As this is not possible anymore in SAE level 5 AD, research will be needed to mitigate these needs. More generally speaking, due to the preference for manual driving over AD and the correlation between a decrease in UX and higher autonomy levels, there is a significant demand for research on communication in AD. The literature review on UMDs in AD shows that it appears advantageous to communicate the intentions of the AV in order to enhance the UX, comprehension, and perceived safety and control of the ride.

This literature review chapter has shown the importance of user-centric design for transparency communication in AD. It has highlighted people's need to feel safe and in control as well as fundamental user-centric principles that should be used when designing XAI applications for AD, thereby showing strong relations to UX theories. This literature review chapter therefore inspired RQ 1 of this thesis:

How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?

To expand the knowledge from scientific research, the next chapter will report a SOTA analysis on the current state of existing market solutions using UMDs for transparency communication in AD.

Chapter 3

State-of-the-Art Analysis

AD technology has made remarkable progress in recent years, with several major companies investing heavily in research and development to create self-driving cars. Assessing the current state of UMDs and feedback modalities in AD requires a comprehensive analysis of what is available on the market, including commercial products and services, as they provide valuable insights into the current usage and limitations of the technologies. In addition to the literature review, this SOTA analysis section will examine existing commercial products to help gain a holistic understanding of the current state of UMDs and feedback modalities for transparency and intent communication in automated driving.

# 3.1 Tesla Full Self-Driving Beta

In some countries, Tesla offers their Full Self-Driving (FSD) beta (Tesla, Inc., n.d.) which, despite the name and some impressive driving footage<sup>1</sup>, classifies currently only as a SAE level 2 system (compare for example: Autoweek (2022); electrek (2023); TOPSPEED (2023)).



Figure 3.1: ADAS visualisation of Tesla (n.d.) in the center screen.

Regarding feedback modalities, Tesla relies on visual and textual, see Figure 3.1, and auditory cues for transparency and intent communication. Auditory cues consist of different beeps signifying the driver that FSD beta has been engaged or disengaged, that hands have to be placed at the steering wheel or that the car performed an emergency stop. However, most of the feedback comes from the visualisation, a world in a miniature, on the central screen, combined with occasional textual overlays. Over the years and different FSD beta releases, the design of the feedback cues has continuously developed; see Figure 3.2. The visual design in beta 7 still felt rough and far from a finished product with its wireframe-like aesthetics. In motion, one could see

<sup>&</sup>lt;sup>1</sup>see for example https://www.youtube.com/@DirtyTesla or https://www.youtube.com/@AIDRIVR

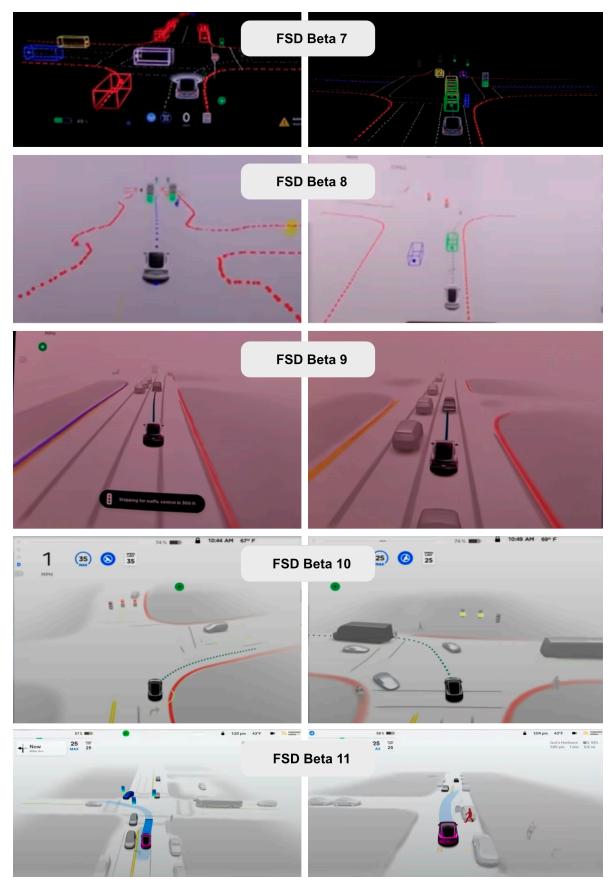


Figure 3.2: Development of Tesla FSD beta visualisations from FSD beta 7 to 11. Screenshots are taken from videos by AI DRIVR (2021); Chuck Cook (2021); Dirty Tesla ( $2022a,b,\ 2023$ ). One beta iteration per row.

that lines and objects were often jittery, resembling more of a live view of the neural network at work. Throughout the betas, a more polished design and new features were introduced.

Many visual cues have been implemented as of 2023 and FSD beta 11. For example, traffic lights are displayed in their current state, drive-relevant objects are highlighted (e.g. cars, pedestrians or cyclists), the car's route is clearly visible and highlights if the path is blocked or not. The biggest change, visually, happened from beta 8 to beta 9, where abstract representations of the world (red dotted lines and boxes for cars) turned into accurate, abstract models. Since then, Tesla FSD beta has distinguished between different vehicle types (for example, cars, bicycles or trucks) and even shows break lights or open doors in the latest version. Furthermore, drivers can zoom in and out using pinch-to-zoom and rotate the virtual camera around the vehicle freely to look at the driving scene from every angle.

However, as impressive as it might be by today's standards, FSD beta is not error-free. For example, when the car stops for a person allegedly crossing the street but does not communicate why it is doing so<sup>2</sup>. In newer versions, FSD beta now sometimes shows a text explaining its actions (see Figure 3.2 row 3 "Stopping for traffic control in 300 ft."). However, these explanations can also reach their limit when the vehicle clearly does not understand what is happening. For example, confusing a horse-drawn carriage for a truck, then a pickup truck, a truck facing the car's way, a person walking behind a pickup truck and a truck again<sup>3</sup>. Sometimes, the car can also perform unexpected manoeuvres like braking without providing the driver with any real explanation<sup>4</sup>.

In conclusion, Tesla FSD beta has developed quite a bit since its initial release and is now featuring a sophisticated world in a miniature visualisation containing many different feedback cues. To a degree, it also allows the driver to interact with the visualisation. However, in case of detection failures, like the horse-drawn carriage example, the system clearly shows its limitations.

## 3.2 Mercedes-Benz Drive Pilot

In 2022, Mercedes-Benz released their SAE level 3 driver assistance system called *Drive Pilot* (Mercedes-Benz, n.d.). Under certain limited conditions on the motorway (high traffic volume, speeds slower than 60km/h, good street conditions and a lead

<sup>&</sup>lt;sup>2</sup>https://www.youtube.com/watch?v=xbw2ZB0Lbk8 around 8:00 min (Accessed: April 2023)

<sup>&</sup>lt;sup>3</sup>https://www.youtube.com/watch?v=oYmDIPNd9hM (Accessed: April 2023)

<sup>&</sup>lt;sup>4</sup>https://www.youtube.com/watch?v=CMeUOGXo15s around 12:05min (Accessed: April 2023)



Figure 3.3: Mercedes-Benz Drive Pilot visualisations and use on the German motorway (photos by golem.de (2022)).

vehicle), the system takes over the driving task, allowing the driver to take their attention off the road to engage in non-driving-related tasks. Thereby, similar to Tesla's FSD beta, Mercedes-Benz uses auditory beeps, a visualisation in the form of a world in a miniature and textual information overlays displayed in the central instrument cluster behind the steering wheel, see Figure 3.3. The Drive Pilot system also communicates with the driver via LED lights in the steering wheel.

To engage the Drive Pilot, two LEDs at the steering wheel light up in white (golem.de, 2022). If it is activated, the lights on the steering wheel turn turquoise. If a takeover is required, the system plays a looping auditory beep, and the steering wheel LEDs light up in yellow. If a takeover is required immediately, the LEDs light up in red. Compared to the visual information, the light cues are mostly only used for TOR communication or to communicate that the system is active.

Besides Tesla's approach, where the driver can freely rotate the camera in the world in a miniature around the vehicle and zoom in and out via pinch-to-zoom, the Drive Pilot offers less playful funtionality of that sort. All information is displayed on the central instrument cluster. Like the FSD beta, the system shows the driver that it differentiates between vehicle types (e.g. trucks or cars). As the Drive Pilot always requires a lead vehicle to work, it highlights it with a green circle and an "A" for autonomous.

Regarding transparency communication, the Drive Pilot seems to leave room for

improvements (golem.de, 2022). Sometimes the system requires the driver to take over in a situation where it is supposed to work but does not provide any explanation. In other situations, the system is unavailable even though all required conditions are met, and it does not explain why that is. Similar to Tesla's FSD beta, the Drive Pilot sometimes clearly shows that it does not understand the world around itself, stating, for example, that it cannot be activated due to a construction site, even though there is no construction site (see Figure 3.3 first row, second image).

In conclusion, the Mercedes-Benz Drive Pilot uses the same feedback cues (auditory, visual, textual) and shows the same limitations regarding wrong explanations like the Tesla FSD beta. Additionally, it adds the feedback modality light to the steering wheel to communicate the system's status and TORs.

## 3.3 Waymo

Waymo, a company by Google's parent company Alphabet Inc., is currently operating SAE level 4 autonomous vehicles in Phoenix, San Francisco and Los Angeles (Waymo LLC, n.d. a,n). They primarily use visual cues combined with textual, auditory and voice feedback modalities for intent and transparency communication. Over the years, Waymo has experimented with different types of visualisations; see Figure 3.4.

Similar to Tesla's FSD beta or the Drive Pilot of Mercedes-Benz, they show what the vehicle recognises in a world in a miniature visualisation. In earlier versions, the visualisation would periodically send out some sort of detection burst to show everything the vehicle's sensors are recognising (compare Figure 3.4 first row, fist image: the white elements). As with the visualisations of other manufacturers, Waymo's world in a miniature shows a reduced version of the world around itself, including, for example, cars, pedestrians or crosswalks. The car's current route is visualised with a green line highlighting if the path is blocked by retracting and decreasing its transparency. In a video of 2022 they also used a red area signalling an upcoming stop and icons above relevant objects to describe their relation to the current driving route (e.g. parked in second row). Green arrows indicate lane changes and an abstract icon on the top left of the screen shows traffic light detection. In earlier versions, indicator signals were represented with a flashing green line on the screen. Drive-relevant objects (e.g. cars or pedestrians in front of the vehicle) are highlighted with a coloured outline. As with Tesla's FSD beta, Waymo's visualisation went through some design changes and, compared to earlier versions, now features a more polished, less technological-feeling look.

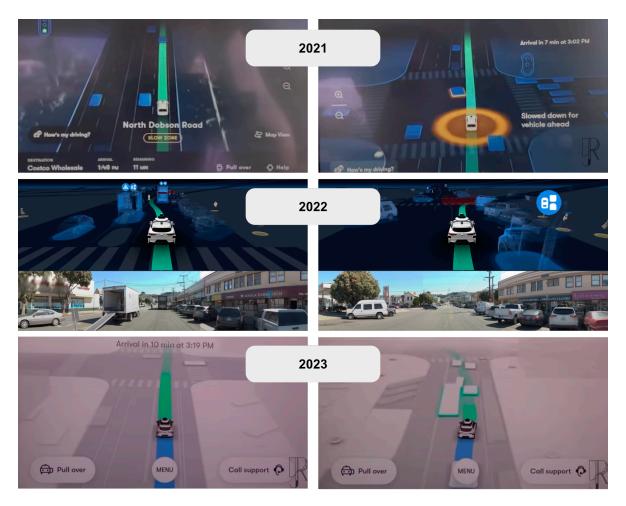


Figure 3.4: Different types of visualisations used by Waymo between 2021 and 2023. Screenshots are taken from videos by JJRicks Studios (2021, 2022); Waymo (2022).

Additionally, the world in a miniature is extended with textual overlays. Despite regular route information, additional, context-sensitive information is shown, for example, highlighting that the car is going through a slow zone or is waiting for an intersection to clear. Critical driving situations are highlighted explicitly in the visualisation and explained via text (see for example: Figure 3.4 first row, second image). Regarding auditory and voice cues, Waymo uses beeps and spoken feedback to let passengers know that the drive is about to start or end or that a human operator is contacted. During the ride, they only use visual and textual feedback.

As with the systems of Tesla and Mercedes-Benz, the transparency communication of Waymo occasionally shows system limitations where passengers are not kept in the loop of what is going on. For example, in one situation filmed by Youtuber JJRicks Studios, the car wants to make a left across lanes of oncoming traffic but cannot do so because of too much traffic. After a long wait, the car suddenly abandons the left turn

and continues driving. At the same time, a human operator is called. No further explanations on the current situation or the vehicle's intentions are provided<sup>5</sup>.

To conclude, Waymo uses a world in a miniature visualisation similar to Tesla's FSD beta and Mercedes-Benz's Drive Pilot for their SAE level 4 AD. For feedback modalities, they mainly focus on visual cues in combination with textual, auditory and voice cues. In terms of intent communication, their system sometimes lacks explanations.

# 3.4 Augmented Reality Navigation and Information

AR modalities that overlay digital information onto the real world have found their way into the cars of today<sup>6</sup>. Manufacturers aim to provide drivers with a more interactive and immersive navigation and driving experience. The idea of HUDs in cars is not new (Swift and Freeman, 1986). However, car manufacturers have recently incorporated world-placed AR navigation and driving information into their newest models. Information about the driving route, lane-keeping or following a lead vehicle using ACC systems is placed directly into the world; see Figure 3.5. Thereby, the different systems of manufacturers are made up in very similar ways. They use the same metaphors and visualisations for different functions and just differentiate themselves by shape or colour.

For navigation, manufacturers use arrows to indicate lane changes or turnings that are placed within the world at the position where turning is due. When the vehicle is changing its rotation the arrows react accordingly. When ACC systems are engaged, they indicate when they detect a leading vehicle that may lead to the system slowing down by placing a highlight bar at their rear end signalling the systems awareness. When lane-keeping systems are triggered, a highlight line is placed on top of the according road marking.

In summary, world-placed AR navigation and driving information modalities are becoming increasingly common in modern vehicles, aiming to improve the safety and convenience of driving by using visual cues placed within the world. Regarding transparency communication, the systems highlight their awareness of and reaction to

<sup>&</sup>lt;sup>5</sup>https://www.youtube.com/watch?v=L6mmjqJeDw0 around 43:30min (Accessed: April 2023)

<sup>&</sup>lt;sup>6</sup>See for example:

https://www.mercedes-benz.de/passengercars/technology-innovation/mbux/displays-and-connectivity.module.html (Accessed: April 2023)

https://www.volkswagen.de/de/elektrofahrzeuge/id-technologie/id-augmented-reality-

navigation.html (Accessed: April 2023)

 $https://www.cupraofficial.at/cupra/cupra-born/cupra-born/technologie \ (Accessed: \ April \ 2023)$ 



Figure 3.5: AR HUDs from Mercedes-Benz, Volkswagen, Kia, Seat and BMW. Screenshots are taken from videos by Battery Life (2021); Brian V (2022); ComputerBase (2021); Motoreport (2022a,b).

driving-relevant objects.

# 3.5 Conclusion

As of today, there are ADAS and CAD as well as AD systems on the market that use UMDs and different feedback modalities for transparency and intent communication. This chapter analysed how different manufacturers are implementing UMDs for communication in their vehicles today. A summary of the feedback modalities used by Tesla, Mercedes-Benz and Waymo can be seen in Figure 3.6. Thereby, the biggest emphasis is placed on visual feedback modalities. Manufacturers explain most of their vehicle's perception, driving actions or intents this way. The visualisation is always extended by occasional text popups explaining certain driving situations. Auditory cues in the form of different beeps are only used for the start or end of a drive or critical situations. Waymo utilises spoken feedback to inform about the start or end of a journey. In the steering wheel, Mercedes-Benz additionally used light as a feedback modality to inform about the system status or if a handover is due. The use of AR as a feedback modality has so far only found its way into ADAS like cruise control or manual driving systems like navigation or lane-keeping displayed in the HUD or centre console. Other than in the literature review, on-device cues are absent in these systems. Interestingly, all systems showed problems with transparency and intent communication in some driving situations where the vehicle's action or route calculation might not be apparent to the passenger.

Modality - System	Visual	Auditory	Light	Textual	Voice
FSD beta					
Drive Pilot					
Waymo					

Figure 3.6: Used feedback modalities by Tesla, Mercedes-Benz and Waymo in their CAD and AD systems. The stronger the colour, the higher the intensity of use in their systems.

The next chapter will report on the methodology used in this thesis. It will define the applied UCD process and the used driving simulators, including their advantages and disadvantages. Then, the used metrics in this thesis are reported, and the implementation of studies and involvement of participants is described.

Chapter 4

Methodology

This thesis argues that AV experiences need to be built around the user, as they are the ones directly exposed to it. It follows the UCD process to iteratively develop concepts and prototypes to generate new knowledge in this area. The following chapter describes the used principles and methodologies in greater detail. First, the UCD process is defined, followed by a description of the used driving simulators. Then, the metrics used in the experiments are defined, followed by how the studies were implemented and analysed and how participants were involved.

# 4.1 User-Centred Design

The UCD process follows the idea of iteratively developing solutions that put the users at the centre and involve them in every step of the process.

The term user-centred was first used in a publication of Kling (1977), talking about users, the "forgotten people in software design" (Kling, 1977, p.3). Kling talks about computer programs being well-made from a technological standpoint but failing to consider their users. He suggests including users in the design process to create better programs. The term UCD, also called human-centred design, was spread further in 1986 by the book User Centered System Design: New Perspectives on Human-computer Interaction by Norman and Draper (1986) and later publications by Norman (1988, 2004). According to Norman (1988), the importance of including the user in the design process lies in behavioural economics: people often do not act the way they are expected to. Therefore, including them in the design process should improve a product by making it better for them to use, not forcing them to change their behaviour. Following the UCD process is generally considered to improve a product's usability and usefulness (Vredenburg et al., 2002). Nowadays, the process of UCD has its own ISO norm (International Organization for Standardization, 2019).

The UCD process does not determine specific methods to use but instead provides a general framework to follow. It comprises four consecutive phases performed as often as needed and is thereby iterative (International Organization for Standardization, 2019; U.S. Dept. of Health and Human Services, 2006), see Figure 4.1. It includes and focuses on the user's needs and requirements at every process phase.

The four distinct phases are:

1. **Specify the context of use:** As the UCD process emphasises the importance of understanding the user, this is the first step to take. By gaining insights into user requirements, needs, usage context or intended use, one can redesign an existing product or design a new one. For an existing product, usability studies can be conducted to collect quantitative data on user behaviour. In contrast, qualitative

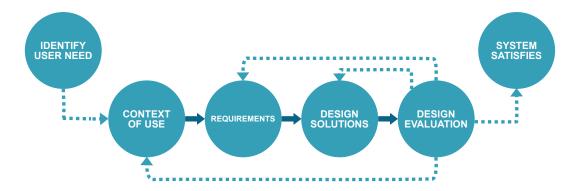


Figure 4.1: Visual representation of the UCD process.

user interviews or competitive analysis can help understand user needs for a new product.

- 2. **Specify the requirements:** After specifying the context, one identifies product requirements. Thereby, it is essential to specify both business requirements and user goals that need to be met. This involves identifying the user's problem, determining the most critical issues to address, and prioritising them based on available resources.
- 3. Create design solutions: The UCD process involves an iterative approach to product design and development based on the identified product goals and requirements. The design process may be done in stages, starting from a rough concept and building towards a complete design. In this phase, the focus is on finding solutions to the user's problems. This may involve strategising user flows, creating sketches, wireframes, mock-up screens, and prototypes. It is important to generate many designs and encourage collaboration, as this can push designers past their initial assumptions. The emphasis should be on developing designs that specifically solve the user's problem.
- 4. Evaluate solutions: Evaluating the product and designs is essential to ensure successful development. The goal of evaluation is to determine whether the user's problems have been solved and if their needs have been met. Subsequently, real users should evaluate the product to collect as much feedback as possible through usability studies and user interviews.

To conclude, the UCD process is a user-centric, iterative and evaluative approach for designing new or improving existing products. Thereby, following the recommendations of Norman (1988) should improve a product but initially did not focus on other aspects like aesthetics, which he referred to as secondary issues

(Norman, 1988; Norman and Draper, 1986). He updated his views in his later publication *Emotional design: Why we love (or hate) everyday things* describing the original ones as overly reductive (Norman, 2004). A quote from his 2013 TED talk thereby summarises it well:

"People used to say, 'Norman's ok, but if you followed what he said, everything would be usable, but it would be ugly.' Well, I didn't have that in mind. [...] My new life is trying to understand what beauty is about, and 'pretty' and 'emotions'." Norman (2003)

As this thesis argues that AV experiences and transparency communication in AD need to be built for the user, it follows the UCD process for its experiments and general approach.

# 4.2 Driving Simulators

Three types of AD simulations have been used for this thesis' research on transparency communication in AD. (1) A VR AD simulator, (2) a physical AD simulator using a static, shuttle-bus-sized structure with multiple monitors and car seats, and (3) a WoZ setup using an electric vehicle on public roads and hiding the driver from the passengers. This section will discuss the general use, advantages, and disadvantages of driving simulators and the three employed simulators for this thesis. A detailed description of every simulator will later be given in the according experiment chapters 6.2, 6.3, 6.4, and 6.5.

The idea of using driving simulators for research has been around for over 60 years (compare, for example, Fox (1960); Hulbert and Wojcik (1960)). Even then, one of the main benefits of using simulators has been discussed: performing safe research without exposing participants to dangerous driving situations (Fox, 1960). Next to being able to perform research on driving situations that would be dangerous in real life, multiple other benefits exist.

Using simulators allows for replicability and control over the setting (Chen and Terken, 2022). This is important as data needs to be comparable between the different participants. An experimental design can also help eliminate various driving factors, including traffic, pedestrians, and accidents. Thereby, the emotional responses of individuals using simulators for driving are similar to those experienced in real-world driving, making them helpful in studying emotions and, in the case of this thesis, UX (Chen and Terken, 2022).

Moreover, by employing three different simulation types (VR, physical simulator, WoZ setup), the experiments reduced simulator-specific biases and increased ecological validity across varying levels of immersion. Especially the WoZ approach allowed participants to experience transparency communication embedded in naturalistic environments, enhancing external validity.

Validity is critical to driving simulators, as they can never represent the real world and all its facets. The validation of driving simulators can be viewed on two levels: relative and absolute validity (Chen and Terken, 2022). Relative validity refers to how closely simulator driving behaviour resembles on-road driving behaviour. In contrast, absolute validity refers to the fact that simulator driving behaviour is not an exact replica of on-road driving behaviour. Most research prioritises relative over absolute validity due to the complexity of simulators and real-world driving conditions. Multiple studies have confirmed the relative validity of driving simulators (compare, for example, Engström et al. (2005); Mayhew et al. (2011); Mullen et al. (2011)). However, they all put the participants in active driving roles. For the experiments of this thesis, participants were not driving themselves due to SAE level-5 AD.

Participants' behaviour and emotions in simulators might not entirely replicate those in real-world driving conditions, especially since physical sensations such as g-forces or genuine accident risks are absent. Additionally, VR setups may introduce simulator sickness and limit exposure time, thereby influencing the ecological validity of results (Weidner et al., 2017).

Furthermore, six factors threaten the validity of a driving simulator setup (Chen and Terken, 2022; Fisher et al., 2011).

- It is important to recruit the right participants and remove records that mask the effect of the data.
- When designing an experiment, it is important to carefully consider the task, user background, and test environment to ensure consistency with the intended application.
- To prevent dropouts in driving simulator experiments due to dizziness caused by the simulator or task, carefully select subjects and avoid turning movements.
- Randomisation of subjects, experimental conditions, and test events is necessary to prevent systematic bias and ensure data validity.

- To prevent learning effects and systematic bias in an experiment, subjects should not participate in repeated experiments, and countermeasures should be considered in the experimental design.
- To ensure data stability, sample size should be increased and changing experimental design considered when there are too few subjects in each test unit.

All of the threat factors mentioned above for the driving simulator validity have been taken into account in the four main experiments of this thesis. The study setup and considerations of threat factors will be described in detail for each experiment later.

# 4.2.1 Driving Simulators Used in this Thesis

This thesis used three different types of driving simulators for the experiments. The reason for that was to strengthen the validity and reliability of the findings by not limiting the research to a single point of verification. As each simulator has its strengths and limitations, using multiple simulators allowed for capturing a broader range of driving scenarios and UXs. Additionally, using multiple simulators could have helped to mitigate any potential biases that may have been present in a single simulator setup. By using a variety of simulators, this thesis tries to increase the generalisability of the results and provide a more robust analysis of the research questions.

# Virtual Reality Driving Simulator

The first experiment, see section 6.2, used a VR autonomous driving simulator. The goal was to have participants experience an autonomous drive with a high level of immersion. Compared to seeing driving footage on a screen, VR allows for depth perception and, therefore, improved perception of the distance and size of objects. In regards to validity, VR simulators produce similar data as non-VR simulators (Weidner et al., 2017). A virtual environment was created in Unity<sup>1</sup>, allowing participants to experience different driving situations and feedback modalities. The VR simulator allowed for a high level of reproducibility and high control over the environment.

Compared to the other two simulators used, the VR simulator had the risk of participants experiencing discomfort or simulator sickness, commonly known as motion sickness (Weidner et al., 2017). Furthermore, VR introduced a learning curve as it is still a new technology for many. This was compensated in the experiment with

<sup>&</sup>lt;sup>1</sup>https://unity.com/

a separate introduction to the system and its feedback modalities. Lastly, as it was static, the VR simulator lacked the feeling of g-forces when accelerating, decelerating or driving through corners. This, in return, also posed the risk of increasing participants' motion sickness as there was a disconnect between the driving scenes and the feeling in the body.

#### Static Shuttle-Bus-Sized Simulator

The second and third experiments, see section 6.3 and 6.4, used a static, closed, shuttle-bus-sized structure equipped with multiple monitors and car seats. The VR simulator allowed for high immersion but could only represent the world using three-dimensional graphics. For the physical simulator build, a drive through Stuttgart, Germany, was recorded with three cameras, showing real environments to participants. The recordings were then projected on different screens acting as windshield and side windows. Furthermore, the driving videos were then extended with different feedback modalities. As with the VR simulator, the physical simulator build allowed reproducibility and environmental control.

Compared to the VR driving simulator, the static simulator had a reduced risk of motion sickness. However, it still shared the problem of missing g-forces regarding immersion, which could have also led to an unrealistic driving experience.

#### Wizard of Oz Simulator

The fourth experiment, see section 6.5, used a WoZ setup (Kelley, 1984). This technique is named after the Wizard of Oz where an operator secretly controls what appears to be an autonomous system. It is particularly advantageous when developing a fully functional system would be excessively costly or complex. The fourth experiment employed this technique to simulate an autonomous driving experience without the need for a fully autonomous vehicle. Following the WoZ setup, a hidden human operator, akin to the 'wizard' behind the curtain in *The Wizard of Oz*, manually controlled certain aspects of the system, creating the illusion that the system is operating autonomously.

Compared to the other two simulators, this setup allowed participants to experience g-forces during driving and generally provided the highest immersion of all setups. For the experiments, an electric vehicle was equipped with a curtain separating the driver from the passenger, creating the illusion of an autonomous drive. This human-in-the-loop approach was used to study user interaction with what they believed was an autonomous system in a controlled yet realistic setting. Participants were more likely to react naturally to driving scenarios, as they were completely immersed in the surroundings rather than just looking at a screen.

However, compared to the other two simulators, the WoZ setup did not allow the same degree of reproducibility and control over the environment, increasing the risk of inconsistency. The driving path and events were always the same, but the experiment had to deal with other road users and the inherent variability of human control. Furthermore, the driver of the experiment vehicle, acting as the 'wizard', had to try to mimic the drive as similarly as possible every time, which introduced a layer of unpredictability and reliance on human performance.

# 4.3 Mixed-Methods Approach

In addition to the use of simulators, a mixed-methods approach was adopted, combining quantitative and qualitative data collection across all studies. This approach allowed the strengths of standardised, statistically robust questionnaires to be complemented by deeper qualitative insights gathered through think-aloud protocols and interviews. Consequently, not only could changes in user experience, perceived control, and understanding be measured, but the underlying subjective interpretations could also be explored.

However, the mixed-methods approach introduced additional challenges: collecting both types of data is resource-intensive and requires careful planning. Qualitative data, while rich, is inherently subjective and demands thorough thematic analysis to prevent bias. Furthermore, reconciling quantitative and qualitative findings, especially when they appear contradictory, requires methodological rigour and careful interpretation.

Overall, the use of simulator experiments combined with a mixed-methods approach enabled a comprehensive exploration of transparency communication for first-time passengers in AD, balancing experimental control with ecological validity, and statistical robustness with rich experiential insight.

# 4.4 Used Metrics

Throughout the experiments, multiple metrics have been used. All of them are subjective measures. To assess the reliability of the different items, Cronbach's Alpha was used to measure the internal consistency as it is beneficial for questionnaires with multiple Likert scale items (Cronbach, 1951).

### Likert Scale Usage

Throughout all questionnaires, a 5- or 7-point Likert scale was used as the response format to assess participants' subjective impressions. The Likert scale enables the quantification of participants' agreement or perception regarding statements about the metrics described in the following. Using a Likert scale offers a balanced and interpretable range of options, allowing the capture of nuanced participant feedback while maintaining statistical analysability (Likert, 1932). The collected Likert scale data further allowed for internal consistency checks via Cronbach's Alpha (Cronbach, 1951) and formed the basis for the quantitative analyses conducted in this thesis.

#### User Experience

This metric assesses the participant's UX in a qualitative and quantitative form. For quantitative data, it uses eight items from the User Experience Questionnaire - Short (UEQ-S) (Schrepp et al., 2017). It is measured on a 7-point Likert scale (strongly disagree – strongly agree) and indicates participants' pragmatic and hedonic quality and their overall UX. Having a high UX score is preferred. This metric has been used in studies like Colley, Belz and Rukzio (2021); Riegler, Aksoy, Riener and Holzmann (2020); Riegler, Weigl, Riener and Holzmann (2020).

For qualitative data structured and semi-structured interviews, user observation and think-aloud testing have been used (Interaction Design Foundation, n.d. b; Nielsen, 2012a).

# Perceived Feeling of Safety

This metric assesses the participant's perceived feeling of safety in a quantitative form by using three items from the Autonomous Vehicle Acceptance Model Questionnaire (AVAM) questionnaire (Hewitt et al., 2019). It is measured on a 7-point Likert scale (strongly disagree – strongly agree) and indicates if participants think using the AV would be dangerous, if they would feel safe, and if they would trust it. Having a high perceived feeling of safety score is preferred. This metric has been used in studies like Detjen et al. (2020); Haghzare et al. (2021); Wiegand et al. (2020).

#### Perceived Feeling of Control

This metric assesses the participant's perceived feeling of control in a quantitative form. As no appropriate questionnaire could be found, a three-item scale partially inspired by the perceived feeling of safety from the AVAM questionnaire (Hewitt et al., 2019) was created. It is measured on a 7-point Likert scale (strongly disagree – strongly agree)

and indicates if participants feel they have adequate control over the information given by the AV, adequate control to get the information about the ride they need and if they have the feeling of being in control during the ride. Having a high perceived feeling of control is preferred.

# Understanding / Ease of Use

This metric assesses the participant's understanding and ease of use of the system in a quantitative form by using three items from the AVAM questionnaire (Hewitt et al., 2019). It is measured on a 7-point Likert scale (strongly disagree – strongly agree) and indicates if participants find the AV easy to use and learn and the interaction clear and understandable. Having a high understanding / ease of use score is preferred. This metric has been used in studies like Detjen et al. (2020); Haghzare et al. (2021); Wiegand et al. (2020).

### Transparency

This metric assesses the participant's perceived system transparency in a quantitative form by using a self-defined two-time 7-point Likert scale (strongly disagree – strongly agree). It indicates if participants perceive the system as transparent and find the interaction with the AV clear and understandable (inspired by the AVAM questionnaire (Hewitt et al., 2019)).

# Perceived Speed

This metric quantitatively assesses the participant's perceived speed using a self-defined one-item 5-point Likert scale (much slower – much faster). It indicates if participants experienced different rides faster or slower than a reference ride.

# Perceived Driving Style

This metric assesses the participant's perception of the AV's driving style compared to their own in a quantitative form by using a self-defined one-time 5-point Likert scale (not at all - very much). It indicates if participants experienced different rides as close to their driving style.

# 4.5 Study Implementation and Participant Involvement

The four main experiments of this thesis used mixed-method within- and between-subjects designs (Field, 2013; Östlund et al., 2011). The best-fitting design was chosen depending on the number of feedback modalities tested and participants available. For experiments with many feedback modalities to test, within-subject designs were chosen and counterbalanced by randomising feedback modalities. For statistical analysis of the quantitative results, different non-parametric tests were used, including the Wilcoxon Signed Ranks, Mann-Whitney and Kolmogorov-Smirnov test, as well as the t-test and ANOVA. Furthermore, the study variables, such as transparency, dimensions of the AVAM, and the UEQ-S, were analysed to determine their intercorrelations. To make sure that there was enough consistency within the data, Cronbach's Alpha coefficient (Cronbach, 1951) was computed for all variables.

Regarding the study population, it was ensured that enough participants were included to detect various effects across different experimental factors (Field and Hole, 2002). Thereby numbers ranged between 22 and 121 participants per experiment. More participants would have increased confidence in the findings if resources allowed for it. However, the available participants allowed for successful statistical calculations in all experiments. Furthermore, it was made sure that participants were not re-used across multiple experiments, as this thesis deals with first-time users of AVs.

# 4.6 Conclusion

This chapter has presented the overall methodology of this thesis and its experiments. First, the UCD process was defined. It is the basis of this thesis' approach and informs the general procedure and experiments. Then, the three different types of simulators used in the experiments were introduced and critically examined, and their advantages and disadvantages were discussed. Next, the metrics utilised in the experiments were established, followed by the implementation and analysis of the studies and the involvement of participants.

The next chapter will report on pre-studies performed to define the requirements of potential users, which informed the design of the four main experiments of this thesis. Therefore, focus groups and expert interviews were conducted. Their results will then be critically discussed, and potential implications derived.

# Chapter 5

Requirement Analysis Regarding Potential Users and Experts As mentioned before, this thesis follows the UCD process, which led to the iterative development of the four main experiments. Furthermore, for the initial requirement analysis, the stage-based, user-centric design process approach of Eiband et al. (2018), see section 2.5, was also included. In order to know what to explain, they propose to derive the potential users' mental model as well as the one of the experts. This can be done, among other things, through workshops, interviews or surveys. Then, the two existing mental models form a target mental model. Focus groups were carried out to derive the potential users' mental model, and expert interviews were conducted for the experts' mental model.

The focus groups and expert interviews were, to a certain extent, exploratory. They helped guide the final direction of the thesis, as it was not completely predetermined at this stage. Following the user-centric approach of UXD, personas were created from the data obtained in the focus groups to summarise the different mental models into manageable artefacts. They thereby helped to shape the overall research direction and experiment designs.

The insights gathered from the focus groups, along with the valuable input obtained from expert interviews, played an important role in shaping the initial direction of this thesis. The diverse perspectives, opinions, and experiences shared by the participants and experts helped to inform the general research direction and, thus, the four main experiments of this thesis.

# 5.1 Focus Groups

To assess the existing mental models of potential users regarding AD and their general situation concerning mobility and smart technologies, focus groups (Morgan, 1996) were conducted. These focus groups served as a platform to gradually introduce and explore the topic of AD and adjacent areas with the participants. The focus groups aimed to uncover the participants' perceptions, beliefs, and expectations surrounding AD by engaging in open and interactive discussions. The structured nature of these sessions allowed for a deeper understanding of how individuals imagine AD and how it fits into their broader understanding of mobility and technology. Furthermore, the focus groups provided an opportunity to explore the participants' experiences, challenges, and wishes related to mobility and smart technologies. This holistic approach helped to contextualise their mental models of AD within the larger framework of their everyday lives and technological interactions.

The focus groups covered several topics, as outlined in Table 5.1. The questions and topics were chosen to slowly introduce participants to the topic of AD and intelligent systems. They engaged in discussions about their transportation preferences, positive and negative experiences, and key considerations. They also explored using smart assistants, including their experiences, data safety, and other smart devices, to gain insights into their interactions with smart devices and technology. The third part focused on participants' experiences with shared mobility, transitioning to AD. Participants then shared their current ideas of AD, possible use cases, desired features, and their feelings about riding in a driverless AV. The focus groups still referred to gaining the passengers' trust. The concept of control and perceived safety was later derived from the focus groups and expert interviews. This is discussed in greater detail in section 6.1.2.

Table 5.1: Main and sub conversation questions for the focus groups.

### 1) What is your main way of transportation?

What are positive experiences?

What annoyances do you face?

What is important to you?

# 2) What are your experiences with smart assistants?

What are positive / negative experiences?

How important is data safety to you?

How does it feel to have a microphone listening all the time?

Do you have a smart watch?

Do you have other smart devices in your life?

# 3) What are your current experiences with shared mobility?

#### 4) What is your current idea about autonomous driving?

What does an autonomous shuttle have to offer?

What are your ideas?

What are use cases of autonomous vehicles?

# 5) How do you feel about sitting in a car that has no steering wheel, pedals or driver?

How can the vehicle gain your trust?

Should the vehicle have ethics?

# 5.1.1 Setup and Participants

In March 2019, three focus groups were conducted, each lasting 90 minutes. The participants included 18 individuals, with seven females and 11 males. The average age of the participants was 30.7 years (SD=7.93). Among the participants, 5 had prior experience with SAE level 2 driving assistants, and 11 had experience with shared

mobility. Additionally, 10 participants worked in computer science-related fields, 4 were students, and the remaining worked in controlling, product management, marketing, and research. It is important to note that all participants were considered average end-users and did not possess expert knowledge in the field of AD.

# 5.1.2 Results

During the focus groups, several key topics emerged as important to the participants revealing a general need for control, transparency and feeling safe. These topics included trust, transparency, and feedback, which were the most frequently discussed. Simplicity, comfort, and privacy were also mentioned, although to a lesser extent. Regarding discussions about AD, participants expressed concerns about losing control (8 mentions). They also desired direct intervention (6) and transparency (4) and mentioned not trusting software developed by humans (3). Furthermore, participants, among other things, wanted to make use of their time in an AV (4), still wanted to have fun driving a car (4), and wished for privacy and comfort (4). Other concerns included the absence of a contact person, the question of who is more prone to making mistakes - humans or technology, and general trust issues with current driving assistance systems. All results regarding AD can be seen in Table 5.2. The complete results, including mode of transportation, smart assistants and shared mobility, can be found in Appendix A.

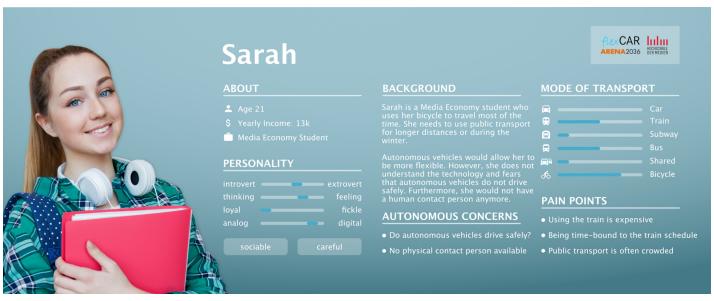
#### 5.1.3 Personas

Following the general approach of UXD and the UCD process, personas were created to understand the needs and preferences of users effectively and to group them into manageable artefacts. See Figure 5.1 for a complete overview. The personas were developed by analysing the data obtained from the focus groups to represent different user archetypes for transparency communication in AD. These personas were valuable tools for informing the overall research direction and designing experiments. Incorporating them into the research process ensured that the experiments and subsequent findings aligned with the users' perspectives and expectations. The personas developed in this study thereby represent the superficial mental models held by the users, allowing for targeted and user-centred design decisions.

Table 5.2: Focus groups results concerning AD separated by topic. Numbers represent mentions.

# Positive

No concerns, trust would be present.			
Desires			
Be able to intervene (e.g. emergency brake, contact person)	6		
Use time in the car effectively			
Transparency in driving, breaking down the system			
Private driving without other passengers			
Would like to continue to have fun driving			
Personalisation			
More privacy and comfort			
Still drive yourself in your free time			
Relaxed driving			
Autonomous driving is not important, good connections are important.			
Private public transportation.			
Use Case	0		
Commuting	3 2		
Shared shuttle			
Motorway			
Replacement for public transport	1		
Concerns			
Loss of control.			
No confidence in software developed by humans			
More trust when all participants drive autonomously			
They have already a problem of trust with today's assistance systems			
No more contact person on the bus / train			
Who makes more mistakes, humans or machines?			
There will be more traffic jams			
Data protection			
Visions			
Get in, be driven to destination, get out	5		
Less accidents	5		
Like an autonomous Car2Go			
Improved traffic flow			
Minors / physically impaired become more mobile			
Less cars because of sharing			
Will take a long time to become reality			
There will still be individual transport			
Fully autonomous driving on some routes			
It will not work in the countryside			
No more changing trains when commuting			
You can but you do not have to drive			
Parallel system for driving, for example on rails			
Features for an additional charge			



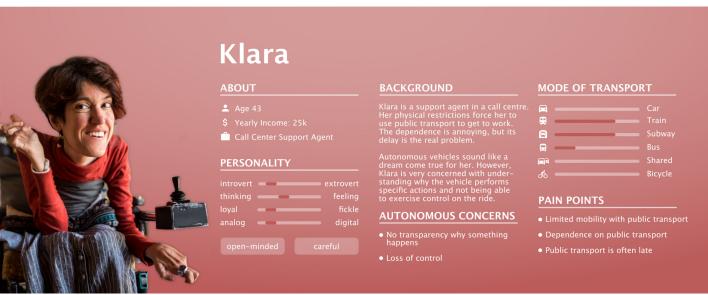




Figure 5.1: The three personas created from the data obtained in the focus groups.

# 5.2 Expert Interviews

As part of the stage-based design process of Eiband et al. (2018), expert interviews were conducted to understand and align their mental models with the users' mental models. Therefore, six experts from related fields were interviewed. These interviews were used to provide additional insights, considering the focus groups' and literature's emphasis on safety, control, and transparency in AD. They allowed gathering expert knowledge of different adjacent areas and gaining firsthand perspectives.

# 5.2.1 Setup and Participants

In July 2020, the expert interviews were conducted with six participants. The experts included a professor specialising in AI and human-machine interaction, an AI researcher, a professor for mobility research, a UX and AI designer, an AI psychology researcher, and a mobile application developer. Semi-structured interviews were used that followed a basic outline, see Table 5.3, but allowed for flexibility in questioning and follow-up discussions.

Table 5.3: Semi-structured expert interview questions.

- 1) What is your Job title?
- 2) What are the main topics and buzzwords of your domain?
- 3) How do you see the general future of autonomous driving?
- 4) How relevant is your subject area for autonomous driving?
- 5) How would you design the general communication between the autonomous vehicle and its user, and what would be important to you if you were sitting in such a vehicle?
- 6) How would you design the AI transparency for the end user?

#### 5.2.2 Results

Table 5.4 summarises the experts' main statements, requirements, and keywords to provide a comprehensive overview. The complete transcripts can be found in Appendix A.

# Professor for AI and Human-Machine Interaction

The professor provided input from an interaction point of view. He emphasised that his primary expertise lies in AI, with human-machine interaction being just one application in a specific field. He explained that human-machine interaction focuses on human error and the potential for computers to outperform humans in decision-making. He highlighted the importance of traceability in these decisions. Regarding communication between the AV and the passenger, the professor stressed

Table 5.4: Expert interviews: field of expertise, interview keywords and main statements.

### Professor for AI and Human-Machine Interaction

human error, traceability, machine learning, comprehensibility, closed world assumption

- See the vehicle's overall condition in an understandable way at any time, even for non-technical people.
- What does the AV perceive, and what does it not?
- I should be able to expand the information.
- Easily access information on any digital device.

#### AI Researcher

object recognition, machine learning, deep learning, computer vision, world view, object segmentation

- Communicate through language. Make it feel natural.
- Provide abstract visual input of the situation.
- Build trust by seeing the world through the AV's eyes.
- Present a simplified form of decision making.
- Provide a 3D world but without too many details.

# Professor for Mobility Research

behaviour, needs research, UCD, open innovation

- To some extent, people want to feel that they are in control.
- Perceived Safety: If I do not think that the car is safe, then, when in doubt, it does not feel safe.
- Is the type of driving style relevant? Should it be close to the one of the passenger?
- Context-dependent information: which information is relevant at a point in time?
- Some information is probably always relevant.
- Too much information may be detrimental to user acceptance.

#### UX and AI Designer

statistics, machine and deep learning, AI ethics, UXD

- An essential step in the early stages of technology is conveying a feeling of security.
- Issues of trust and the feeling of control must be addressed.
- People are trying to be in control of something they are not. When the machine acts autonomously, it must provide an explanation.
- Create a transparency of the machine's state that is understandable to the novice user.
- There are different levels of transparency. What is needed to trust the machine at all? What is nice to have? What makes it a unique experience?

#### AI Psychology Researcher

experience centred design, UCD

- Different people need different amounts of information.
- You need to provide the corresponding information so the respective user group understands it.
- The AI must be able to adapt to my needs for information.
- Provide a situation- and person-adapted presentation of information.
- The AV should not only show the state of the system but also its limitations.

#### Mobile Application Developer

product design, human centred design

- Explain where you are and what is around you.
- The user should be able to control the car with their smartphone.
- There should be different levels of transparency and feedback.

the need for easily understanding the vehicle's state at any given time in a way that is clear to both technical and non-technical individuals. Knowing what the AV perceives and does not perceive is crucial. Therefore, passengers should quickly grasp the vehicle's condition without needing constant monitoring. For transparent AI communication, the professor suggested the need for a clever visualisation of the vehicle's state that can be easily accessed on any digital device, for example, a smartphone. This system would seamlessly transfer information to the user's device, eliminating the need for manually searching information. Additionally, he emphasised the importance of immediate access to relevant information without intrusive alerts or distractions. Furthermore, he said that the amount of displayed information should be tied to the seriousness of the situation. Simple situations would not need as much explanation as complicated ones. He concluded by expressing the desire for a user-friendly interface that lets users quickly focus on what matters and have all necessary information readily available.

#### 5.2.3 AI Researcher

The AI Researcher provided insights from a technological point of view. He highlighted the relevance of AD for machine learning research and mentioned object recognition as a critical topic in AD. He generally gave input on the technological side of things and explained the technological complexity regarding the training of an AI algorithm. Regarding transparency, the expert discussed the challenges of traceability and decision-making in deep learning algorithms. He highlighted a problem of neural networks: providing explanations is difficult, as tracing back decisions to the input is hard. Providing explanations that semantically explain driving decisions is called context knowledge or world knowledge. However, if it is possible depends on the used models or algorithms. He highlighted that, for example, object recognition in deep neural networks only works on a pixel-based level and therefore does not have a knowledge of the world.

For the communication between the AV and the passenger, the AI researcher suggested the importance of visualising what the vehicle sees, using object segmentation to highlight semantic objects, and providing simplified representations of decision-making processes to enhance AI transparency for passengers. He further emphasised that natural language for communication could be beneficial. The expert also touched upon the challenges of the need for communication when the AI encounters situations it cannot handle. He suggested using subtle feedback, such as sounds or notifications, to inform passengers about uncertainties or errors.

# 5.2.4 Professor for Mobility Research

The professor for mobility research came from a background that is interested in using digital technologies for sustainable transportation. Regarding the use of AVs, he highlighted that it is important to create confidence in the technology and that people will have the needs of perceived safety and control. When an AV does not feel safe to the passenger, it is, when in doubt, not safe. Furthermore, he also mentioned that the driving style could play an important role, raising the question of whether it should be close to one of the passengers, defensive or quick. Regarding transparency communication, he emphasised that it is important to provide context-dependent information and thus to know which information is when how relevant to the passenger. For example, in case of an emergency stop, knowing why the stop happened is usually important because it is not a normal occurrence. However, in other situations, such information may not be very useful or could even negatively impact user acceptance. Thereby, it will also be important to convey information in a way that is understood by humans and can be processed in a sufficient amount of time. He further highlighted that the way of communication will probably change over time and will be different for first-time users compared to reoccurring users.

# 5.2.5 UX and AI Designer

The expert provided insights from a UX designer perspective who is, among other things, creating user-centric AI interactions. He thereby sees AI as a means to an end to design UXs. Regarding AVs, he emphasised that conveying a feeling of security is essential, especially in the early stages. He thereby drew a comparison to aeroplanes that are statistically speaking very safe but still trigger panic attacks for some The expert emphasised that the perceived feeling of safety and the passengers. understanding of AVs depend on making them as transparent as possible. Regarding transparency communication, he highlighted that AI systems can always produce errors and that a form of transparency communication is needed that is understood by everyone. Using the aeroplane analogy again, he said that people would often try to be in control, even though they are not. Highlighting the importance of a perceived feeling of control. This, in his eyes, needs to be addressed through good transparency communication, describing why certain actions are happening. In a wider sense, transparency in AD for him also shows the passenger where they currently are and where they are going. He thereby defines transparency as a construct comprising multiple levels, some more important than others, that combined form transparency.

# 5.2.6 AI Psychology Researcher

The AI psychology researcher provided insights from an experience-centred interior design point of view, with her main goals being to create positive experiences in interaction and being the link between AI and UX. Regarding the communication between the AV and the passenger, she highlighted that there would not be a one-fits-all solution. She emphasised that at the beginning of a new technology, there will be users who need a lot of information. At the same time, others might not. Therefore, it will be important to adapt and provide the right amount of information to respective groups to understand it. In terms of AI transparency communication, the expert said that the kind of information used to create transparency will depend on the type of driving situation. For example, urgent situations will need different kinds and amounts of information than regular ones. She referred to this as a "situation- and person-adapted presentation of information" (see Appendix A). Furthermore, she said that it should not only be about showing the AV's state but also its limitations, as this is also part of transparent communication. For her, transparency refers to understanding the process and challenges involved in reaching a particular outcome and creating a customised representation for the user in that specific context. This results in a comprehensive and clear representation.

# 5.2.7 Mobile Application Developer

The expert mentioned that he has never owned a car. Therefore, he provided the point of view of a public transport user with high technological knowledge. He mentioned that he could imagine AR technology in AVs displaying relevant information on the windshield or windows. Regarding the communication between the passenger and the AV, he would use a smartphone app as it is currently the usual way and known and accepted by users. He drew up the comparison to smart home devices that are also often controlled via an application. Regarding AI transparency communication, he highlighted that different levels of transparency would be needed. In the beginning, more information would be interesting. He further emphasised that as a passenger, he would like to choose the amount of information, just like a developer managing debug output. At the same time, non-technological people might just want to get to their destination and not be overwhelmed with information.

# 5.3 Discussion of Focus Groups and Expert Interviews

This section discusses the outcomes derived from both focus groups and expert interviews. The results will be examined and analysed in relation to one another and the literature review, highlighting their interconnections and allowing for a comprehensive understanding.

# 5.3.1 Perceived Feeling of Safety and Control

The focus group participants' statements regarding the perceived feeling of control are consistent with the literature review findings in section 2.3. Participants expressed a strong desire to exert control over their interactions with an AV and expressed concerns about the potential loss of control. This further highlights the importance of addressing the need for perceived control in the design and development of such systems. Furthermore, some participants already have existing trust issues with current assistance systems and software developed by humans. This implies that building confidence in the technology is crucial for its successful adoption and acceptance.

In addition to the focus group participants, two experts, the Professor for Mobility Research and the UX and AI designer, have also emphasised the importance of designing for the need for perceived control. They have highlighted that addressing this need and the need for perceived safety is particularly crucial during the initial stages of using the technology. Building user confidence in the system is vital to foster its adoption and continued use. The UX and AI expert further emphasised that meeting these needs depends on making the system as transparent as possible. Transparency in the system's functioning and decision-making processes can help users understand the technology better. They can feel more in control, develop a sense of understanding and confidence in the system's capabilities, and have positive experiences.

Overall, the statements of both the focus group participants and the experts emphasise the importance of addressing the need for perceived safety and control and align with the literature review findings.

# 5.3.2 Transparency and System Understanding

The focus group participants expressed a strong desire for transparency in the driving experience and a breakdown of how the AV operates. These requests are in line with the extensive research on XAI and communication through UMDs discussed in

sections 2.5, 2.6, and 2.7.

The experts elaborated in greater detail on this topic from several points of view. From a technological perspective, they emphasised the importance of providing human-understandable traceability of the AV's decision-making process. This means ensuring that users can easily comprehend and follow the reasoning behind its actions. To support this, experts suggested visualising the AV's perception of its surroundings and potentially highlighting relevant objects or factors influencing its decisions. On the communication side, experts highlighted the importance of delivering context-dependent information. The AV should be capable of understanding which information is relevant and needed by the passengers at a certain point in time, often dependent on the salient driving situation. Furthermore, the AV should be able to explain why it is taking specific driving actions, ensuring that passengers have a clear understanding of the decisions being made by the system.

In conclusion, the focus group participants and experts emphasised the need for transparency and explainability in AVs. These findings align with existing research on XAI and UMDs.

### 5.3.3 Amount of Information

In the context of providing information to passengers, the experts highlighted an interesting point. They recommended to tailor the amount of information based on the seriousness or complexity of different driving situations. They argued that more complex and critical situations would require greater levels of explanation and detail. This approach, referred to as "situation- and person-adapted presentation of information" (see Appendix A), aims to provide passengers with the necessary information to understand driving situations effectively. Additionally, the experts noted that passengers' information requirements may change over time. As they become more familiar with AVs, their need for detailed information may decrease. To accommodate this, the experts suggested that passengers should be able to choose how much information they receive, allowing for a more personalised and customisable experience.

The concept of transparency was also discussed in relation to UXD. The UX and AI designer emphasised that transparency is a multi-level construct with different levels of importance to different users. This implies that the level of transparency in providing information should be adaptable and customisable, considering individual user preferences and needs.

It is worth noting that while this topic has been addressed in a few publications in the literature review chapter, most research has typically presented all users with the same amount of information. The experts' recommendation to tailor information delivery based on the seriousness and complexity of driving situations and individual preferences and thereby recognising the importance of considering users' unique perspectives and requirements aligns with the subjective nature of UXD.

#### 5.3.4 Feedback Modalities

The focus group participants did not provide any feedback on the use of certain feedback modalities, which means their opinions on how communication between the AV and the passenger should be handled are unknown. However, the experts who participated in the interviews provided concrete ideas and suggestions.

The Professor for AI and human-machine interaction proposed that necessary information should be easily accessible on any device, such as a smartphone. The mobile application developer also emphasised the importance of displaying information through on-device cues. In addition, the developer mentioned the potential use of AR for information transmission. AR technology could be employed to overlay digital information or visual cues onto the real-world environment, providing passengers with contextual information about their surroundings or the vehicle's operations.

The AI researcher suggested using conversational language for information transmission to make the interaction with the AV feel more natural to the user. This implies that the vehicle could engage in dialogue-like exchanges, responding to passenger inquiries or providing updates in a conversational manner. Furthermore, the AI researcher highlighted the need to visualise what the AV "sees" in a simplified representation of the world, often referred to as a world in miniature. This would help passengers to better understand and interpret its actions.

Lastly, the mobility researcher took a more abstract perspective, emphasising that the methods of communication are likely to change over time and may vary depending on whether the passenger is a first-time user or a recurring user. This suggests that communication strategies should be adaptable and tailored to different users.

Although the experts' suggestions were not uniform, they all represented some of the modalities discussed in the literature review. Their proposed modalities for information transmission utilised various technologies, such as smartphones, on-device cues, AR, conversational language, and simplified visual representations. These suggestions reflect

the diverse range of possibilities for effectively communicating with passengers in AVs.

#### 5.3.5 Failures

During discussions, focus group participants expressed their lack of confidence in software developed by humans. This sentiment has raised the question of who makes more errors, the human or the machine.

To address this concern, the UX and AI designer emphasised that AI systems are not infallible and can encounter errors. In such cases, transparent communication becomes essential, ensuring passengers are informed about the failures and understand the situation. This transparency is crucial for understanding confidence in AVs. The AI psychology researcher further emphasised the importance of conveying the current state of the AV, as well as its limitations. This aspect of uncertainty communication was explored in detail in section 2.6.3 of the literature review.

An intriguing aspect to consider is how failure situations might impact the perception and acceptance of transparency communication. The professor of Mobility Research highlighted the need to understand not only when certain information is relevant but also how it may vary based on the driving situation. Some information may not be useful or could even have a negative impact on passenger acceptance, depending on the context.

In conclusion, the experts' recommendations align with the research discussed in the literature review. Transparent communication and conveying the AV's state and limitations are important. Therefore, understanding the impact of failure situations on transparency and acceptance is necessary.

#### 5.3.6 Conclusion

To summarise, this requirement analysis was driven by a user-centric philosophy. Therefore, focus groups with potential users and expert interviews were conducted to help guide the final direction of this thesis' research. The results align with the literature review findings and emphasise the importance of designing systems that cater to users' needs for safety, control, and transparency. Following the UCD process, personas were developed from the focus groups results to inform the following experiments in the next chapter. A recurring theme was the desire for a deeper understanding of the system, where the experts provided detailed insights into the technological and communicative aspects. This has led to the consideration of various feedback modalities, including on-device cues, AR, and conversational interfaces, to

enhance transparency and system understanding. Thereby, the approach to information presentation is anticipated to be contextually dependent, varying in detail and depth based on the situation. The diverse expert opinions on transparency communication technologies, coupled with the understanding of user needs for control and safety, directly informed the design of the upcoming experiments. These experiments aim to explore the effectiveness of different communication strategies through feedback modalities, their influence on passengers' UX, their perceived feeling of safety and control, and system understanding. Furthermore, the requirement analysis findings also informed one experiment on failure situations in AD and their impact on the metrics above.

# Chapter 6

Investigating Uni- and Multimodal Displays in Autonomous Driving for Transparency Communication

# 6.1 Introduction

This chapter discusses the four main experiments conducted as part of this thesis. Each experiment will be thoroughly introduced, providing background information and context. The setup of each experiment will be explained, including the methodology, materials used, and any specific procedures followed. The findings will be analysed and discussed, considering any patterns, trends, or significant observations that emerged. This analysis will help to draw conclusions from the results, highlighting the implications and significance of the findings.

Furthermore, this chapter will not only focus on each individual experiment but also explore the relationships and connections between them. By comparing and contrasting the results and conclusions of each experiment with the current state of research, a deeper understanding of the overall research topic is gained.

Finally, this chapter concludes with a comprehensive overview of the main experiments conducted in this thesis, the obtained results, and the broader implications of the findings.

# 6.1.1 Experiments

The main goal of the experiments was to research different UMDs for transparency communication and their implications on the passengers' UX in AD. As the literature review, focus groups, and expert interviews have shown, multiple metrics, including the perceived feeling of safety and control or system understanding, might have an influence on the passengers' UX. The experiments gradually explored the use of UMDs in AD and their influence on different metrics. Also, they accounted for new research being published at this time in their setups. Furthermore, the development of the experimental scenarios and feedback modalities was informed by the personas created earlier in the research process. They served as a conceptual guide to ensure that different passenger archetypes and their diverse needs regarding transparency communication were considered during the design phase.

All four experiments have also been published at different conferences:

• Increasing the User Experience in Autonomous Driving through different Feedback Modalities (Schneider et al., 2021) - The first experiment focussed on fundamental research regarding different unimodal feedback modalities for transparency communication in AD for different driving situations and their implication on the UX, system understanding and perceived feeling of control.

- Explain Yourself! Transparency for Positive UX in Autonomous Driving (Schneider et al., 2021) The second experiment investigated live and retrospective uni- and multimodal feedback modalities and their impact on the UX, perceived safety and control, system understanding and acceptance.
- Velocity Styles for Autonomous Vehicles affecting Control, Safety, and User Experience (Schneider et al., 2021) The third experiment incorporated the driving style of the AV as another variable. It investigated how audio-visual alteration influenced participants' perception of the driving style and how combined with multimodal feedback for transparency communication, it influenced participants' perceived feeling of safety and control.
- Don't fail me! The Level 5 Autonomous Driving Information Dilemma regarding Transparency and User Experience (Schneider et al., 2023) The fourth experiment took non-critical failure situations during an autonomous drive into account. It looked at if and how they change passengers' perception of transparency communication and if new ways of communication are needed. Furthermore, it looked at the influence on the UX, perceived feeling of safety and control, system understanding, and attitude towards the system.

# 6.1.2 Focus on First-Time Users and Exclusion of Trust and Secondary Tasks

The literature discussion in chapter 2 and the focus groups have revealed that individuals express a wide range of concerns regarding AD. These concerns have the potential to deter them from using an AV altogether. Moreover, if they decide to give an AV a try, a negative initial experience could permanently discourage them from using one in the future (compare Hassenzahl and Tractinsky (2006); Kahneman et al. (1999)). Consequently, this thesis' main focus lies on first-time users of AVs. The aim is to create positive experiences by focusing on transparency, safety, control, and understanding, to enable the adoption and acceptance of this new mode of transportation. Given this focus on first-time users, it was decided to exclude research regarding trust. Trust in a system is significantly influenced by the amount of time a user spends interacting with it, as shown by recent studies that have examined the impact of repeated interactions with intelligent systems on trust levels (Rossi et al., 2020; Van Maris et al., 2017). As this thesis specifically focuses on first-time users, this led to the decision not to focus on trust research, as drawing reliable conclusions from one-time tests would be challenging. Furthermore, focusing on first-time users led to omitting secondary tasks in the experiment designs to evaluate their experiences accurately. By excluding secondary tasks, it can be better understood

how first-time users interact with and experience the AV without external distractions. This approach allows a more accurate assessment of the initial UX.

# 6.1.3 Sampling Rationale and Justification

This thesis aims to investigate the influence of transparency communication through uni- and multimodal feedback modalities on first-time passengers' UX, perceived feeling of safety and control, and system understanding in SAE Level 5 ac! (ac!). Therefore, a careful sampling strategy was necessary to ensure alignment with the identified research gaps.

Compared to prior research on transparency and user communication in driving automation (e.g., Beattie et al. (2014); Häuslschmid et al. (2017); Large et al. (2019); Wintersberger et al. (2017)), where participant numbers were often limited to 15–30 individuals per study, this thesis sought to balance methodological robustness with practical feasibility. Accordingly, participant numbers were selected to allow for meaningful statistical analysis without overextending available resources, thereby enabling the conduction of multiple complex experiments across different simulation environments. Importantly, a focus was placed on ensuring that participants had no prior experience with AVs to align with the focus on first-time passengers highlighted in the motivation of this thesis and to avoid bias introduced by familiarity.

The sampling across the four experiments was thereby purposefully varied to contrast with previous research practices:

- Experiment 1 (VR Driving Simulator): 22 participants were recruited, focusing on a controlled within-subject design to assess multiple feedback modalities (light, sound, text, world-in-miniature, vibration) in proactive, non-critical driving situations. Although relatively small, the sample size fits the tradition of early-stage exploratory research in new simulation environments and aligns with comparable VR driving studies (e.g., Gruenefeld et al. (2018)).
- Experiment 2 & 3 (Physical Driving Simulator): 40 participants (split into two groups) were involved in a mixed-method within- and between-subjects design. This sample size was intentionally increased compared to typical prior studies to better capture potential differences between various feedback modalities (UI, light, AR, text) and address criticisms regarding the limited generalisability of smaller simulator studies.
- Experiment 4 (WoZ Simulator): A combination of 113 participants online and 8 participants on-site was used. This dual-sampling approach—combining

qualitative richness from small on-site think-aloud sessions with broader validation through online sampling—contrasts previous work where either qualitative depth or quantitative breadth was favoured but rarely both (e.g., Detjen et al. (2020)). It also acknowledges the increasing call within HCI and UX research for triangulated approaches to system evaluation.

Across all experiments, it was ensured that participants were not re-used to maintain the integrity of studying true first-time UXs, addressing a gap where previous transparency studies often overlooked the importance of prior user exposure (compare, for example, Wiegand et al. (2020)). Furthermore, participant recruitment emphasised diversity in age and gender where feasible to improve the ecological validity of the findings.

In sum, the sampling rationale was explicitly designed to contrast previous fragmented approaches by combining methodological depth, participant diversity, and consistent alignment with the core focus on first-time passenger experiences.

# 6.2 Experiment 1: Increasing the User Experience in Autonomous Driving through different Feedback Modalities

This experiment was conducted in 2019 and published at the 26th International Conference on Intelligent User Interfaces in 2021: Increasing the User Experience in Autonomous Driving through different Feedback Modalities (Schneider, Ghellal, Love and Gerlicher, 2021).

The primary objective of this first experiment was to conduct fundamental research on unimodal feedback modalities in the context of transparency communication in AD in different types of driving situations. The study aimed to explore different types of feedback modalities, such as visual or auditory cues, and understand how they influence the passengers' UX, perceived feeling of control, understanding of the AV and their perceived nervousness (Personas: Sarah, Klara and Kareem).

Insights were gained into which cues are most effective. The results obtained from this initial experiment, combined with an ongoing literature review, served as the foundation for the research setup of the second experiment. The findings provided valuable insights into the strengths and weaknesses of different feedback modalities and motivated research on multimodal cue combinations.

# 6.2.1 Driving Situations

In the context of AD, it is important to consider different types of driving situations that can occur. During a workshop with employees of an automotive manufacturer and researchers from a research campus in Germany, different types of general driving situations were developed. These situations can be categorised into four groups: proactive non-critical, proactive critical, reactive non-critical, and reactive critical.

- Proactive non-critical situations refer to scenarios where the AV has sufficient time to react and respond appropriately. These situations do not pose any immediate danger to human health or lives.
- Proactive critical situations occur when the AV has enough reaction time but faces a potentially hazardous situation that could endanger human health or lives.
- Reactive non-critical situations arise when the AV does not have sufficient

reaction time to respond adequately. However, these situations do not pose an immediate risk to human health or lives.

• Reactive critical situations are the most concerning as the AV lacks enough reaction time, and there is a potential danger to human health or lives. To mitigate risk, these situations require urgent and immediate action from the AV.

# 6.2.2 Driving Simulator



Figure 6.1: City scene of the VR prototype.

A Unity-based<sup>1</sup> VR prototype was developed to simulate short driving scenarios in an AV; see Figure 6.1. All assets were purchased from the Unity Asset Store<sup>2</sup>. Testers wore an Oculus Rift S VR headset<sup>3</sup> to experience and fully immerse themselves in the virtual driving scenarios. The prototype's driving examples take place in a single-lane city area. This choice was made because urban driving presents more complex situations than highway driving, involving factors such as pedestrians, crosswalks, traffic lights, and oncoming traffic. In these urban areas, issues concerning AD rather tend to arise (Frison et al., 2019). To address this, providing feedback about driving decisions and thereby creating transparency is proposed to increase the sense of control, understanding of the AV and improve the overall UX.

The VR prototype includes four driving scenes, each representing one of the aforementioned different types of driving situations. In the *proactive non-critical* scenario, a small construction site obstructs the AV's path, requiring it to wait for oncoming traffic to pass before bypassing the site. In the *proactive critical* scenario,

<sup>&</sup>lt;sup>1</sup>https://unity.com/ (Accessed: August 2023)

<sup>&</sup>lt;sup>2</sup>https://assetstore.unity.com/ (Accessed: August 2023)

<sup>&</sup>lt;sup>3</sup>https://www.oculus.com/rift-s/ (Accessed: August 2023)

the AV detects a car attempting to overtake another vehicle in oncoming traffic within a safe distance, prompting it to apply early braking to avoid a dangerous situation. The *reactive non-critical* scenario involves a sudden appearance of a dog behind a parked car running onto the street, requiring the AV to perform an emergency brake. Lastly, in the *reactive critical* scenario, the AV encounters a car in oncoming traffic attempting to overtake without safe distance, requiring an emergency brake to prevent an accident.

# 6.2.3 Feedback Modalities and Design

Five different feedback modalities were created based on the literature review at this time and the input from the expert interviews<sup>4</sup>. These include cues of light, world in a miniature visualisation, text, audio, and vibration, each providing varying levels of information transmission. The aim was to find out how they influence the UX, the perceived feeling of control and understanding of the AV and any potential nervousness of the passengers. At this time, only the research of Häuslschmid et al. (2017) investigated the influence of feedback modalities on the UX in AD in the form of a world in a miniature visualisation. The perceived feeling of control and understanding had not been investigated yet.

# Light



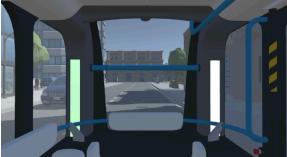


Figure 6.2: Feedback modality light. Left: proactive non-critical, right: proactive critical.

Based on the research on feedback using light cues (Borojeni et al., 2016; Meerbeek et al., 2016) and the concept of continuous feedback (Dingus et al., 1997; Faltaous et al., 2018; Seppelt and Lee, 2007), light bars are located at the front left and right sides of the AV's interior; see Figure 6.2. These light bars adopt a traffic light-inspired

 $<sup>^4{</sup>m Videos}$  can be found under the link in Appendix A.

system to communicate the driving status and reactions. The light bars are designed to emit different colours, each representing a distinct message. A white light indicates that everything is operating normally and that no immediate situations of interest or concern exist. A green light signifies that an obstacle or a driving situation has been detected, but the situation does not require a response from the AV. This could indicate a stationary object or a car passing in the opposite lane. It simply shows that the AV is aware of its surroundings. When a yellow light is displayed, it indicates that an obstacle or a driving situation has been recognised. The AV will react to it and, for example, engage the braking system to mitigate any potential collision. This informs the passenger that the vehicle is taking necessary precautions. Lastly, a red light indicates a dangerous driving situation, like a significant risk of collision, prompting the AV to initiate an emergency braking manoeuvre. This urgent signal alerts everyone in the AV that immediate action is being taken to avoid an accident.

In addition to these indications, the light bars are designed to communicate the direction of events occurring on either the front, left, or right side of the AV. If an event occurs on the front left side, the left light bar changes colour accordingly, providing a localised visual cue. The same applies to events on the front right side, where the right light bar changes colour. Moreover, suppose an event happens directly in front of the vehicle. In that case, both light bars change colour simultaneously, providing a clear and comprehensive indication of a potential hazard ahead.

#### Audio

Based on research from the literature review (compare, for example, Lee et al. (2004); Lewis et al. (2013); Politis et al. (2015b); Salminen et al. (2019)), passengers were exposed to a set of abstract sounds for transparency communication, referred to as auditory icons or earcons (Brewster et al., 1993). These sounds were designed to communicate three types of driving situations that could occur during the AV ride and consisted of different patterns to communicate varying urgencies (Lewis et al., The first earcon, known as "continue drive," is indicated by a brief and calming two-note chime. This sound was intended to convey a sense of relaxation and inform passengers that the AV is continuing its journey without any immediate concerns or changes. In the event of a "reaction" situation, where the AV recognised a specific event or circumstance and needed to respond, a neutral two-note chime was utilised. This sound was deliberately chosen to be non-alarming and neutral to provide passengers with a sense of reassurance that the shuttle is aware of the situation and will take appropriate action. For situations categorised as "warning," which involve potentially dangerous conditions, a sequence of three consecutive beep sounds was employed. These beeps were designed to sound alert and communicate the presence of a hazardous situation that requires immediate attention. This sound aimed to capture passengers' attention (Gang et al., 2018) and prompt them to be prepared for potential risks.

By incorporating these auditory icons, the study aimed to investigate the communication between the AV and its passengers by using abstract sounds. These sounds should provide passengers with a clear and recognisable audio feedback system, enabling them to understand the current state of the AV and its awareness.

#### Visualisation

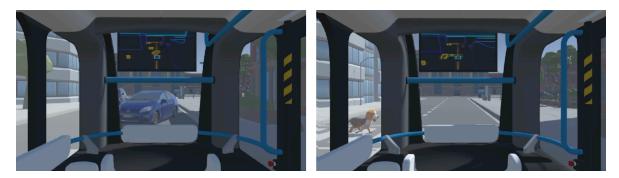


Figure 6.3: Feedback modality world in miniature. Left: reactive critical, right: reactive non-critical.

Based on the literature review and expert interviews, a visual representation inspired by the concept of a world in miniature (Häuslschmid et al., 2017), which is said to improve passengers' UX, is displayed on a screen. This visualisation is designed to provide passengers with valuable information about the AV's awareness and driving relevant objects. Drawing inspiration from the visual representations of the state-of-the-art review used by Tesla (see section 3.1) and Waymo (see section 3.3), this display showcases recognised objects, vehicles, pedestrians, and other relevant elements in the environment; see Figure 6.3. By presenting this information visually, passengers can easily comprehend and match these objects within their surroundings in real-time.

Additionally, the visualisation also includes route information, allowing passengers to have an understanding of upcoming driving directions and turns.





Figure 6.4: Feedback modality text. Left: proactive non-critical, right: reactive non-critical.

#### Text

Based on the literature review, textual feedback cues were designed (compare, for example, Fröhlich et al. (2019); Jarosch and Bengler (2019); Kunze et al. (2018); Telpaz et al. (2017)). This approach is based on the concept of "why-messages" introduced by Koo et al. (2015) and the experiment by Walch et al. (2015) where feedback that includes a reason was favoured. The prototype has four distinct driving situations for which these text messages are designed; see Figure 6.4. When encountering a construction site, the text message "construction site" is displayed to inform passengers about the ongoing roadwork or potential obstacles ahead. During overtaking of oncoming traffic, the message "overtaking" is shown. The text messages take on a more urgent tone in more critical scenarios. When an animal is crossing the road, the message "!!animal!!" is displayed to alert passengers about its presence and the need for caution. Similarly, when there is a risk of encountering a head-on collision due to overtaking of oncoming traffic, the message "!!ghost driver!!" is shown to convey the potential danger of an oncoming vehicle in the wrong lane.

Visually, these text messages are consistently displayed in the same format to ensure familiarity and ease of comprehension for passengers. This standardised presentation aims to help passengers quickly understand the driving situation. By employing these text messages, the vehicle aims to provide well-understandable information to passengers. Other than the abstract feedback modalities above, the textual modality displays the reason for the AV's reactions.

## Vibration

Based on the research in the literature review (see, for example, Ho et al. (2007); Huang et al. (2019); Lee et al. (2004); Politis et al. (2013); Telpaz et al. (2017)), vibrations in the seat are employed as an abstract way of communication to convey



Figure 6.5: The vibration motor was installed in the small metal tube and controlled via the Arduino Uno.

different driving situations. So far, vibrotactile cues have only been used for warning or TORs cues. For lower urgency situations, lower impulses were used and vice versa (Lewis et al., 2013).

For proactive situations, the seat vibrates three times consecutively. Each vibration lasts approximately 0.3 seconds, providing a distinct and noticeable pattern. This vibrating pattern serves as information to passengers about an upcoming driving situation. In reactive situations, the seat vibrates six times in a rapid sequence. The duration of each vibration is shorter, lasting around 0.1 seconds. This rapid and intense vibrating pattern is designed to capture passengers' attention and indicate an immediate reaction of the AV. These vibration patterns aim to provide passengers with a tactile feedback mechanism that abstractly communicates proactive and reactive driving situations.

Besides the vibrotactile one, all feedback modalities are incorporated into the virtual world of the VR prototype. The vibration is achieved using a vibration motor connected to an Arduino Uno<sup>5</sup>, which communicates directly with the Unity prototype. The

<sup>&</sup>lt;sup>5</sup>https://store.arduino.cc/products/arduino-uno-rev3 (Accessed: August 2023)

motor is placed inside a small metal tube that rests on the seating surface, under the participants' thighs, providing tactile feedback, see Figure 6.5.

# 6.2.4 Experiment

# Study Design

In this experiment, a mixed-method within-subjects design was employed. Each participant experienced all feedback modalities with all four driving situations. To ensure balance and minimise order effects, a Latin square design was used to counterbalance the sequence in which the feedback modalities were presented.

All participants in the study were first-time users of an AV and had no prior knowledge or information about the different feedback modalities. The experiment's main objective was to investigate whether unimodal feedback modalities can provide a positive UX by increasing the pragmatic and hedonic qualities during an autonomous ride. Furthermore, the experiment aimed to examine the impact of the different feedback modalities on the passengers' sense of control and understanding of the AV. Additionally, it was examined whether the feedback modalities influence the perceived level of nervousness during the ride.

To measure quantitative data, a questionnaire was administered after each feedback modality. The questionnaire consisted of two parts. The first part included a self-developed 3-item 5-point Likert scale questionnaire measuring the perceived control, understanding, and how nerve-racking the ride is, with the third question being reverse-scored to avoid response patterns, see Table 6.1. The second part utilised the UEQ-S (Schrepp et al., 2017), a standardised questionnaire, to assess the participants' experience during the rides.

In addition to the questionnaire, qualitative feedback was collected by asking the participants to think aloud during the tests. Furthermore, after each test, an unstructured interview was conducted with each participant to gather additional insights and perspectives.

Once the participants had experienced all different feedback modalities, they were asked to indicate their preferred feedback modality for each driving situation. They were also asked to select their theoretically preferred pair of feedback modalities for each situation, getting a first indication for multimodal combinations of modalities.

Table 6.1: Self-developed 5-point Likert scale questionnaire for the experiment.

- 1) During the drive, I had the feeling to keep control.
- 2) I understand why the shuttle acted the way it did.
- 3) The drive was nerve-racking.

# Hypotheses

Four hypotheses were examined in the experiment:

 $H_1$ : Providing information about autonomous driving through unimodal feedback modalities in different driving situations creates a positive user experience compared to receiving no such feedback.

**H<sub>2</sub>:** Providing information about autonomous driving through unimodal feedback modalities in different driving situations increases the passenger's feeling of control compared to receiving no such feedback.

**H<sub>3</sub>:** Providing information about autonomous driving through unimodal feedback modalities in different driving situations increases the understanding of an autonomous vehicle compared to receiving no such feedback.

 $\mathbf{H_4}$ : Providing information about autonomous driving through unimodal feedback modalities in different driving situations makes an autonomous ride less nerve-racking compared to rides without such feedback.

#### **Participants**

The study involved a sample of 22 participants, with 12 of them being female and ten male. The participants' ages ranged from 21 to 36 years (M=28.36, SD=4.04). All participants held a valid driver's license. Among the participants, 12 reported having prior experience with shared mobility. Additionally, 9 participants had experience with ADAS and CAD, indicating some level of exposure to vehicles with autonomous features. To ensure that visual impairments did not influence the results, all participants reported having a normal or corrected-to-normal vision. The entire test session lasted approximately one hour, allowing sufficient time for participants to experience and provide feedback on the different driving situations and feedback modalities.

# Procedure

Following an introductory session covering the test topic and a demographic questionnaire, the testers were provided with a brief tutorial on how to use the VR prototype. Through the VR experience, they were virtually seated in the AV and

introduced to the various feedback modalities. Next, the participants went through all five feedback modalities and a baseline scenario with no feedback. Each of them included all four types of driving situations. The order in which they experienced the situations and feedback modalities was randomised to minimise potential order effects. During the drives, the testers were instructed to focus solely on the ride and were not subjected to any distractions. The testers were asked to complete the questionnaire after each feedback modality. This allowed them to provide feedback and insights regarding their experiences with each feedback modality and the corresponding driving situations.

# 6.2.5 Results

The following subsection presents the results of the UEQ-S and the self-defined 3-item questionnaire. Furthermore, statements and observations obtained through the think-aloud method and the unstructured interviews conducted after each test session are reported. This qualitative data provides additional depth and context to the participants' experiences and the results of the questionnaires. Lastly, an analysis of the feedback modality ratings provided by the participants and their desired imaginary modality pairs are presented.

# User Experience Questionnaire Short (UEQ-S)

In order to test the Hypothesis H<sub>1</sub>, the data from the UEQ-S was analysed. The results are presented in Figure 6.6. To assess the reliability of the measurements, Cronbach's alpha coefficient was calculated (Cronbach, 1951). The UEQ-S provides a scale for evaluating UX, where values above 0.8 indicate a positive evaluation and values below -0.8 indicate a negative evaluation. These values were compared across the different feedback modalities.

Starting with the no-feedback baseline, the participants rated it as having a neutral PQ with a positive tendency (M=0.55,  $\alpha$ =0.77). The HQ was also rated as neutral with a negative tendency (M=-0.40,  $\alpha$ =0.86). The overall score for the no-feedback baseline is also neutral (M=0.07).

Moving on to the feedback modalities, the participants rated the feedback modality light with a positive PQ (M=2.05,  $\alpha$ =0.94), a neutral HQ with a positive tendency (M=0.63,  $\alpha$ =0.91) and an overall positive score (M=1.34).

Similarly, the feedback modality sound was rated positively for PQ (M=1.19,  $\alpha$ =0.88) and neutral for HQ with a negative tendency (M=-0.35,  $\alpha$ =0.93). The overall score for this modality was also neutral (M=0.42).

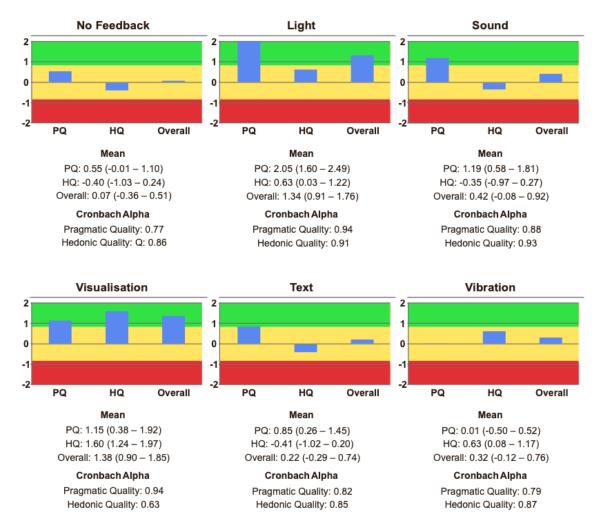


Figure 6.6: Results of the UEQ-S regarding the different feedback modalities. The values within brackets represent the lower and upper 95% confidence intervals.

The visualisation feedback modality world in miniature received positive ratings for both PQ (M=1.15,  $\alpha$ =0.94) and HQ (M=1.60,  $\alpha$ =0.63). The overall score is positive (M=1.38).

For the feedback modality text, participants rated it positively for PQ (M=0.85,  $\alpha$ =0.82) and neutral for HQ with a negative tendency (M=-0.41,  $\alpha$ =0.85). The overall score for this modality is neutral (M=0.22).

Lastly, the feedback modality vibration received neutral ratings for both PQ (M=0.01,  $\alpha$ =0.79) and HQ with a positive tendency (M=0.63,  $\alpha$ =0.87). The overall score is neutral (M=0.32).

In summary, the analysis of the UEQ-S data reveals that the various feedback modalities were rated differently by participants. The light and visualisation feedback modalities were generally perceived positively, while sound, text, and vibration

feedback modality	$M_{\text{no-feedback}}$	${ m M_{feedback}}$	p
no feedback – light	0.07	1.34	<.0001
no feedback – sound	0.07	0.42	0.024
no feedback – visualisation	0.07	1.38	<.0001
no feedback – text	0.07	0.22	0.19
no feedback – vibration	0.07	0.32	0.13

Table 6.2: Statistical analysis of UEQ-S results through Wilcoxon Signed Rank test.

modalities received neutral evaluations.

Subsequently, statistical differences between the data were calculated. As the data was not normally distributed, the Wilcoxon Signed Rank test was used. The results can be seen in Table 6.2. The feedback modalities using light and visualisation created a positive and significantly better UX compared to the no-feedback baseline. The modalities using sound, text and vibration created a neutral UX and were not significantly better than the no-feedback baseline. Therefore, Hypothesis  $H_1$  can partly be accepted.

# Perceived Feeling of Control, Understanding and Nervousness

To assess the validity of hypotheses H<sub>2</sub>, H<sub>3</sub>, and H<sub>4</sub>, a Wilcoxon Signed Rank test was employed, as the data were not normally distributed, to compare each feedback modality against the no-feedback baseline. The results can be seen in Table 6.3.

Among all the feedback modalities, only the light feedback modality yielded a significant increase in the testers' feeling of control during the ride ( $M_{\text{no-feedback}}=1.09$ ,  $M_{\text{light}}=2.23$ , p<.05). The visualisation feedback modality world in miniature was on the edge of being significant ( $M_{\text{no-feedback}}=1.09$ ,  $M_{\text{visualisation}}=1.91$ , p=0.05). Therefore, Hypothesis  $H_2$  can partly be accepted.

Regarding understanding the shuttle's actions, none of the feedback modalities demonstrated any significant improvement compared to the no-feedback baseline. Contrary, the vibration modality significantly decreased the passengers' understanding of the AV's actions ( $M_{\text{no-feedback}}=3.55$ ,  $M_{\text{vibration}}=2.95$ , p<.05). Therefore, Hypothesis  $H_3$  cannot be accepted.

Furthermore, regarding the nerve-racking aspect of the drive, vibration was the only unimodal feedback modality that showed significance. It made the drive significantly more nerve-racking compared to the no-feedback baseline (reverse-coded,  $M_{\text{no-feedback}}=2.64$ ,  $M_{\text{light}}=1.77$ , p=<.05). Therefore, Hypothesis H<sub>4</sub> cannot be

accepted.

In summary, the results indicate that only the light feedback modality significantly enhanced the testers' feeling of control. Vibration feedback, on the other hand, had significant negative effects on understanding the AV's actions and increased the nerveracking nature of the drive. These findings will be contrasted with the qualitative data of the experiment in the discussion section.

Table 6.3: Results of the self-developed 3-item questionnaire analysed through Wilcoxon Signed Rank test.

Question 1: During the drive, I had the feeling to keep control. (1 – disagree, 5 – agree)

feedback modality	$M_{\text{no-feedback}}$	${ m M}_{ m modality}$	p
${\rm no~feedback-light}$	1.09	2.23	<.05
${\rm no~feedback-sound}$	1.09	1.64	0.16
no feedback - visualisation	1.09	1.91	0.05
${\rm no~feedback-text}$	1.09	1.41	0.38
${\rm no\ feedback-vibration}$	1.09	1.50	0.26

Question 2: I understand why the shuttle acted the way it did. (1 – disagree, 5 – agree)

feedback modality	$M_{\text{no-feedback}}$	${ m M}_{ m modality}$	p
${\rm no~feedback-light}$	3.55	3.50	0.85
${\rm no~feedback-sound}$	3.55	3.23	0.21
no feedback – visualisation	3.55	3.23	0.31
${\rm no~feedback-text}$	3.55	3.68	0.52
${\rm no\ feedback-vibration}$	3.55	2.95	<.05

Question 3: The drive was not nerve-racking (reverse coded). (1 – disagree, 5 – agree)

•		0 (	/ \	,	_	,	,
feedback modality	$M_{\text{no-feedback}}$	${ m M}_{ m modality}$	p				
no feedback – light	2.64	2.64	1.0				
${\rm no~feedback-sound}$	2.64	2.32	0.27				
no feedback – visualisation	2.64	2.86	0.47				
${\rm no~feedback-text}$	2.64	2.45	0.53				
no feedback – vibration	2.64	1.77	<.05				

# Correlation with User Experience

Subsequently, the Pearson Correlation was calculated to see if the perceived feeling of control, understanding of the AV or nervousness is correlating with the passengers' UX. For all results, see Table 6.4.

Regarding the perceived feeling of control, the results of the Pearson correlation indicate a significant, large positive relationship for the HQ for the no-feedback baseline (r(20) = .565, p = .006). And a significant, very small negative relationship

Table 6.4: Pearson Correlations between the UX and the perceived feeling of control, understanding of the AV and passengers' nervousness.

Correlation Control with UX						
$\mathbf{U}\mathbf{X}$	$\mathbf{no} ext{-}\mathbf{feedback}$	$\mathbf{light}$	sound	visualisation	$\mathbf{text}$	${f vibration}$
PQ	r=239	r=018	r = .391	r=435	r=289	r =372
ΓQ	p = .285	p = .938	p = .072	p=.043	p = .191	p = .088
HQ	r = .565	r=233	r = .045	r=347	r = .031	r=292
11Q	p=.006	p = .297	p = .841	p = .114	p = .892	p = .188
Total	r = 262	r =174	r = .268	r=484	r =149	r=394
Total	p = .238	p = .440	p = .228	p=.022	p = .510	p = .069
		Correlation	ı Understa	anding with UX		
$\mathbf{U}\mathbf{X}$	$\mathbf{no} ext{-}\mathbf{feedback}$	$\operatorname{light}$	sound	visualisation	$\operatorname{text}$	$\mathbf{vibration}$
PQ	r=437	r =759	r=363	r=353	r=028	r = .010
1 Q	p=.042	p < .001	p = .097	p = .107	p = .903	p = .965
HQ	r = .234	r=307	r =065	r=443	r = .282	r =168
110	p = .295	p = .165	p = .773	p=.039	p = .204	p = .454
Total	r=107	r =613	r =263	m r= $455$	r = .150	r =098
Iotai	p = .635	p = .002	p = .238	p=.033	p = .506	p = .664
		Correlation	on Nervous	sness with UX		
$\mathbf{U}\mathbf{X}$	no-feedback	$\operatorname{light}$	sound	visualisation	$\mathbf{text}$	vibration
$\mathbf{PQ}$	r=477	r =112	r = .216	m r=597	r =148	r =108
1 &	p=.025	p = .621	p = .333	p=.003	p = .512	p = .633
HQ	r = .285	r =213	r = .112	r =316	r = .159	r = .246
1102	p = .199	p = .343	p = .620	p = .152	p = .479	p = .269
Total	r=095	r=209	r = .202	r =603	r = .009	r = .090
Iotai	p = .675	p = .352	p = .369	p=.003	p = .969	p = .691

for the PQ (r(20) = .435, p = .043) and overall UX (r(20) = .484, p = .022) for the visualisation modality.

Regarding the understanding of the AV, the results of the Pearson correlation indicate a significant, very small negative relationship for the PQ for the no-feedback baseline (r(20) = .437, p = .042). Furthermore, results indicate a significant, very small negative relationship for the PQ (r(20) = .759, p < .001) and overall UX (r(20) = .613, p = .002) for the light feedback modality. And a significant very small negative relationship for the HQ (r(20) = .443, p = .039) and overall UX (r(20) = .455, p = .033) for the visualisation modality.

Regarding passengers' nervousness, the results of the Pearson correlation indicate a significant, very small negative relationship for the PQ (r(20) = .477, p = .025). And a significant very small negative relationship for the PQ (r(20) = .597, p = .003) and overall UX (r(20) = .603, p = .003).

# Concurrent Think Aloud and Unstructured Interview

This subsection reports the participants' think-aloud and interview statements.

For the light modality, the feedback from 13 testers indicated that they liked red as a warning colour. 12 testers felt that the green light was unnecessary and could be omitted. However, 7 testers found the green light understandable and effective. Moreover, 12 test subjects reported that the light's ability to distinguish objects on the left, right, or in front of the car worked well.

Moving on to the sound modality, 10 testers expressed that the sounds used were annoying and would become unpleasant over time. 3 liked the "continue drive" sound, while 3 did not. In contrast, 7 of the test subjects appreciated the warning sound.

Regarding the world in miniature visualisation, 7 testers suggested including some form of highlight in the visual representation. For instance, they proposed highlighting an overtaking car or an animal in red. Additionally, 6 test subjects desired to see the AV's intentions displayed in the visualisation. Of those 6, 3 testers specifically mentioned the preference for combining the visualisation with textual information. Furthermore, 7 testers reported feeling the need to constantly compare the visualisation to the real world, finding it reassuring to see what the AV sees.

Regarding the text modality, 6 testers considered it redundant and unnecessary, indicating that it did not provide any additional value compared to the real-world situation. Contrary, 3 testers expressed the desire for the reasons behind the vehicle's actions and its next course of action to be displayed. Additionally, 6 testers found that the text took too long to read and comprehend. Contrary, 2 testers mentioned that they felt the text contained insufficient information. Meanwhile, 10 testers wished for a highlight system, such as a traffic light colour metaphor, to indicate the level of risk in a given situation.

Lastly, when it comes to the vibration modality, 11 testers found it annoying and unpleasant. Four testers specifically mentioned that the vibration feedback created a sense of urgency or the need to take action, even though they were unable to do so as the AV was in control. Moreover, 3 testers found the vibration feedback difficult to understand or interpret.

To summarise, the distinction between objects via light was generally well-received. In terms of sound, some testers found the sounds annoying, while others liked the warning sound. Testers suggested highlighting certain elements in the visualisation and displaying the AV's intentions. The text modality received mixed feedback, with some testers considering it redundant and others wanting more information. The vibration modality was generally disliked and seen as unnecessary, stressful or confusing.

# Feedback Rating and Desired Pairs

This subsection presents the participants' favourite feedback modalities per driving situation and their theoretically desired feedback modality pairs per driving situation.

Looking at the results of Table 6.5, it is evident that among the various feedback modalities, light was the most preferred choice for proactive situations. Following light, the visualisation emerged as the second most favoured modality for proactive situations. In contrast, sound was the preferred feedback modality for reactive situations where immediate response and reaction were necessary. Light was the second most preferred choice for reactive situations.

Table 6.6 provides insights into the feedback modality pairs that testers would choose if given the opportunity. In proactive situations, testers expressed a preference for the combination of light and visualisation. Additionally, testers desired pairing visualisation and text for non-critical situations in proactive scenarios. In reactive situations, testers indicated a preference for the combination of light and sound. Additionally, the pairing of light and vibration was also desired.

Overall, the findings highlight the varying preferences for feedback modalities in different situations, with light, visualisation, sound, and text being the most commonly favoured options.

	Proact. Non-Crit.	Proact. Crit.	React. Non-Crit.	React. Crit.
Light	10	13	6	7
Sound	1	0	8	8
Visualisation	8	7	2	1
Text	3	2	1	1
Vibration	0	0	5	5

Table 6.5: Votes of favourite feedback modality per driving situation.

# 6.2.6 Discussion

When examining the results for hypothesis  $H_1$ , it becomes evident that providing feedback through different modalities can significantly enhance the passengers' UX

	Proact. Non-Crit.	Proact. Crit.	React. Non-Crit.	React. Crit.
Light – Sound	2	4	8	8
Light – Visual.	8	7	2	1
$\operatorname{Light}-\operatorname{Text}$	2	4	2	2
Light – Vibration	0	1	6	6
Sound – Visual.	1	0	0	1
Sound – Text	1	0	2	2
Sound – Vibration	0	0	1	1
Visual. – Text	8	5	0	0
Visual. – Vibration	0	1	1	1
Text – Vibration	0	0	0	0

Table 6.6: Votes of desired feedback modality pairs per driving situation.

compared to a no-feedback baseline. However, not all feedback modalities led to a positive UX, and not all PQ and HQ scores were higher than the baseline.

The modalities sound, text, and vibration showed neutral overall scores.

Sound had a positive PQ but a negative HQ, which could be explained with testers' feedback that the sounds could be annoying in the long run (10 mentions). The positive PQ may be explained by participants' statements that they liked the "continue drive" (3) and warning sound (7), possibly perceiving them as pragmatic.

Text had the lowest overall score of the five modalities possibly due to being considered redundant (6), hard to comprehend quickly (6) and lacking some sort of highlighting system (10).

Vibration had a low overall score and a lower PQ than the baseline possibly due to being deemed annoying and confusing by testers (11). Furthermore, they stated that it created a sense of urgency for them while at the same time they could not take any action (4). This is understandable, as the modality was derived from designs concerning driver warnings and TORs which require the driver to take action.

On the other hand, light and visualisation were found to create a positive UX. This was also confirmed by Löcken et al. (2020) and Dandekar et al. (2022). Light had a high positive PQ score, possibly explained through the well working directional differentiation (12), but a neutral HQ possibly due to the unnecessary green light (12).

The visualisation had positive scores for both PQ and HQ, even though participants wished for some sort of highlighting system (7), with testers finding it helpful and reassuring to see what the AV sees (7). This result confirms the research of Häuslschmid et al. (2017) regarding the positive effect of a world in miniature visualisation on the passengers' UX in AD.

Hypothesis H<sub>2</sub>, suggesting that unimodal feedback modalities increase the feeling of control, was only supported for the light modality, which led to a significantly increased result. The visualisation showed a p-value close to significance. Furthermore, it could be shown that there is a significant, very small negative relationship between the perceived feeling of control and the PQ and overall UX for the visualisation modality. As the perceived feeling of control decreases, the UX tends to be slightly worse for the visualisation modality. Interestingly, there also is a significant, large positive relationship between the feeling of control and the HQ for the no-feedback baseline. As the feeling of control increases, the HQ tends to be higher, suggesting that when users perceive a greater sense of control in a situation where no feedback is given, they tend to experience more pleasure or enjoyment.

Hypothesis H<sub>3</sub>, proposing that unimodal feedback enhances understanding of the AV's actions, was not proven true. Vibration even significantly reduced understanding. Testers' feedback about vibration being annoying and unpleasant (11) and sometimes difficult to understand (3) supports this result.

It is possible that the feedback modalities were unable to enhance understanding due to the inherent clarity of the situations, where the AV's actions may have been evident to the passengers even without additional feedback. However, there seems to be a significant, very small negative relationship between the understanding and the PQ for the sound modality, as well as between the understanding and the PQ and overall UX for the light modality and HQ and overall UX for the visualisation modality. As the understanding decreases, the UX tends to be slightly worse for some feedback modalities.

Hypothesis H<sub>4</sub>, suggesting that unimodal feedback reduces the nerve-racking aspect of an autonomous ride, was not supported either. Again, the vibration modality had a significant negative impact, possibly for similar reasons as mentioned before. Regarding correlations, there seems to be a significant, very small negative relationship between the passengers' nervousness and the PQ for the no-feedback baseline and between the nervousness and the PQ and overall UX for the visualisation modality. This indicates that increased nervousness tends to slightly reduce the UX in AD.

The participants' votes regarding their favourite feedback modalities depending on the driving situation shows that they preferred softer feedback for proactive situations (light and visualisation) and more prominent feedback for reactive situations (sound and light), aligning with previous findings (Politis et al., 2015b). Light was consistently favoured. Although sound did not create a positive UX, testers still preferred it for proactive situations, possibly due to is pragmatic attributes.

When examining the desired feedback modality pairs, testers preferred light combined with visualisation and visualisation combined with text for proactive situations. This aligns with their think-aloud statements and the positive UX indicated by the UEQ-S results. For reactive situations, testers preferred more noticeable feedback, such as extending light with sound or vibration, despite sound and vibration not creating a positive UX. This could be due to the fact that a positive UX is not salient for passengers in critical situations. This is supported by testers acknowledging that vibration is annoying but still desiring it for reactive situations.

In conclusion, providing feedback through light or visualisation enhances the UX of passengers in AVs. Furthermore, light significantly increases the perceived feeling of control, and visualisation shows the potential for the same effect. Unimodal feedback did not significantly improve the understanding of the AV or reduce the nerve-racking aspect of its ride, with vibration even having a negative impact. Furthermore, some very small correlations between variables could be shown, and one large significant relationship indicates that when users perceive a greater sense of control in a situation where no feedback is given, they tend to experience more pleasure or enjoyment. Test subjects desired softer feedback for proactive situations and more prominent feedback for reactive ones. Considering different feedback modalities based on the type of situation could be beneficial. The mixed-method approach helped confirm and explain the questionnaire results.

# 6.2.7 Limitations

The experiment had several limitations. Firstly, using a VR prototype meant that the participants did not experience the physical sensations of g-forces and real danger that would be present in a real-world driving scenario. This lack of physical feedback could potentially impact their reactions and behaviour.

Furthermore, the digital world created may not have provided a fully immersive experience due to limitations in graphics and sound. However, it is worth noting that participants exhibited signs of immersion, as they were scared by the dangerous overtaking situation.

Another limitation of the study was the restriction to participants with an average age of 28. This narrow age range may limit the generalisability of the findings to a broader population, as different age groups may have different reactions and preferences when it comes to AD experiences.

# 6.2.8 Conclusion & Outlook

This experiment aimed to investigate the effectiveness of various unimodal feedback modalities in improving the UX in AD through transparency communication. The impact of light, sound, visualisation, text, and vibration feedback on passengers' perception of control, understanding of the AV's actions, and overall nervousness during the ride was examined.

The results show that, in general, the presence of feedback modalities can improve the UX compared to a scenario with no feedback at all. However, only light and visualisation modalities were able to create a positive UX. Furthermore, light feedback had a significant effect on enhancing the participants' feeling of control, while visualisation feedback showed promising results in this aspect as well.

Interestingly, the feedback modalities did not significantly improve the passengers' understanding of the AV's actions or reduce their nervousness levels. Vibration feedback even had a negative impact on both of these factors. This suggests that the choice of feedback modality is crucial. Tactile feedback was useful in warning and TORs research but not for AD due to the inability of the passenger to intervene. Therefore, the following experiments excluded vibrotactile feedback modalities.

The study also revealed that passengers preferred softer and less intrusive feedback modalities for proactive driving situations, where the vehicle anticipates and responds to potential hazards. On the other hand, more prominent feedback modalities were desired for reactive situations, where the vehicle reacts to unexpected events. This finding highlights the importance of tailoring the feedback modalities to specific driving situations to optimise the UX.

The next experiment explores multimodal feedback modalities to investigate further their impact on passengers' understanding of the AV's actions and their implications for the overall UX during autonomous rides.

# 6.3 Experiment 2: Explain Yourself! Transparency for Positive UX in Autonomous Driving

This experiment was conducted from 2019 to 2020 and published in the Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems: Explain Yourself! Transparency for Positive UX in Autonomous Driving (Schneider, Hois, Rosenstein, Ghellal, Theofanou-Fülbier and Gerlicher, 2021).

The primary objective of the second experiment was to investigate the effectiveness of different multimodal feedback modalities in different driving situations within the context AD. Furthermore, the impact of live and retrospective information was examined. Insights from the first experiment, the literature review, and expert interviews were used to design the experiment.

The experiment focused on two types of feedback: live feedback during the ride and retrospective feedback after the ride. Live feedback combined the modalities light, text, and AR object highlighting to convey information to the passengers in real time. Retrospective feedback was provided through on-device cues after the ride.

The experiment aimed to gain insights into how these multimodal feedback modalities influenced the passengers' overall UX, their understanding of the AV, and their perceived feeling of safety and control (Personas: Sarah, Klara and Kareem). Additionally, the experiment examined the influence of when transparency communication is displayed. This aspect allowed assessing whether the timing of providing transparency communication during the ride has any significant impact on passengers.

Overall, the second experiment provided valuable insights into the effects of different multimodal feedback modalities in transparent communication during AD. Furthermore, insights for the other two experiments were provided.

# 6.3.1 Driving Scene

A 8:44 minutes long driving scene through Stuttgart, Germany was recorded with three GoPro Hero 5<sup>6</sup> cameras filming to the front and sides of the vehicle. The ride intended to capture common urban driving situations. Eight main situations were captured, two of them were scripted:

 $<sup>^6 \</sup>mathrm{https://gopro.com/}$  (Accessed: August 2023

- 1. There is a construction site in front of a traffic light where the lane that continues straight abruptly comes to an end. The AV has to switch lanes.
- 2. A person walks across the road before the AV.
- 3. A bike is moving at a slow pace ahead of the AV on the road (scripted).
- 4. A delivery driver appears behind their van and crosses the road in front of the AV.
- 5. A vehicle in oncoming traffic takes the ride of way.
- 6. A delivery driver on the oncoming lane opens their door and enters the truck.
- 7. A vehicle attempts to parallel park, the AV has to reverse (scripted).
- 8. A person opens the door of their parked car. The AV has to avoid it.

# 6.3.2 Driving Simulator

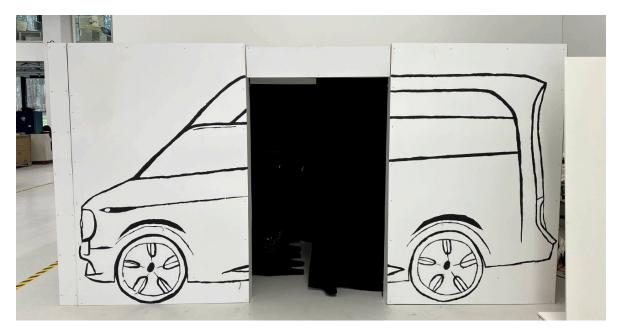


Figure 6.7: Outside of the stationary driving simulator.

A stationary driving simulator was utilised for the experiment, see Figure 6.7. This simulator was designed to replicate the experience of being inside an AV. It consisted of four car seats arranged in a configuration similar to an actual vehicle. To create a realistic driving environment, a large screen was positioned in front, serving as the windshield, while four smaller screens acted as windows on the sides.

The simulator could display recorded footage captured by the three GoPro cameras. This footage was synchronised and played back on all screens, providing participants with a comprehensive view of the simulated autonomous drive. The intention was to immerse participants in a realistic driving scenario.

In terms of size, the simulator measured approximately 5 meters in length and 2.2 meters in width. This size resembled a van, allowing participants to enter the simulator from the side like they would with an actual vehicle. This setup aimed to enhance the authenticity of the experience and enable participants to interact with the simulator like a real-world vehicle. To further support this, the outlines of a van were painted on the outside.

# 6.3.3 Feedback Modalities and Design

As mentioned earlier, the experiment, among other things, aimed to research the impact of live- and retrospective transparency communication in AD. For the live feedback communication, a multimodal combination of feedback modalities was designed. For the retrospective feedback, on device cues were used in the form of a smartphone application.

#### Live Feedback



Figure 6.8: LED light strips were installed to the side of the windshield monitor for communication.

Three modalities were combined for the live feedback.

1) LED Strips: They were installed on the sides of the screen that imitated the windshield to provide feedback to participants; see Figure 6.8. These LED strips were designed based on the findings from the first experiment. As participants had expressed that the presence of green colour was unnecessary, the LED lights incorporated only two colours: yellow and red. The purpose of these lights was to indicate the reactions of the AV to different driving situations and the direction of relevant objects. The LED lights would turn yellow when the AV responded to a non-critical driving situation. When the AV reacted to a critical driving situation, the LED lights would change to red.



Figure 6.9: The text modality overlay displayed on the windshield screen. Left: destination and time until arrival. Centre: street name and distance to next driving direction change. Right: current speed limit and current speed of the AV.

2) Text Overlay: To provide passengers with essential driving information and to enhance their understanding of the AV's behaviour, a text overlay was displayed at the bottom of the windshield screen in the simulator; see Figure 6.9. This overlay allowed participants to access important details about their simulated autonomous drive. On the left side of the text overlay, the destination and the estimated time until the AV reaches that destination were displayed. In the centre of the text overlay, the name of the street they were currently on and the distance until the next driving direction change was shown. This feature provided passengers with crucial navigation

information, allowing them to anticipate upcoming turns or manoeuvres. On the right side of the text overlay, the current speed limit and the speed at which the AV was travelling were projected.

3) Augmented Reality: The third modality simulated an AR projection of driving relevant information on the windshield screen, to further increase passengers' understanding of driving situations (Wintersberger et al., 2017), see Figures 6.10 and 6.11. For one part, it was based on the feedback from the expert interviews. (1) The AI researcher's feedback to highlight relevant objects, (2) the input of the Professor for mobility research to not overwhelm with too much information and make the available information quickly graspable and (3) providing different amounts of information depending on the type of situation as suggested by the AI psychology researcher. Furthermore, the AR feedback modality was inspired by research from the literature review. It focussed on forms and symbols that utilise colour and animation as suggested by Kunze et al. (2018) and displayed navigation-relevant information directly onto the road (Kim and Dey, 2009). Furthermore, potential hazards were specially highlighted (Fröhlich et al., 2019).

The AV's driving trajectory was displayed with a teal line which was moved back when an object, for example, a car, blocked the path to let passengers know about the AV's awareness, see Figure 6.10. Furthermore, driving relevant objects were highlighted within the world. For static objects that directly influence the drive, a bounding box was drawn around them combined with an icon and a text describing the object; see Figure 6.10. Moving, driving-relevant objects were highlighted with a triangle. A circle with a small triangle at the bottom indicated their assumed direction of travel; see Figure 6.11. They were highlighted in different colours depending on their relevance to the drive. (1) White: relevant to the drive, but currently, another object is more relevant. (2) Orange: currently relevant to the drive. (3) Red: currently relevant to the drive and potentially creating a hazardous situation.



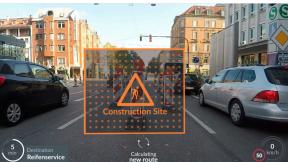


Figure 6.10: Left: the AV's projected driving trajectory (teal) and blocked path (dark teal). Right: AR object highlighting paired with a textual reason.





Figure 6.11: Left: highlighting driving relevant object (orange) and displaying its assumed direction of travel. Right: Highlighting new driving relevant object in red to notify about critical situation and displaying its assumed direction of travel.

# Retrospective Feedback

Mobile App: For the retrospective feedback after the ride via on-device cues, a clickable app mockup was created<sup>7</sup>; see Figure 6.12. In the experiment of Melcher et al. (2015), on-device TORs increased participants' perceived feeling of safety. In this thesis' experiment, the app allowed participants to experience the trip and relevant driving situations again and provided them with explanations. On a map, they could see the travelled route and every relevant driving situation highlighted. This information was also accessible to them via a timeline view. When they decided to click on a driving situation, they received an explanation of the AV's action via text. They further had the opportunity to watch a short video sequence of the driving situation, to remember it better, where the textual explanation was read to them via a text-to-speech voice.

# 6.3.4 Driving Situations

The pre-recorded autonomous drive oriented itself at the length of a typical, german taxi ride (Statistisches Amt, 2016) and was 8:45 minutes long. In total, eight driving scenes occurred that triggered transparency communication.

1. Construction Site: There is a construction site in front of a traffic light, and the lane that continues straight ends. The AV is required to halt and recalculate the route, and the available lanes only permit left or right turns. The LED strip

<sup>&</sup>lt;sup>7</sup>The complete app mockup can be found in Appendix A.

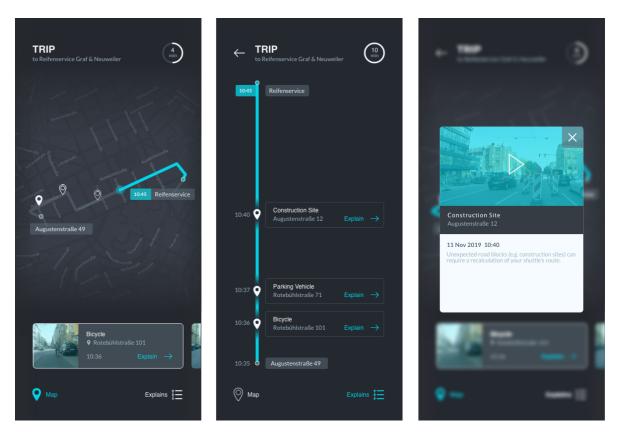


Figure 6.12: Screenshots of the app prototype handed to testers after the autonomous ride. Left: overview of the trip and highlight of relevant driving situations. Centre: timeline view of relevant driving situations. Right: retrospective explanation of relevant driving situation via text and video.

lights change to yellow. The construction site is emphasised with a yellow, squared outline in AR. The size and colour intensity of the anticipated lane changes. A processing status is displayed over the construction site, showing "route changed" with an updated estimated arrival time. The lane visualisation is updated and forms a path around the obstacle. The AV then proceeds to make a right turn.

- 2. **Pedestrian:** A pedestrian crosses the road in front of the AV. The vehicle, already waiting, must pause before resuming its journey. The nearest LED strip light to the pedestrian changes to yellow. A yellow squared outline is put over the pedestrian in AR. The size and colour intensity of the expected lane changes. After the pedestrian has exited the road, all highlights are removed.
- 3. Cyclist: A bicycle is moving slowly in front of the AV. The vehicle must reduce speed and cannot overtake the cyclist. The LED strip lights initially turn red and then change to yellow, alerting the driver to the cyclist's presence. Simultaneously, a yellow squared outline appears around the cyclist in AR. The size and colour intensity of the expected lane changes. Once the cyclist has safely left the road,

all highlights are removed.

- 4. **Delivery Driver:** A delivery truck driver steps onto the road from behind their truck and proceeds to cross the road. The AV must come to a sudden stop. The LED strip lights promptly change to red, indicating the need for the vehicle to stop. The delivery person is highlighted in AR with a distinct red squared outline. The size and colour intensity of the expected lane changes. All highlights are removed once the delivery person safely completes their crossing.
- 5. **Right of Way:** The AVs right of way is violated by another vehicle. It needs to reduce its speed, to let the oncoming traffic pass. The LED strip lights change their colour to yellow. The oncoming vehicle is highlighted in AR with a yellow squared outline. The size and colour intensity of the expected lane change to indicate the vehicle's presence. Once the oncoming vehicle has safely passed, all highlights are removed.
- 6. Open Vehicle Door: A delivery person on the opposite lane opens the driver's door. The AV must come to a stop as the open door creates a narrow passage that cannot be safely passed. The LED strip light in the closest proximity to the delivery person transitions to a yellow colour. The delivery person is highlighted in AR with a distinct yellow squared outline. The size and colour intensity of the expected lane changes to account for the narrowed passage. Once the delivery person closes the door, all highlights are removed.
- 7. Parallel Parking: A vehicle tries to parallel park. Therefore, the AV needs to reverse. The LED strip lights shift their colour to yellow. The other vehicle is highlighted with a yellow squared outline in AR. Furthermore, a processing circle indicates ongoing adjustments and informs about the reversing manoeuvre required. The size and colour intensity of the expected lane changes. Once the other vehicle has completed the parking manoeuvre, all highlights are removed.
- 8. **Open Vehicle Door:** A driver opens the door of their car parked parallel to the road. The AV needs to reduce its speed as it drives past the person at a safe distance. The LED strip light in the closest proximity to the driver transitions to a yellow colour. The driver is highlighted with a distinct yellow squared outline in AR. The size and colour intensity of the expected lane changes. After safely passing the person, all highlights are removed.

# 6.3.5 Experiment

### Study Design

In this experiment, a mixed-method within- and between-subjects design was used. All participants in the study were first-time users of an AV and had no prior knowledge or information about the different feedback modalities. The study aimed to determine whether live feedback through multimodal modalities and retrospective feedback through on-device cues could enhance the overall UX. Furthermore, it was investigated if they can increase passengers' understanding of the AV and their perceived feeling of safety and control. Lastly, it was examined if there is an effect of when to display transparency communication, during the ride or afterwards.

Multiple questionnaires were used to measure quantitative data. For the UX, the UEQ-S was used again. To measure participants' understanding of the AV, questions 4, 5 and 6 of the AVAM questionnaire (Hewitt et al., 2019) were used on a 7-point Likert scale and combined to one variable. Questions 13, 14 and 15 measured their attitude towards using technology. Furthermore, questions 24, 25 and 26 were used for the perceived feeling of safety. For the perceived feeling of control, participants rated the statement "During the ride, I had the feeling to stay in control" on a 7-point Likert scale. The questionnaires were used after the autonomous ride and a second time after participants had experienced the retrospective feedback via on-device cues.

Additionally, following the ride and after experiencing the retrospective feedback, participants were interviewed to obtain qualitative input. They were asked to discuss their emotions throughout the autonomous drive, any uncertain or unsettling driving circumstances, and their interactions with the system, especially regarding the AV's transparency communication. Additionally, they were given the chance to contribute any additional ideas or remarks.

#### Hypotheses

Five hypotheses were examined in the experiment:

 $\mathbf{H_{1.1}}$ : Explaining the AV's behaviour with multimodal feedback modalities during the ride and with on-device cues after the ride increases the perceived feeling of safety.

 $\mathbf{H}_{1.2}$ : Explaining the AV's behaviour with multimodal feedback modalities during the ride and with on-device cues after the ride increases the understanding and ease of use of the AV.

 $\mathbf{H_{1.3}}$ : Explaining the AV's behaviour with multimodal feedback modalities during

the ride makes the ride more interesting.

**H<sub>2</sub>:** Explaining the AV's behaviour with multimodal feedback modalities during the ride and with on-device cues after the ride increases the UX.

 $\mathbf{H_3}$ : Explaining the AV's behaviour with multimodal feedback modalities during the ride and with on-device cues after the ride increases the perceived feeling of control.

# **Participants**

The study included 40 participants, divided into two groups (group A: 10 female, 10 male; group B: 4 female, 16 male), with an average age of 24.65 (SD=4.97). Group A had an average age of 24.6 (SD=4.51), while Group B had an average age of 26.1 The majority of participants (55%) primarily relied on public (SD=5.43).transportation, with the next most common modes of transportation being cars (37.5%), bicycles (5%) and walking (2.5%). 25% of people had no prior experience with autonomous systems, 50% had used cruise control or other forms of driving assistance, 12.5% had used lane assists and other semi-automated systems, 5% had used highly automated driving systems like take-over driving assistants, and 7.5% had used AVs in research settings. A mixture of employees from a German automaker, faculty members and staff from a university, and employees from a research campus made up the study's participants. To mitigate the influence of visual impairments on the findings, all participants confirmed having normal vision or corrected-to-normal vision. The testing session lasted around 30 minutes, giving participants enough time to interact with the system and provide comments. Each participant received a 10 Euro Amazon gift card as compensation for their participation.

# Procedure

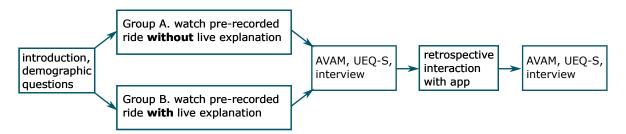


Figure 6.13: Study design of the second experiment.

First, participants were generally introduced to the experiment and filled out a demographic questionnaire regarding age, gender, existing knowledge about AVs and their mobility patterns. Then, the experiment split the participants into two even groups of 20 for the autonomous ride (between-subjects design); see Figure 6.13. The

first group A experienced the pre-recorded ride and was *not* provided with any transparency communication. The second group B was provided with the multimodal feedback modalities for transparency communication. During the ride, participants solely focussed on the ride and did not engage in other tasks. Afterwards, both groups filled out the same questionnaires and conducted the same interview. Then, both groups (within-subjects design) received the retrospective feedback via on-device cues, filled out the same questionnaires, and conducted the same interviews again.

# 6.3.6 Results

This subsection presents the outcomes of the AVAM questionnaire and UEQ-S, along with the self-defined control item. Additionally, statements gathered from the post-interviews are reported. The qualitative data is utilised to offer additional understanding and context to the quantitative data.

# Autonomous Vehicle Acceptance Model Questionnaire

To confirm hypotheses  $H_{1.1}$ ,  $H_{1.2}$ , and  $H_{1.3}$ , the AVAM questionnaire was used. Because the distribution of findings among groups was not normal, instead of employing an ANOVA, the Wilcoxon Signed Ranks test for dependent samples and the Mann-Whitney test for independent samples were utilised. All results can be seen in Table 6.7. The internal consistency of the variables was assessed by calculating Cronbach's Alpha coefficient.

Hypothesis  $H_{1.1}$  - Increased Perceived Feeling of Safety: The data reveals no significant variations among the different groups. Consequently, there is no evidence available to support the Hypothesis  $H_{1.1}$ .

Hypothesis  $H_{1.2}$  - Increased Understanding and Ease of Use: The mobile app significantly impacted the perceived ease of use and understanding of the system. This effect was observed in group A, which was not provided with live explanations  $(A_{\text{drive}}=5.15, A_{\text{app}}=5.93, p<.01)$ . However, the mobile app did not significantly affect group B, where live explanations were given. Additionally, a significant difference was observed between the groups while they were driving  $(A_{\text{drive}}=5.15, B_{\text{drive}}=5.82, p<.05)$ . Overall, group B gave the system's ease of use and understanding a better rating than group A. The mobile application comparison between the groups did not produce statistically significant findings. Therefore, Hypothesis  $H_{1.2}$  can partly be accepted.

Hypothesis  $H_{1.3}$  - Increased Interest: The data indicates that there are no

Table 6.7: Results of the AVAM items. Group A was not provided with live feedback during the drive.

# Perceived Safety (Items 24, 25, 26)

Cronbach's  $\alpha:0.871$ 

	$A_{ m drive}$	$A_{\mathrm{app}}$	$\rm B_{drive}$	$\rm B_{app}$	
values	5.23	5.30	5.45	5.62	
SD	1.30	1.53	1.14	1.23	
p	.18	.1865		.136	
	${ m A_{drive}}$	${ m B_{drive}}$	${f A_{app}}$	${ m B_{app}}$	
values	5.23	5.45	5.30	5.62	
SD	1.30	1.14	1.53	1.23	
p	.34	105	.36	15	

# Effort Expectancy (Items 4, 5, 6)

Cronbach's  $\alpha : 0.8$ 

	${f A_{drive}}$	${f A_{app}}$	${ m B_{drive}}$	${ m B_{app}}$	
values	5.15	5.93	5.82	6.05	
SD	1.19	1.12	0.86	0.81	
p	.00	$\boldsymbol{.0025}$		.1175	
	${f A_{drive}}$	${ m B_{drive}}$	$\mathbf{A}_{\mathbf{app}}$	${ m B_{app}}$	
values	5.15	5.82	5.93	6.05	
$\operatorname{SD}$	1.19	0.86	1.12	0.81	
p	.04	195	.48	35	

# ${\bf Attitude\ Towards\ Using\ Technology}\ ({\rm Items}\ 13,\ 14,\ 15)$

Cronbach's  $\alpha: 0.769$ 

	$\mathbf{A_{drive}}$	${ m A_{app}}$	${ m B_{drive}}$	${ m B_{app}}$	
values	4.17	4.33	4.55	4.60	
SD	1.38	1.45	1.44	1.38	
p	.2	.251		.312	
	$\mathbf{A_{drive}}$	${ m B_{drive}}$	${f A_{app}}$	${ m B_{app}}$	
values	4.17	4.55	4.33	4.60	
SD	1.38	1.44	1.45	1.38	
p	.20	04	.24	85	

significant differences in this variable across the groups. Therefore, Hypothesis  $H_{1.3}$  is not supported by any evidence.

# User Experience Questionnaire Short (UEQ-S)

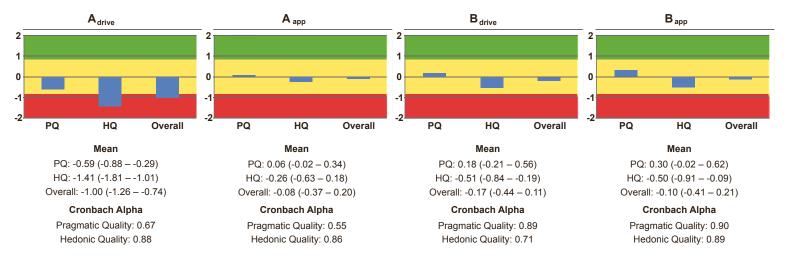


Figure 6.14: Results of the UEQ-S. Group A was not provided with live feedback during the drive.

To test Hypothesis H<sub>2</sub>, the data of the UEQ-S were analysed; see Figure 6.14. According to the UEQ-S criteria, values above 0.8 indicate a positive evaluation, while values below -0.8 indicate a negative evaluation. Values in between are neutral. The internal consistency of the results was assessed using the Cronbach's alpha coefficient.

Participants provided ratings for different scenarios: the drive without live explanations ( $A_{drive}$ ), the smartphone app after the drive without live explanations ( $A_{app}$ ), the drive with live explanations ( $B_{drive}$ ), and the smartphone app after the drive with explanations ( $B_{app}$ ).

For  $A_{drive}$ , participants rated the PQ as neutral with a negative tendency (M=-0.59,  $\alpha$ =0.67), the HQ as negative (M=-1.41,  $\alpha$ =0.88), resulting in an overall negative score (M=-1.00).

For  $A_{app}$ , participants rated the PQ as neutral (M=0.06,  $\alpha$ =0.55), the HQ as neutral with a negative tendency (M=-0.26,  $\alpha$ =0.86), leading to an overall neutral score (M=-0.08).

For  $B_{drive}$ , participants evaluated the PQ as neutral (M=0.18,  $\alpha$ =0.89) and the HQ as neutral with a negative tendency (M=-0.51,  $\alpha$ =0.71), resulting in a neutral overall score (M=-0.17).

For  $B_{app}$ , participants rated the PQ as neutral with a positive tendency (M=0.30,  $\alpha$ =0.90), the HQ as neutral with a negative tendency (M=-0.50,  $\alpha$ =0.89), and the overall score as neutral (M=-0.10).

Statistical tests of the not normally distributed data revealed significant differences between  $A_{\rm drive}$  and  $A_{\rm app}$  (p<.001) based on the Wilcoxon Signed Rank test, as well as between  $A_{\rm drive}$  and  $B_{\rm drive}$  (p<.001) based on the Mann-Whitney test.

The findings from the UEQ-S indicate that providing transparency communication through a smartphone app after an autonomous drive without live information results in a significant improvement in passengers' UX from negative to neutral. Similarly, using the app after an autonomous drive where explanatory information is present yielded similar results without a noticeable increase in UX. On the other hand, compared to no additional information, giving passengers explanatory information during an autonomous drive considerably improved their UX from negative to neutral. This shows that explanations given during an autonomous drive as well as explanations given later can enhance passengers' UX. However, since the results are still below the threshold of 0.8 and therefore not positive, Hypothesis H<sub>2</sub> is only partially supported.

# Perceived Feeling of Control

Table 6.8: Results for the perceived feeling of control. Group A was not provided with live feedback during the drive.

# Perceived Control Item: During the ride I had the feeling to stay in control.

-	Α	Α	D	<b>D</b>
	${f A_{drive}}$	$\mathbf{A}_{\mathbf{app}}$	${ m B_{drive}}$	$ m B_{app}$
values	2.70	3.40	3.70	4.20
SD	1.69	1.35	1.34	1.51
p	.0205			.0255
	${f A_{drive}}$	${ m B_{drive}}$	${f A_{app}}$	$ m B_{app}$
values	2.70	3.70	3.40	4.20
SD	1.69	1.34	1.35	1.51
p .0175			.044	

Table 6.8 shows the results of the perceived feeling of control. The feeling of control is significantly increased for both groups when the smartphone app was used after the autonomous ride ( $A_{drive}=2.70$ ,  $A_{app}=3.40$ , p<.05) ( $B_{drive}=3.70$ ,  $B_{app}=4.20$ , p<.05). This shows that retrospective explanations even positively influence the perceived feeling of control of passengers who received live explanations during the

ride. Additionally, when transparency communication is present during an autonomous ride, the feeling of control is significantly increased ( $A_{drive}=2.70$ ,  $B_{drive}=3.70$ , p<.05). Therefore, evidence supports Hypothesis H<sub>3</sub> - Increased Feeling of Control.

Additionally, the relationship between UX and the perceived feeling of control was analysed by calculating the Pearson correlation, see Table 6.9. Pearson correlation was chosen for the analysis as it is particularly suited for examining linear relationships between continuous variables and is widely employed in UX research contexts where Likert-scale based questionnaire data are treated as interval data (Field, 2013). In Table 6.9 it can be seen that all word pairs of the UEQ-S, except for complicated-easy, exhibited weak to moderate significant positive correlations with the feeling of control. This suggests that various aspects of the passengers' UX in AVs are associated with the perception of control. Interestingly, the dimensions related to HQ displayed stronger correlations with the feeling of control than the PQ dimensions. Therefore, a perceived feeling of control influences factors such as enjoyment, satisfaction, and emotional response and plays a more important part in the hedonic side of UX than mere functional aspects. No significant correlations were found for the UX and the perceived feeling of safety or understanding.

By exploring these correlations, the validity of the scales tailored for this thesis — particularly the adapted constructs for perceived feeling of control — can be further supported. Significant relationships between control and hedonic quality dimensions indicate that the scales meaningfully capture variations in UX relevant to first-time passengers' perceptions, aligning with the theoretical foundations on user needs and experiences discussed earlier. Thereby, the analysis not only supported the internal consistency, measured via Cronbach's Alpha, but also provided first evidence that the different tailored constructs behave consistently and meaningfully in relation to each other, strengthening their validity within the context of this thesis.

# Post Interview

Participants were interviewed after the autonomous drive and after using the mobile app in order to get qualitative data. The interviews aimed to gather information regarding the participants' feelings throughout the trip, any uncomfortable or confusing situations they came across, the effectiveness of the AV's transparency communication, and any additional observations they may have had.

The transcribed statements from both groups were counted and classified based on

UEQ-S item	Pearson Corr.	p (1-tailed)
obstructive – supportive	.255*	.011
complicated - easy	.071	.265
inefficient-efficient	.219*	.026
$\operatorname{clear}-\operatorname{confusing}$	.328**	.001
boring – exciting	.359**	.001
not interesting – interesting	.341**	.001
conventional-inventive	.335**	.001
usual – leading edge	.333**	.001

Table 6.9: Pearson Correlations between the perceived feeling of control and the UX.

similar meanings; see Table 6.10. Both groups shared the perception that the AV's driving felt slow. However, the reason for this differed between the two groups, either due to the shuttle's decision-making process or its actual driving behaviour. Participants in group B, who had access to the transparency communication, demonstrated an increased awareness of the AV's decision-making. Consequently, their focus moved from perceiving the driving as slow to perceiving the AV's decision-making process as slow.

The AV's driving reactions to certain situations confused 13 participants in group A, who were not provided with transparency communication during the ride, and 7 participants in group B. In contrast, 12 individuals in group B were able to comprehend the driving reactions of the AV, and 11 participants in group B found the transparency communication during the ride to be understandable. This is also reflected in the data of the UEQ-S where group B had a significantly increased UX during the ride and the significant shifts in the AVAM effort expectancy outcomes. While some participants thought the ride to be interesting (4 in group A, 2 in group B) others found it to be uninteresting (9 in group A, 3 in group B).

When comparing the perceived feeling of control, it was found that more participants in group A (5) reported a sense of lacking control compared to group B (3). These findings provide some support for the significant outcome of Hypothesis HH<sub>3</sub>. However, it is worth noting that a considerable number of participants from both groups (10 from group A and 14 from group B) reported feeling well during the ride.

Regarding the smartphone app, more participants in group A (14) than in group B (6) found the app helpful. In comparison, more participants in group B found it unnecessary or unhelpful (13) compared to group A (6). This can be due to group B participants already receiving live explanations during the ride and not needing them

6

14

13

6

Statement category	Statements regarding the drive		${ m B_{drive}}$
Shuttle manoeuvre	The situation detection is slow.	2	12
Shuttle manoeuvre	The shuttle drives cautiously and slowly.	8	3
Shuttle manoeuvre	A human would have reacted faster. 1		4
Shuttle manoeuvre	Interesting to see how the shuttle acts.	4	2
Shuttle manoeuvre	In some situations, the shuttle's reaction was unclear.	13	7
Shuttle manoeuvre	uttle manoeuvre The shuttle's reactions were (always) clear.		12
Shuttle communication	The AR information is comprehensible.	_	11
Shuttle communication	The AR information was shown too late.	_	2
Participant feelings	I am not in control.	5	3
Participant feelings	The drive is boring.	9	3
Participant feelings	I was feeling well.	10	14
	Statements regarding the app	${ m A_{app}}$	$\mathrm{B}_{\mathrm{app}}$

The app is unnecessary or not helpful.

The app is helpful.

Table 6.10: Participants' interview answers grouped by statement.

again after the ride.

Арр

App

In terms of the smartphone app, a higher number of participants in group A (14) found the app to be helpful compared to group B (6). Conversely, more participants in group B expressed that the app was unnecessary or unhelpful (13) when compared to group A (6). The findings suggest that participants in group B, who had access to real-time transparency communication during the ride, did not see the need for additional information from the app after the ride.

To summarise, participants were interviewed after the autonomous ride and smartphone app usage to gather qualitative data. They shared their feelings, experiences, and opinions on the shuttle's transparency communication. Both groups perceived the driving as slow, but there was a distinction in whether it referred to decision-making or actual driving. Participants in group A felt less in control compared to group B, matching the questionnaire results. In terms of app usage, group A found it helpful. In contrast, group B found it unnecessary, probably due to their access to live feedback during the autonomous ride.

### 6.3.7 Discussion

Looking at Hypotheses  $H_{1.1}$  and  $H_{1.3}$ , they were not confirmed by the experiment. Neither the multimodal live transparency communication nor the retrospective on-device explanations (other than when used for TORs (Melcher et al., 2015)) increased the perceived feeling of safety, nor did they change the participants' attitude towards using this technology.

Looking at the quantitative data for safety, it can be seen that the ratings were high (>5) across all experiment combinations. Participants, therefore, did not report any issues regarding their perceived feeling of safety in the first place. A possible explanation for this could be the static driving simulator. As participants were not driving autonomously in real traffic but watched a video of a recorded drive, there was never any imminent threat present regarding their safety. This is further supported by the statements from the interviews, where both groups said they felt well during the ride.

Regarding their attitude towards using this technology, values were also very similar (around 4) across each condition. Experiencing live transparency communication or retrospective on-device explanations did not have any influence. This could be explained by looking at the individual word pairs of the UEQ-S. The pair boring-interesting was rated the lowest for each condition. Furthermore, participants could not actively interact with the AV during the ride and therefore were only consumers of this new technology for half the time. When they were actively engaging with the smartphone app, participants stated that the app was unnecessary, especially for group B, which was provided with live information during the ride.

Regarding Hypothesis  $H_{1.2}$ , participants reported a significantly increased understanding and ease of use between driving without and with live transparency communication and driving without live information and receiving retrospective information afterwards via the smartphone app.

Interestingly, values were high (>5) for any condition. This result seems a bit unexpected when looking at the qualitative statements. Four group A, 13 participants (65%) and 7 participants for group B (35%) stated that the AV's reactions were not always clear to them.

The significant change between the two driving conditions, however, matches the interview statements with 5 participants of group A (25%) stating that the AV's reactions were clear to them, versus 12 participants (60%) of group B.

Furthermore, the significant increase between driving without live information and receiving on-device cues afterwards also matches the interview statements, where more participants of group A (14) compared to group B (6) reported the app to be helpful. However, the perception and evaluation of the app could be affected by the overall positive feeling of safety that participants reported during the ride. It is possible that in real-life situations where the ride presented more complexity or criticality, there would be a heightened need for in-depth explanations afterwards.

Regarding the results of the UEQ-S, providing live transparency communication during the ride significantly increased participants' UX. Group A, without live explanations, reported an overall negative UX with the HQ having a considerably bigger impact on the UX. The lack of transparency and real-time information possibly contributed to a less satisfactory experience for participants. On the other hand, in group B, where participants had access to live explanations, the overall UX was rated as neutral, possibly due to the increased transparency and understanding of the AV. However, the experience rating is still far from being positive (M=-0.17), with the HQ still having a slightly negative tendency (M=-0.51). This can be explained by the interview statements that some participants thought that a human might react faster (4 mentions), that still, in some situations, the AV's reactions were unclear (7) and that sometimes AR information was shown too late (2). Interestingly, for group A, a similar experience could be reached when they were provided with on-device explanations afterwards. Showing that live and retrospective transparency communication seem to have the same influence on passengers. However, the question arises if it is favourable to leave passengers with a negative experience during the ride and then provide them with information after. According to the Professor for mobility research expert, a possible option could be to let passengers choose their way of communication as their preference might change after multiple drives.

All modalities led to a significant increase in the perceived feeling of control. Live, as well as retrospective transparency communication, led to increased perceived control in participants. This finding is interesting, as participants had no option to exert direct control at any point in time. Yet, providing them with transparency communication significantly increased their perceived feeling of control. Even the group with live communication reported a significant increase after the retrospective on-device cues. This is a substantial finding, as the perceived feeling of control significantly correlated with the passengers' UX.

In conclusion, the experiment did not confirm Hypotheses  $H_{1.1}$  and  $H_{1.3}$ , as the live transparency communication and retrospective on-device explanations did not significantly impact participants' perceived feeling of safety or their attitude towards using the technology. Ratings for safety were consistently high, and participants generally felt well during the ride. However, there were some concerns about the clarity of the AV's reactions.

There was a significant increase in understanding and ease of use when live transparency communication was provided. The perceived feeling of control was significantly increased for all experiment conditions. The overall UX was negative for group A without live explanations. In contrast, group B, with live explanations, had a neutral experience. The importance of real-time information and transparency was highlighted, but improvements are needed in communicating AV reactions. Further research is needed to address the clarity and timing of AV reactions explanations and enhance the overall UX.

### 6.3.8 Limitations

The experiment poses several limitations. A static driving simulator was used with recordings shown on screens putting participants in a rather abstract setting. Therefore, they did not experience real-life acceleration and deceleration forces or traffic. Furthermore, no driving noises or visual depth were present. These factors might, among other things, have led to the high rating of perceived safety.

Furthermore, the participants' rather low average age of 25 might have influenced the results of their attitude towards the technology. The experiment might have yielded different results with older participants. Lastly, participants had no real destination that they needed to reach. Therefore, they could be rather seen as attendees than passengers, which might have also influenced the results.

### 6.3.9 Conclusion & Outlook

The experiments goal was to investigate the influence of multimodal live transparency communication and retrospective on-device cues on the passengers' UX, their understanding, attitude towards technology and perceived feeling of safety and control in AD. The live feedback was a combination of the feedback modalities light, text and AR. The retrospective feedback used a smartphone app for information transmission.

Results show that providing live explanations during an autonomous ride significantly increases passengers' UX, as does retrospective feedback via a smartphone app if no live information was present. However, none of the modalities created a positive UX for passengers but only a neutral one leaving room for improvement.

Furthermore, live transparency communication significantly increased passengers' understanding, as did the retrospective information if no feedback was present during the ride. In contrast, live or retrospective information did not have any influence on passengers' perceived feeling of safety or their attitude towards the technology. Regarding the perceived feeling of control, live and retrospective transparency communication led to a significant increase for all groups.

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The next experiment will explore multimodal feedback modalities regarding their use of influencing passengers' perception of the AV's driving style and their impact on the perceived feeling of safety and control.

# 6.4 Experiment 3: Velocity Styles for Autonomous Vehicles affecting Control, Safety, and User Experience

This experiment was conducted parallel to experiment 2 from 2019 to 2020 and published in the Proceedings of the 2021 ACM Symposium on Spatial User Interaction: Velocity Styles for Autonomous Vehicles affecting Control, Safety, and User Experience (Schneider, Hois, Rosenstein, Lazzara, Love and Gerlicher, 2021).

The primary goal of the third experiment was to investigate the use and placement of different feedback modalities to evaluate their influence on simulating different driving styles in AVs. Thereby, the special characteristic is that the actual driving style was always the same and only manipulated visually and auditorily by the feedback modalities. Furthermore, their influence on the perceived feeling of safety and control was investigated (Personas: Sarah, Klara and Kareem).

As the Professor for mobility research mentioned in the expert interview, a personalised driving style of an AV might play a role in users' AD experience. This has also been investigated by different researchers, showing that users prefer AVs to emulate their own driving style (Basu et al., 2017), at least if their own driving style is not assertive (Yusof et al., 2016). Features such as acceleration and distance to other objects in different events seem to influence passengers' comfort and anxiety in an AV on a real driving track (Dillen et al., 2020). Being able to choose the AV's driving style thereby seems to increase the perceived feeling of control (Kim et al., 2021).

This experiment assumed that in the future, AVs will all have the same basic driving style and that there will be no "race-car-AVs" on the left lane of the motorway. Therefore, it was investigated how the exact same driving style can be manipulated to feel different by using feedback modalities.

The results gave important information about the pros and cons of different feedback modalities and their influence on the perceived driving style and, thus, on the perceived feeling of safety and control.

## 6.4.1 Driving Scene

A 1:44 minutes long driving scene on a two-lane federal highway was recorded using three GoPro Hero 5<sup>8</sup> cameras. Like the second experiment, the cameras filmed to the front and sides.

During the ride, the AV approaches a vehicle in front on the right lane, changes to the left lane to overtake two vehicles and back. Later, it leaves the two-lane federal highway via an off ramp onto a country road and follows it for a bit.

# 6.4.2 Driving Simulator



Figure 6.15: Inside view of the driving simulator.

In the experiment, the same setup as in experiment 2 was used for the driving simulator, see Figure 6.15, but with a few modifications. The simulator was still accessed from the side and equipped with four car seats. Again, multiple screens were used to create the illusion of a windshield and windows, displaying the autonomous drive recorded by multiple cameras. To enhance the experience and test the influence of sound on the perceived AV driving style, a 5.1 surround sound system was installed in the driving simulator.

<sup>&</sup>lt;sup>8</sup>https://gopro.com/ (Accessed: August 2023)

### 6.4.3 Feedback Modalities and Design

As mentioned in the introduction, the experiment's main goals were (1) to investigate the influence of feedback modalities on the perceived AV driving style by visually and auditorily changing the same driving recording and (2) investigating the driving style's influence on the perceived feeling of safety and control. Therefore, a combination of audio, UI overlay, AR projection and LED strips was used.

The experiment differentiated between two general driving styles called *moderate* and *racy*, reflecting a defensive and more sporty driving style.

### Audio

During the experiments, the 5.1 surround system was used to play different engine sounds depending on the driving style to influence the perception of speed (Denjean et al., 2012). Furthermore, street sounds were also simulated. For the moderate style, a quiet electric engine sound was played. For the racy style, a louder electric engine sound was played.

### **UI** Overlay

Several visual factors can significantly alter the perception of speed according to the research of Pretto et al. (2012). In their study, reducing the vision in the distance using fog caused participants to significantly overestimate their speed. Furthermore, reducing vision in the front using so-called anti-fog led to participants underestimating their speed. This experiment used the concept of anti-fog to simulate different speeds.

Following the research of Pretto et al. (2012), a UI overlay is positioned at the lower third of the viewport to cover up the fast-moving part of the street for the moderate driving style. Thereby, focus is put on the distance where everything is moving slower; see Figure 6.16. Furthermore, blue colours were used to create a feeling of calm (Heller, 1989; Tobias, 2018). The speedometer does not show decimals to make changes in acceleration seem less abrupt.

For the racy driving style, the foreground was not covered up to show the fast-moving part of the road; see Figure 6.17. Red was used to colour the UI elements as it is associated with being active, dynamic or energetic (Heller, 1989; Tobias, 2018). Furthermore, the speedometer has more sharp-edged details and displays decimals to make speed changes feel faster. The goal was to make it feel even more turbulent, as it was no longer placed on a solid colour background.



Figure 6.16: UI overlay for moderate driving style.

Furthermore, both UI overlays contained a map showing the current route and transparency information regarding the AV's driving reactions and upcoming driving manoeuvres (compare, for example, Koo et al. (2015); Kunze et al. (2018); Telpaz et al. (2017); Walch et al. (2015)).

### AR Projection

Similar to the second experiment, an AR projection of the expected route was displayed (compare Kim and Dey (2009); Kunze et al. (2018); Wintersberger et al. (2017)). However, in this experiment, the AR projection was only shown when there were changes to the route, specifically for lane changes; see Figure 6.18. To further assist, arrows pointing in the direction of the change were displayed.

For the speedy driving style, a blur effect was added to the windshield's edges, creating a visual effect of speed (Rosado, 2007).

### LED Strips

Inspired by research of Meschtscherjakov et al. (2015), LED strips were installed from front to back on the left and right sides of the ceiling; see Figure 6.19. In the moderate



Figure 6.17: UI overlay for racy driving style.

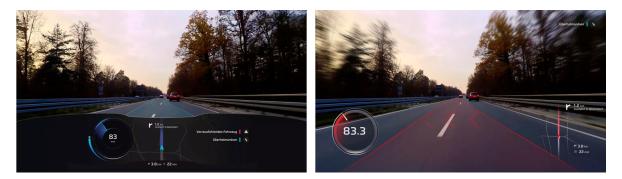


Figure 6.18: AR projection for lane changes.

mode, they were used to counteract the driving speed by using slow-moving blue lights from front to back. In the sporty mode, they were used to increase the perceived feeling of speed by rapidly moving red lights from front to back.

### **Seating Position**

To further influence the perceived AV driving style, different seating positions were used. It was assumed that the more relaxing the seating position of the passenger, the slower the perceived driving speed. Therefore, passengers experiencing the moderate driving style were seated in a reclined position. Passengers of the racy style were sat upright.

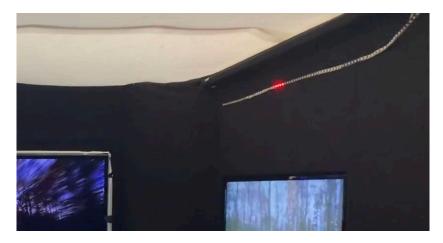


Figure 6.19: LED strips at the ceiling.

## 6.4.4 Experiment

### Study Design

In this experiment, a between-subjects design was used. All participants were first-time users of AVs and did not have knowledge or experience of the different feedback modalities. The study's goal was to examine the influence of feedback modalities on the perceived driving style and, in turn, the influence on the perceived feeling of safety and control.

A self-developed, 5-point Likert scale questionnaire with 12 items was used; see Table 6.11. It measured how close the driving experience was to participants' driving style and if they had the feeling of being in control. Furthermore, it was investigated how the different feedback modalities influenced the perceived feeling of safety.

### Hypotheses

Four hypotheses were examined in the experiment:

 $\mathbf{H_1}$  – reference ride vs group-specific ride: Participants from the moderate and racy groups perceive the group-specific ride as different from the reference video and closer to their own personal driving style.

 $\mathbf{H_2}$  – **perceived speed difference:** A slightly slower or faster driving style can be simulated, even though the shown drive is identical to the reference ride. Thus, participants perceive a difference in speed due to additional visual and modified acoustic information only.

 $\mathbf{H_{3.1}}$  – increased perceived feeling of control: Due to the imitated driving style adjustments, the feeling of control can be increased by the moderate or racy ride in contrast to the reference ride (for both participant groups).

 $\mathbf{H_{3.2}}$  – increased perceived feeling of safety: Due to the imitated driving style adjustments, the feeling of safety can be increased by the moderate or racy ride in contrast to the reference ride (for both participant groups).

### **Participants**

In total, 42 participants (21 female, 21 male) with an average age of 25.8 years (SD=9.3) and normal or corrected-normal vision participated. The study's participants comprised a mixture of employees, faculty members and staff from a university, and workers from a research campus. Most participants were already experienced with semi-automated driving features (31 participants). Each experiment was conducted with a single participant at a time, as the simulation was designed to provide an individualised experience. Due to the experimental setup, participants can be distinguished into two participant groups: The moderate group (16 participants) and the racy group (26 participants) depending on their driving speed preference selection, described in the following.

### Procedure

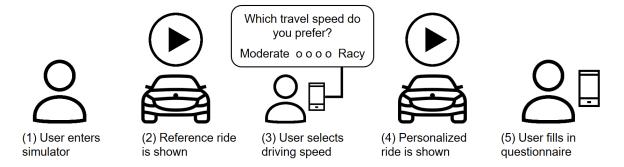


Figure 6.20: Experimental setup procedure.

The experimental setup is illustrated in Figure 6.20.

(1) Participants were introduced to the experiment, which consisted of experiencing two driving scenarios. An application on a smartphone led participants through the steps of the experiment by starting the simulation and collecting

participants' demographic questionnaire answers; see Figure 6.21.

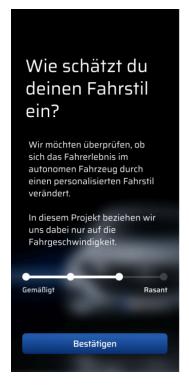






Figure 6.21: Smartphone app guiding participants through the experiment.

- (2) A pre-recorded driving scenario on a highway was presented for a duration of 1:44 minutes via displays and audio. During this pre-recorded autonomous ride, the AV changes lanes and onto different roads with moderate traffic and average weather conditions during the daytime. The average recorded speed was 78 km/h, with a minimum of 46 km/h and a maximum of 97 km/h. For the experiment, this ride was used as the reference ride.
- (3) After the ride ended, participants interacted with the smartphone app to continue. Within the app, participants were asked to select their preferred driving style with regard to their own driving speed. In particular, they had to choose between *moderate* and *racy*, using a 4-Point Likert Scale to set a clear preference for slower or faster speeds. The app then informed the participants that the driving style was updated accordingly.
- (4) Participants were then shown the same pre-recorded drive as before (the reference ride). This time though, based on their preferred driving style selection, additional visual and auditive information was presented via the different feedback modalities discussed above.

Table 6.11: Self-defined questionnaire items.

	т.	
Semantic	Item	Question
context		
reference ride	Q1	How much did the experience reflect your own
		driving style?
	Q2	I had the feeling to be in control during the
	·	experience.
	Q3	How safe did you feel during the experience?
moderate or	Q4	How did you perceive the experience in relation to
racy ride	-	the reference video?
v	Q5	How much did the experience reflect your own
	Ū	driving style?
	Q6	I had the feeling to be in control during the
	900	experience?
	Q7	How safe did you feel during the experience?
feeling of safety	Q8	How much did the driving style impact your feeling
reeming or search	900	of safety?
	Q9	How much did the user interface impact your feeling
	-00	of safety?
	Q10	How much did the video effects impact your feeling
	-0-0	of safety?
	Q11	How much did the audio effects impact your feeling
	Ū	of safety?
	Q12	How much did the lighting effects impact your feeling
	~C	of safety?
		01 0010 Uj .

(5) After completing the second ride, the smartphone app ended the simulation. Participants were then asked to fill out a self-defined questionnaire presented again by the app; see Table 6.11. The questionnaire addressed their overall feeling and their reaction to the experience.

### 6.4.5 Results

This section presents the results of the self-developed 12-item questionnaire; see Table 6.13. Various statistical analyses were carried out to examine the hypotheses. The data was divided into two driving modes, namely moderate and racy, based on participants' choices. Non-parametric tests were utilised for hypothesis testing due to the non-normal distribution of the data. The reliability of the measurement scales was assessed using Cronbach's Alpha coefficient. All scales demonstrated satisfactory coefficients ( $\alpha > 0.60$ ) and were included in the subsequent analysis.

Item	Coding of Likert points					
	1	2	3	4	5	
Q1, Q5, Q8,	not at all	not really	undecided	somewhat	very much	
Q9, Q10,						
Q11, Q12						
Q2, Q6	strongly	$\operatorname{disagree}$	neither	agree	strongly	
	$\operatorname{disagree}$		agree nor		agree	
			disagree			
Q3, Q7	very	insecure	moderately	secure	very secure	
	insecure		secure			
Q4	much	slower	somewhat	faster	much	
	slower		equal		faster	

Table 6.12: Likert scale codings for questionnaire items.

Table 6.13: Results of the self-developed 12-item questionnaire. (1) Wilcoxon rank sum test, (2) Wilcoxon signed rank test.

Hypothesis	Items	p-v	alue
		Moderate	Racy
H <sub>1</sub> moderate vs. racy	$Q1+Q5^{(2)}$	0.136	0.048*
H <sub>2</sub> perceived speed difference	$Q4^{(1)}$	0.00	)1***
$H_{3a}$ increased perceived feeling of control	$Q2+Q6^{(2)}$	0.009**	0.038*
$H_{3b}$ increased perceived feeling of safety	$Q3+Q7^{(2)}$	0.016*	0.408

Several tests were employed to conduct inferential statistics, such as correlation analysis and hypothesis testing. Spearman's correlation test was used to examine the relationship between variables. One-sided Wilcoxon tests were utilised for both paired (H1, H3) and unpaired (H2) samples. The demographic dataset's dichotomous categorical variables were converted into 1/2-coding categories for the correlation analyses. This transformation allowed for a more suitable analysis of the data, facilitating correlation analyses and hypothesis testing. This allowed for comprehensive data analysis and the hypotheses' evaluation.

First, the perception of the group-specific rides compared to the reference ride was analysed. It was found that participants in the racy group perceived the group-specific ride as significantly different compared to the baseline video (Racy<sub>ref</sub>=3.46, Racy=3.88, p<.05). Additionally, they felt that the group-specific ride aligned more closely with their own driving style.

On the other hand, participants in the moderate group did not show a significant difference between the group-specific ride and the reference ride (Moderate<sub>ref</sub>=3.63, Moderate=3.88, p>.05).

Therefore, hypothesis  $H_1$ , which suggests that participants would perceive the group-specific ride differently from the reference ride and closer to their own personal driving style, can only be partially accepted.

Next, the results regarding the perceived driving speed of the two groups were compared. The results revealed a significant difference in the perceived driving speed. Participants in the racy group reported experiencing the ride as significantly faster compared to those in the moderate group (Moderate=2.94, Racy=3.58, p<0.01). This finding supports hypothesis H<sub>2</sub>, which predicted that the racy group would perceive the ride as faster.

Additionally, the subjective feeling of control and the subjective feeling of safety were compared between the reference and group-specific rides. The results indicated a significant increase in the feeling of control for both the moderate and racy groups in the group-specific ride compared to the reference ride (Moderate<sub>ref</sub>=1.88, Moderate=3.00, Racy<sub>ref</sub>=2.15, Racy=2.54, p<.05). This finding supports Hypothesis  $H_{3a}$  which predicted that a driving style closer to one's increases the perceived feeling of control.

Regarding the subjective feeling of safety, a significant increase was observed only in the moderate group (Moderate<sub>ref</sub>=3.50, Moderate=4.13, p<.05). However, there was no significant difference in the feeling of safety between the reference ride and the racy group (Racy<sub>ref</sub>=3.96, Racy=4.00, p>.05). Therefore, Hypotheses  $H_{3b}$ , which predicted an increase in the feeling of safety with a driving style closer to one's own, can only be partially accepted.

### 6.4.6 Discussion

In the future, AVs will probably drive with the same speed and style. Therefore, a particular challenge might be the different types of preferred driving styles since there is no one-fits-all solution (Park et al., 2020).

The experiment allowed participants to choose between two styles regarding speed (moderate and racy). Then it altered the same drive with different audiovisual feedback modalities. While the moderate group did not perceive the altered style closer to theirs, the racy group, in fact, did. The experiment could therefore confirm

research regarding combinations of audiovisual and light effects and their impact on the perceived speed (Denjean et al., 2012; Meschtscherjakov et al., 2015; Pretto et al., 2012).

Furthermore, it was shown that the perceived feeling of safety and control in an autonomous ride could be increased when altering the driving style to one closer to the passenger's style. The feeling of control was significantly increased for both groups, with the moderate group showing the higher increase (Moderate<sub>ref</sub>=1.88, Moderate=3.00, Racy<sub>ref</sub>=2.15, Racy=2.54, p<.05). While this time they were able to directly exert control by choosing their driving style before the drive, during the ride they could not exert any control. Thereby, this experiment confirms the results of the other two experiments, that feedback modalities are able to increase the perceived feeling of control of passengers even though they do not have any direct control during the ride.

Moreover, the perceived feeling of safety was increased, but only for the moderate group. A possible reason for this might be the increased feeling of speed of the racy group that experienced their ride significantly faster than the moderate group. A ride that feels faster most likely may not increase the feeling of safety at the same time.

Therefore, giving people the control to personalise their driving experience by altering an autonomous ride to appear slower increases the feeling of control and safety. Altering an autonomous drive to appear faster increases only the feeling of control.

Looking at possible reasons for the subjective feeling of safety (Q8-Q12), participants of both groups were indifferent about the driving style's impact on the feeling of safety (Q8, Moderate=3.06, Racy=2.90). While there is no correlation between the modalities and the feeling of safety, participants of both groups (moderate and racy) still subjectively rated the UI (Moderate=4.13, Racy=3.96) and video effects (Moderate=3.94, Racy=4.00) significantly higher (p<.05) than audio (Moderate=2.81, Racy=2.69) and lighting effects (Moderate=2.50, Racy=2.80). Indicating that UI and AR modalities are more effective for a design that aims at supporting the feeling of safety in AD.

To summarise, it is possible to alter the perceived feeling of speed of an autonomous ride by using audiovisual feedback modalities. Altering the driving style to one closer to the passengers' style increases the feeling of safety and control for moderate styles and the feeling of control for faster styles. Participants rated UI and AR higher than audio and lighting effects in terms of supporting the feeling of safety in AVs.

### 6.4.7 Limitations

As with the other experiments, one limitation was using a driving simulator. The driving experience was primarily an audio-visual projection presented through screens and a stereo system. Performing such tests in real-world traffic and road conditions would have potentially yielded greater reliability and validity concerning the attitude and reactions of the participants.

In contrast to this limitation, the driving simulator allowed for comparing the experienced rides in a controlled setup. This way, participants were shown exactly the same video footage of the driven ride during the reference ride and the audio-visually modified ride. The presented results thus also indicate that users perceive their experienced speed differently to some extent. Pure audio-visual modifications affect their perceived safety and control, even though they did not experience centrifugal forces in the driving simulator.

The driving style in this study is simulated with regard to velocity changes only. However, a driving style consists of more than just speed information. For example, the driven trajectory, acceleration behaviour or distance to the cars ahead also contribute to a person's driving style.

Furthermore, the sample group presents demographic limitations, ranging from 20 to 30 years of age. A broader range of participants would have been preferable, especially elderly drivers with more comprehensive experience and a different perception of traffic situations. This would have allowed a broader generalisation of the research findings.

### 6.4.8 Conclusion & Outlook

This experiment's goal was to investigate the influence of different feedback modalities on passengers' perception of speed and, in turn, on their perceived feeling of safety and control. The feedback modalities were chosen based on their influence on the perceived speed, according to research.

The results show that users perceive the speed of an AV differently based on audio-visual modifications only when they are asked to select their preferred driving speed (rather moderate or rather racy). Furthermore, it was shown that a combination of these modalities, and the users having the possibility to choose their preferred driving style, not only changes the perception of speed but also increases the feeling of control and safety. While a more defensive driving style increases both, a

racy driving style does only increase the feeling of control. Providing passengers with different feedback modalities in the form of audio, visuals, and lighting allows them to perceive the same drive differently and therefore allows for (perceived) personalisation. There is an indication that UI and AR effects have a greater impact on the feeling of safety compared to audio and lighting effects. However, this topic still needs further investigation.

Overall, this contribution demonstrates that individualisation and individual perception of safety and control can be achieved by audio-visual modifications only, without having to change the actual driving speed behaviour of an AV.

The next experiment will explore the influence of non-critical failure situations in AD on the passengers' UX, their perceived feeling of safety and control and other relevant factors.

# 6.5 Experiment 4: Don't fail me! The Level-5 Autonomous Driving Information Dilemma regarding Transparency and User Experience

This experiment was conducted in 2021 and published in the Proceedings of the 28th International Conference on Intelligent User Interfaces in 2023: Don't fail me! The Level 5 Autonomous Driving Information Dilemma regarding Transparency and User Experience (Schneider et al., 2023).

The primary goal of this fourth experiment was to find out how non-critical failures from the AV influence the transparency communication and thus the participants' UX, perceived feeling of safety and control, system understanding and acceptance. In this experiment, non-critical failure situations are defined as situations where the AV makes a wrong driving decision but, at no point, creates a situation that leads to health-critical situations. In critical situations, system designs must ensure safety and dependability. However, failures that result in unexpected behaviour should be taken into account in non-critical scenarios. For example, when a pedestrian is standing next to a crosswalk, not planning to cross, but the AV stops and does not continue its drive nonetheless.

This experiment was motivated by multiple factors.

- 1. The statements of the focus group participants about not trusting software developed by humans (Personas: Sarah and Kareem).
- 2. The AI researcher expert stating feedback is needed to inform about errors.
- 3. Research, showing that AI systems are not error-free (compare, for example, Alcorn et al. (2019); Obermeyer et al. (2019)).
- 4. Real-life driving situations by Tesla's Full Self-Driving Beta<sup>9</sup> or Waymo vehicles<sup>10</sup>.

<sup>&</sup>lt;sup>9</sup>Compare, for example:

https://www.youtube.com/watch?v=wFEoAa1YOdE~(Accessed:~August~2023)

https://www.youtube.com/watch?v=2u6AgLuwVqI (Accessed: August 2023)

<sup>&</sup>lt;sup>10</sup>Compare, for example:

https://youtube.com/shorts/a-Mvdy6NNCY?feature=share (Accessed: August 2023)

https://www.youtube.com/watch?v=fMFzs0NZ\_Mc (Accessed: August 2023)

These factors led to RQ-2 of this thesis:

How do failure situations affect the passengers' perception of transparency communication?

While research discussed in the literature review has looked at failure situations in CAD communicated through uncertainty communication (compare, for example, Beller et al. (2013); Faltaous et al. (2018); Helldin et al. (2013)), passengers in AD will not be able to take control over the driving task. Therefore, new challenges might arise for UMDs and transparency communication in AD for non-critical failure situations.

In non-critical failure situations, the AV might not be aware of its failure. Otherwise, it might have prevented it in the first place. This experiment examined whether providing transparency information in non-critical failure situations changes the participants' UX, perceived feeling of safety and control, system understanding and acceptance.

Therefore, it used a conversational UI as feedback modality and allowed participants to interact with it via a chat-like interface. The modality was tested in an online study, using a video driving simulator and an on-site study, using a WoZ driving simulator.

The experiment confirmed the previous experiments regarding transparency communication effects but also revealed problems of transparency communication in non-critical failure situations leading to an information dilemma.

# 6.5.1 Driving Simulator

For the experiment, two types of driving simulators were created. (1) a video driving simulator, accessed through an online questionnaire, showed the view through a car windshield and a central infotainment screen displaying the feedback modality; see Figure 6.22. (2) a WoZ driving simulator that hid the driver from the passenger with a black curtain to emulate the feeling of an AV; see Figure 6.23. Both simulators let participants experience the same 2.5km drive that lasted approximately 5 minutes.

The conversational UI was implemented as a Telegram<sup>11</sup> bot that sent conversational messages to the passengers when a relevant driving situation was happening allowing them to react with two pre-defined options; see subsection 6.5.3. For the WoZ prototype, a tablet was mounted at the passenger side, allowing participants to interact with the conversational UI. Messages were sent by a

<sup>&</sup>lt;sup>11</sup>https://telegram.org/ (Accessed: August 2023)



Figure 6.22: Screenshot of the video driving simulator.



Figure 6.23: The WoZ simulator. The driver was hidden from the passenger with a black curtain.

researcher in the back of the vehicle, and participants were unaware of that. The conversational UI was recorded and put over an infotainment screen in a car interior for the video driving simulator. The video prototype was built with an online questionnaire. After each transparency communication video scene, participants decided in the questionnaire how they wanted to interact with the prototype.

# 6.5.2 Driving and Failure Situations

Six different driving situations occurred during the simulated autonomous ride that triggered the conversational UI to send a message to the passengers; see Figure 6.24. The first three were regular driving situations, and the last three were non-critical failure situations.

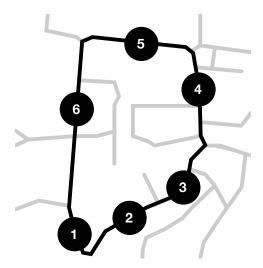


Figure 6.24: The driving route included six different driving situations.

The three non-critical failure situations were inspired by real-world occurrences and were faked during the WoZ study and in the video prototype.

- 1. The AV informs the passenger that it detected a crosswalk where no one is crossing.
- 2. The AV informs the passenger that it detected a green traffic light that it would be passing.
- 3. The AV informs the passenger that it detected a green traffic light that it would be passing.
- 4. The AV thinks that a person next to a crosswalk wants to cross the road<sup>12</sup>. It stops and waits for 10 seconds until the ride is continued.
- 5. The AV thinks that multiple parked cars are the end of a traffic jam<sup>13</sup>. It stops behind the car in front and does not pass the vehicle for 12 seconds.
- 6. The AV confuses an advertisement poster showing a stop sign for a real stop sign and comes to a halt<sup>14</sup>. It continues the ride shortly after.

# 6.5.3 Feedback Modalities and Design

The statements of the expert interviews inspired the functionalities of the conversational UI. (1) The mobile application developer's feedback that there should

 $<sup>^{12}</sup>$  Tesla Full Self-Driving beta crosswalk error: https://www.youtube.com/watch?v=xbw2ZB0Lbk8 around minute 8 (Accessed: August 2023)

 $<sup>^{13}</sup> Tesla$  Full Self-Driving beta stopped car error: https://www.youtube.com/watch?v=2u6AgLuwVqI around 1:26 (Accessed: August 2023)

 $<sup>^{14}</sup>$  Tesla Full Self-Driving beta stops for the wrong stop sign:  $https://youtube.com/shorts/lwmbiVY3Ovw?feature=share\ short\ (Accessed:\ August\ 2023)$ 



Figure 6.25: The conversational UI feedback modality. In this case, the second option has been selected and more information is shown to the user.

be different levels of transparency. (2) The input of the Professor for mobility research that too much information may be harmful. The statement of the Professor for AI and human-machine interaction that the passenger should be able to expand the transparency information.

Therefore, the conversational UI only sends a basic message about the situation the first time. A short, soft-sounding two-note chime accompanies each message. The passenger can then decide if they want to request more information. If they do so, they are presented with a detailed text about the situation that led to the AV's driving decision. The messages, again, followed the concept of "why-messages" and presenting reason (Koo et al., 2015; Walch et al., 2015). Furthermore, an image of the driving situation is displayed, including highlighting of the object relevant to the AV's driving decision (Fröhlich et al., 2019; Kunze et al., 2018); see Figure 6.25.

The following messages were sent by the conversational UI for the different driving situations:

- 1. **Crosswalk:** "I have detected a pedestrian crossing." On request: An image of the driving situation is shown. The crosswalk is highlighted with an orange rectangle.
- 2. **Traffic light:** "I have detected a traffic light." On request: An image of the driving situation is shown. The traffic light is highlighted with an orange rectangle.
- 3. **Traffic light:** "I have detected a traffic light." On request: An image of the driving situation is shown. The traffic light is highlighted with an orange rectangle.

- 4. Crosswalk: "I detected a person at the roadside." On request: An image of the driving situation is shown. The pedestrian is highlighted with an orange rectangle. "I have detected a pedestrian at the side of the road who might plan to walk onto the road. I'll wait until the pedestrian has crossed the road."
- 5. **Traffic jam:** "This ride will be delayed a bit." On request: An image of the driving situation is shown. The parked car is highlighted with an orange rectangle. "My sensors have detected the end of a traffic jam, so unfortunately, the journey will be delayed."
- 6. **Stop sign:** "I have spotted a stop sign." On request: An image of the driving situation is shown. The stop sign is highlighted with an orange rectangle.

### 6.5.4 Experiment

### Study Design

In this experiment, a mixed-method between- and within-subjects design was used. All participants used an AV for the first time and did not know or had experienced the feedback modalities before. The goal was to investigate the influence of non-critical failure situations on the UX, perceived feeling of safety and control, and acceptance.

Data was generated in two ways, (1) an online study using the video driving simulator and (2) an on-site study using the WoZ simulator.

The online study primarily aimed to gather quantitative data using different questionnaires while also allowing participants to provide qualitative feedback through a text field. Conversely, the on-site experiment focused on collecting qualitative data through think-aloud statements (Lewis, 1982) and participant observation through a researcher in the back and a camera installed in the vehicle. Due to pandemic-related health and safety regulations, the number of individuals allowed for on-site testing were restricted.

Multiple questionnaires were used to gather quantitative data. For the UX, the UEQ-S was used again. Multiple items from the AVAM were used to measure the system understanding, attitude towards technology, intention to use and perceived safety. Self-defined questionnaires with a 7-point Likert scale inspired by the AVAM wording were used to assess the perceived feeling of control (3 items) and transparency of the system (2 items), see Table 6.14.

Table 6.14: Self-defined questionnaire for the perceived feeling of control and transparency.

### Perceived Feeling of Control

I would have adequate control over the information given by the vehicle

I would have adequate control to get the information that I need about the ride

I have the feeling of being in control during the ride

### Transparency

The system is transparent

My interaction with the vehicle would be clear and understandable (AVAM item 5)

### Hypotheses

Seven hypotheses were examined in the experiment:

 $\mathbf{H_{1a}}$ : The users' desire to take control of the driving task intensifies due to a system failure.

 $\mathbf{H_{1b}}$ : When a system failure occurs, the users' desire to take control of the driving task is reduced when providing additional information upon request.

 $\mathbf{H_{2a}}$ : The user experience is enhanced by providing additional information (more transparency) upon request.

 $\mathbf{H_{2b}}$ : The system acceptance is enhanced by providing additional information (more transparency) upon request.

 $\mathbf{H_{2c}}$ : The perceived feeling of control is enhanced by providing additional information (more transparency) upon request.

 $\mathbf{H_{2d}}$ : The perceived feeling of safety is enhanced by providing additional information (more transparency) upon request.

 $\mathbf{H_{3a}}$ : System failures lead to passengers requesting additional information.

 $\mathbf{H_{3b}}$ : The negative impact of system failures on the user experience is mitigated by offering additional information upon request.

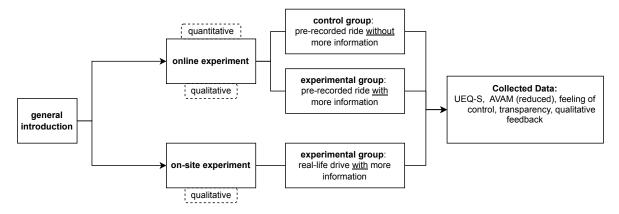


Figure 6.26: Experimental setup.

### Procedure

The experimental setup is illustrated in Figure 6.26. First, participants were generally introduced to the experiment. Then, they experienced the (pre-recorded) autonomous ride. Afterwards, they filled out the UEQ-S, AVAM questionnaire, and the self-defined questionnaire and were able to give quanlitative feedback.

For the online experiment, participants were put into one of two groups. (1) The experimental group experienced the ride with the conversational UI and could request more information. (2) The control group experienced the ride with the conversational UI and could not request more information. Furthermore, participants of the online experiment were asked after every driving situation if they hypothetically wanted to take over the driving task.

As the number of on-site participants was limited due to pandemic-related health and safety regulations, all participants experienced the autonomous ride with the conversational UI and had the ability to request more information.

### **Participants**

The participants were divided into two groups (1) online experiment and (2) on-site experiment.

113 people individually participated in the online experiment, with 41 being female and 72 being male. They comprised 70 students, 37 employees and 6 categorised as other. The online experiment consisted of two groups: the control group (44 participants), which did not have the option to request more information, and the experimental group (69 participants), which was given the option. The average age of the control group was 27.7 (SD=10.13), while the average age of the

experimental group was 27.3 (SD=9.60).

A larger number of participants was chosen for the experimental condition to ensure that enough participants were available for all potential user choice combinations. This decision was made because participants were given the opportunity to interact with the system in two ways: by requesting more information or hypothetically taking over the driving task.

Most participants' primary mode of transportation was by car (55.8%). Public transport was used primarily by 24.8% of participants, while 11.5% indicated walking, 6.2% bicycles, and 1.7% other modes of transportation. Regarding prior experiences with autonomous systems, 36.3% of participants had no previous exposure. 39.8% had experienced driving assistance systems, 16.8% semi-automatic driving systems, 5.3% highly automated driving systems, and 1.8% had experience with AVs through research.

8 people individually participated in the on-site experiment, with 1 being female and 7 being male. They comprised 6 students, 1 employee and 1 categorised as other. The average age of the on-site participants was 24.5 (SD=1.60). 4 of them named public transport as their primary mode of transportation, 2 indicated walking, 1 car and 1 bicycle. Regarding prior experiences with autonomous systems, 2 had experienced driving assistance systems, 2 semi-automatic driving assistance systems and 1 highly automated driving systems.

### 6.5.5 Results

This section presents the quantitative results of the AVAM questionnaire and UEQ-S, the self-defined control questionnaire, and the number of times participants hypothetically wanted to take over the driving task. Furthermore, quantitative data from think-aloud feedback and observation are reported. The qualitative data is used to understand the quantitative results further.

Between-group and within-group comparisons were conducted using t-tests and ANOVA. All reported results use a one-tailed significance level of p<.05, given the expectations about the direction of the effects.

The data from the on-site experiment was not comparable due to the small sample size, so it was not included in the statistical analysis. Nevertheless, the on-site experiment aligns with the findings from the online study, suggesting that the results

can be applied to real-life driving scenarios.

### Quantitive Results

Table 6.15: Used variables.

Variables	Min-Max	Mean (SD)	α
(1) Transparency	1-7	3.16 (1.33)	.71
(2) PQ of the UX	1-7	3.33(1.42)	.81
(3) HQ of the UX	1-7	3.98(1.49)	.87
(4) Perc. feeling of control	1-7	3.63(1.33)	.80
(5) AVAM - Effort	1-7	2.50(1.40)	.68
(6) AVAM - Attitude	1-7	3.65(1.53)	.79
(8) AVAM - Intention to use	1-7	3.63(1.60)	.79
(9) AVAM - Safety	1-7	3.33(1.42)	.75

The findings suggest that there is a significant difference in the frequency of takeover requests between failure and non-failure situations, supporting Hypothesis  $H_{1a}$  (p<.01, t=-11.24). Participants were significantly more likely to request to take over the driving task when a failure occurred (243 of 339 possible requests) compared to when there was no failure (74 of 339 possible requests).

On the other hand, the results indicate that providing additional information upon request did not have a significant influence on the preference to take over the driving task in a failure situation (p>.05, t= -.15). Consequently, Hypothesis  $H_{1b}$  was rejected, indicating that the provision of additional information did not affect the participants' inclination to take over the driving task in the event of a failure (TORs<sub>additional feedback</sub>=71.01%, TORs<sub>no additional feedback</sub>=72.73%).

While these findings highlight the importance of failure situations in triggering the desire to take over the driving task, they also suggest that providing additional information may not alter this preference.

To test Hypotheses  $H_{2a}$ - $H_{2d}$ , the relationships between transparency and the dependent variables were examined, including PQ and HQ of the UX, AVAM variables (effort, attitude, intention to use, safety), and the perceived feeling of control. Significant correlations in the expected direction were observed between transparency and all these variables; see Table 6.16.

A mediation analysis using the Sobel test was conducted to gain a deeper understanding of the relationship between transparency, the perceived feeling of control, and the UX. For the PQ, a significant indirect effect of transparency mediated by the subjective feeling of control was found (p<.01). The direct effect of

Table 6 16.	Correlations	hotwoon	transparency	and	donandant	variables
1able 0.10.	Correlations	between	transparency	and	dependent	variables.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Transparency								
(2) Pragmatic Quality of the UX	.39**							
(3) Hedonic Quality of the UX	.30**	.46**						
(4) Perc. feeling of control	.58**	.50**	.33**					
(5) AVAM - Effort	.49**	.38**	.22**	.40**				
(6) AVAM - Attitude	.34**	.65**	.48**	.57**	.33**			
(8) AVAM - Intention to use	.35**	.54**	.26**	.53**	.17*	.65**	48**	
(9) AVAM - Safety	.29**	.36**	.10	.47**	.18*	.49**	59**	.67**

transparency on the PQ became non-significant when accounting for the direct effect of the subjective feeling of control. Similarly, for the HQ, a significant indirect effect of transparency mediated by the subjective feeling of control (p<.01) was observed. The direct effect of transparency on the HQ was no longer significant when considering the direct effect of the subjective feeling of control.

Therefore, the influence of transparency on the PQ and HQ is entirely explained by its impact on the subjective feeling of control. The subjective feeling of control plays a crucial role in linking transparency to the PQ and HQ of the UX.

However, providing additional information upon request did not significantly change the participants' transparency level between the experimental groups (p>.05, t= 1.63). Therefore, there were no significant differences between participants who received additional information and those who did not in regards to the other variables (p>.05). The only exception was the subjective feeling of control, where participants who could request additional information showed a significant increase compared to those who did not (p<.05, F= 3.51). Therefore, Hypotheses  $H_{2a}$ - $H_{2d}$  show only partial confirmation concerning the impact of the subjective level of transparency.

Regarding Hypothesis  $H_{3a}$ , participants requested additional information significantly more often when faced with a system failure (95 of 207 possible requests) compared to normal system behaviour (53 of 207 possible requests) (p<.05, t= -1.87), confirming Hypothesis  $H_{3a}$ .

Regarding Hypothesis  $H_{3b}$ , the results did not confirm an interaction effect of additional information on UX (p>.05), rejecting the Hypothesis. This suggests that providing additional information upon request does not significantly mitigate the negative effects of system failures on the UX.

### Qualitative Results

Table 6.17: Qualitative statements by on-site and online participants (only few online participants provided statements).

Statement category	On-site	$\mathbf{Online}$
Transparency of the system was recognised by participants.	6	3
Transparency of the system was unnecessary.	-	2
Transparency of the system was not enough.	-	3
Participants would have preferred to take over the driving	3	3
task.		
Participants doubt that the system would be accepted by	1	6
customers.		
Participants are satisfied with the driving style.	4	-

In the online study, participants were given the option to provide feedback comments at the end. 34 participants provided feedback. Comparatively, the on-site participants, who were asked to verbally express their opinions, provided a greater amount of feedback. Overall, a slight positive trend suggested that the system was perceived as transparent in both experiments, with the on-site experiment showing a stronger inclination towards this perception. It is important to acknowledge that this qualitative participant feedback does not provide a broad interpretation or analysis. Nevertheless, it indicates that users generally tend to view the system as transparent.

### 6.5.6 Discussion

Regarding transparency communication, the experiment shows similar results to the previous experiments. Providing passengers with information via feedback modalities increases transparency. This transparency, in return, increases the perceived feeling of control, which leads to an increase of the PQ and HQ of the UX. This increase in the perceived control can be considered important, particularly for non-critical failure situations, as participants showed a need to take over the driving task, which will not be possible in AVs.

However, while transparency communication has a positive effect in terms of control ("It was good that it [the conversational user interface] informed me in this situation."), requesting more information in failure situations did neither have a positive influence on participants' transparency or UX nor did it reduce their need to take over the driving task. This lack of impact could be attributed to the fact that requesting more information does not change participants' perceptions of the failure situation. Instead, it merely emphasises that the AV is unaware of the failure, potentially leading to a negative impact on the UX. Participants expressed concerns about the frequency of

such failures, indicating that repeated exposure to these situations would have negative effects over time ("It would definitely upset me over time if something like this happens more often."). This creates an information dilemma. Transparency communication has demonstrated effectiveness across multiple metrics in the context of AD. However, the same transparency communication may not always be advantageous if it exposes the system's limitations by explaining behaviours that are unintended or unexpected from the user's perspective.

As the AV is unaware of its failure, the question arises of how to know when failure situations happen. With participants requesting additional information significantly more often in non-critical failure situations than in regular ones, this increase in requests could be used as an indication to find failure situations. An uptick in requests may indicate that passengers do not comprehend the current behaviour or perceive the AV's driving as incorrect.

Interestingly, despite the theoretical notion in the field of UX that negative experiences can lead users to discontinue product usage (Hassenzahl and Tractinsky, 2006; Kahneman and Tversky, 1979), this experiment did not find evidence of non-critical failure situations influencing participants' attitudes towards AD. The attitude of both groups remained unchanged before and after the experiment. There could be several reasons for this lack of attitude change. Firstly, it is possible that the testers in this study had a generally tolerant attitude towards AD, which may have influenced their perception towards non-critical failures. Secondly, the experiment provided participants with a one-time experience, which may not have been sufficient to create significant changes in attitude. Long-term exposure or repeated interactions might be necessary to observe substantial shifts in attitude. Additionally, it is worth considering that the predominantly simulated driving environment used in the experiment may have limited the realism and emotional impact of the non-critical failure situations, potentially mitigating their influence on attitude change.

### 6.5.7 Limitations

As with any study, this experiment poses some limitations. As it was conducted during the Covid-19 pandemic, most tests had to be performed online. As with the second and third experiments, driving videos lack any immersion regarding driving forces. Furthermore, participants were not seated in a physical vehicle-like simulator build but in front of their computer, possibly further decreasing any feeling of immersion. Nonetheless, it has been shown that results of driving simulator studies are transferable to real-world results (Mullen et al., 2011).

Regarding the on-site study, the WoZ experiment did not lack any physical driving forces or general driving immersion. However, participants were aware of the human driver, even if the driver was not visible to them. Despite this, participants' feedback consistently referred to the vehicle or the conversational user interface, indicating a successful immersion in the WoZ experiment.

Lastly, the study's sample had limitations, with an average age under 30 and most participants being university students. A more diverse sample would have been beneficial to improve the generalisability of the findings.

### 6.5.8 Conclusion & Outlook

This experiment's goal was to investigate the influence of non-critical failure situations on transparency communication using UMDs and the influence on passengers' UX, perceived feeling of safety and control, system understanding and acceptance.

The findings indicate that transparency communication in AD enhances factors like the UX and passengers' perceived control, confirming the previous experiments. However, this effect may vary in non-critical failure situations. As passengers cannot take control in AD scenarios and expressed their desire to do so, informing them about system limitations may not be effective. As the AV is unaware of its own failures, providing additional incorrect information does not benefit passengers. It can actually have a negative impact on the UX.

In the design of transparency communication in AVs, there is a dilemma regarding how the system communicates with passengers. Transparent communication improves factors like the UX and system understanding. However, it can also reveal unintended behaviour that may highlight the system's limitations. Since AVs lack awareness, establishing a feedback loop between humans and the AVs could help reduce the negative effects of these limitations. This is important because the feeling of control influences the effect of transparency on UX. Furthermore, the experiment results show that providing passengers to request additional information significantly increases their perceived feeling of control. By actively involving humans through feedback, AV systems could better address limitations. For instance, an increase in requests for more information could indicate a failure or a situation where the passenger does not understand the system's behaviour. This increase in requests could be used as a signal to design an interface that proactively provides additional information to passengers.

Another potential approach would be to implement a human-in-the-loop design (5000.59, 1998), allowing passengers to provide real-time feedback to the system regarding the effectiveness of its explanations and whether they understood the driving behaviour. Additionally, the option to contact a human operator could be provided upon request, potentially enhancing passengers' feeling of control and, consequently, their UX.

Overall, this experiment again confirms the effectiveness of transparency communication via UMDs in AD but simultaneously shows that non-critical failure situations may require a different approach to transparency communication. More research on this first finding regarding communication in non-critical failure situations is needed.

The next section will discuss the four experiments in context to each other and in relation to recent research regarding this area.

# 6.6 Discussion of Experiments

This section will discuss the four main experiments of this thesis both in terms of their interconnections and relevance to existing research. The experiments were carried out between 2019 and 2021. Since then, more research on the topic of transparency communication in AD through UMDs has been published. Therefore, this section will analyse and compare this subsequent research with the findings from the experiments, providing a comprehensive understanding of the topic and its evolving landscape. An overview summary of the four experiments can be seen in Figure 6.27.

Modality - Increase	Exp. 1 Visual	Exp. 1 Light	Exp. 2 AR + light + text	Exp. 2 mobile app (retrosp.)	Exp. 3 UI + light + AR	Exp. 4 Convers. UI
UX						
Safety						
Control						
Understanding						
Attitude towards techn.						
Change perc. speed						

Figure 6.27: Reduced summary of the four experiments. Teal: the metric was significantly improved; red: the metric was not improved; purple: the metric significantly correlates with transparency; teal-purple: metric was significantly increased and significantly correlates with transparency; white: not tested.

# 6.6.1 User Experience

Regarding the influence of UMDs in AD on the UX through different feedback modalities, the experiments were able to confirm each other. Unimodal visual, light, on-device and conversational UI modalities, as well as the multimodal combinations of AR, light and text, led to a significant measurable increase in the participants' UX. While in experiments 2 and 4, all modalities increased the UX or showed a significant correlation between the UX and transparency communication, in experiment 1, only the world in miniature and light transparency communication did. The sound, text and vibration modalities led to no increase. Interestingly, while text alone did not increase passengers' UX, in combination with AR and light it did.

Thereby, experiment 2 shows that there is a correlation between the UX and the perceived feeling of control. This was further examined and confirmed in experiment 4, showing that increasing transparency and perceived control leads to an increase in UX.

Regarding adjacent research, experiment 1 confirmed the findings of Häuslschmid et al. (2017) that a world in miniature visualisation increases the UX in AD. Experiment 4 somewhat confirms the research of Large et al. (2019) with a self-driving pod. While Large et al. used a conversational voice agent and found an increase in UX, experiment 4 used a conversational UI, leading to the same result.

In terms of retrospective transparency communication and UX, little other research is available. While experiment 2 shows that retrospective information can increase passengers' UX if they were not exposed to transparency communication during the ride, it does not mean that it should be recommended over live information. This is confirmed by the experiment of Wiegand et al. (2020) that shows that most of their participants chose to request explanations during the ride and not retrospectively.

The research of Detjen, Salini, Kronenberger, Geisler and Schneegass (2021) further confirmed the results of experiment 2. In their experiment, providing live information via AR increased passengers' UX. Furthermore, providing live information via a HUD led to a less significant increase in the UX.

Dandekar et al. (2022) and Löcken et al. (2020) used a very similar setup to experiment 1, using light bars left and right of the windshield and different colour coding to transmit live information. Their research confirms the results of experiment 1 with light bars leading to a significant increase in passengers' UX.

While a world in miniature visualisation combined with textual information increased some sub-scales of the UEQ in the experiment of Flohr et al. (2023), they provided another interesting insight. In their experiment, participants preferred to have context-dependent live information shown instead of permanently displaying transparency communication.

In conclusion, the different experiments principally confirm a positive influence of transparency communication through UMDs on the UX of first-time AV users. However, not every feedback modality seems suitable for increasing passengers' UX. This could

also be due to how the modalities were set up and could yield different results when designed in another way. Furthermore, the experiments confirm existing research and are confirmed by newer research.

### 6.6.2 Perceived Feeling of Safety

Other than for the UX, only experiment 3 positively influenced the perceived safety. Experiments 2 and 4 did not yield significant increases in this aspect. It is worth noting that the positive influence observed in experiment 3 may be attributed more to the use of UMDs to influence speed perception and driving styles rather than directly transmitting transparency information. Furthermore, participants could choose their preferred driving style and thus exert control, which might have also led to an increased feeling of safety. This suggests that the effects of UMDs on perceived safety can be multifaceted, involving various cognitive and perceptual factors related to driving behaviour.

The lack of increased perceived feeling of safety in experiments 2 and 4 could be attributed to the specific feedback modalities employed. In the study by Häuslschmid et al. (2017), a world in miniature visualisation was found to significantly enhance perceived safety. Although this visualisation was utilised in experiment 1, the experiment did not specifically focus on evaluating safety-related outcomes.

Detjen et al. (2020) explored the use of light feedback to indicate driving direction changes and found that while this live feedback only slightly impacted participants' acceptance of AVs, perceived safety was identified as the main factor in increasing acceptance.

In experiment 2, combining an AR feedback modality with light and textual feedback did not significantly increase passengers' perceived feeling of safety. However, Colley, Krauss, Lanzer and Rukzio (2021) demonstrated that using AR, light, or a HUD as unimodal modalities led to a significant increase in perceived safety. Interestingly, there was no significant difference among the modalities, as each one resulted in an increase compared to a no-feedback baseline. This suggests that different feedback modalities can be equally effective in enhancing passengers' perceived safety.

In conclusion, only experiment 3 demonstrated a significant increase in passengers' perceived feeling of safety. The feedback modalities used in experiments 2 and 4 did not significantly improve this aspect. However, previous research has shown that a world in miniature visualisation, light, HUD, or AR can be used effectively to enhance

passengers' feeling of safety. Thus, while the experiments of this thesis rather allow for the conclusion that perceived speed and driving style have a greater impact on the perceived feeling of safety than transparency communication through UMDs, adjacent research also found transparency communication to have a positive influence. These findings underscore the potential of providing information via different feedback modalities to create a sense of safety for passengers in AVs.

# 6.6.3 Perceived Feeling of Control

The experiments conducted in this study aimed to investigate the impact of transparency communication via UMDs on participants' perceived feeling of control. This feeling is an important aspect in AD scenarios, as passengers may not have direct control over the vehicle but still desire a sense of agency and influence, as seen in the literature review.

All four experiments successfully increased participants' perceived feeling of control, except for the first experiment, where only the unimodal modality of light led to a significant increase. In this experiment, the world in miniature visualisation, textual, auditory, and vibrotactile modalities did not significantly impact participants' perceived feeling of control. However, in the subsequent experiments, both unimodal and multimodal feedback modalities were effective in enhancing it.

Comparing these findings with previous research, the first experiment's results did not align with the research conducted by Beattie et al. (2014) on increasing perceived control through auditory icons. It is possible that the discrepancy in results can be attributed to various factors, such as differences in study setup, sample size, or the design of the feedback modality.

On the other hand, using a conversational UI, as explored in experiment four, partially supports the increase of control found in the study by Large et al. (2019) where a conversational voice interface was used for transparency communication.

In conclusion, the findings of the experiments highlight the potential of transparency communication via UMDs to provide passengers with a perceived feeling of control in AD scenarios. This is particularly important considering that passengers may not have direct control over the driving task in the future. By utilising different modalities of transparency communication, designers can create interfaces that empower passengers and give them a sense of agency, even when they do not have actual control over the AV.

### 6.6.4 System Understanding

The experiments in this thesis also explored the impact of transparency communication via UMDs on passengers' understanding. Experiments 1, 2, and 4 investigated explicitly whether information transmitted through UMDs helps to increase passengers' understanding of the AV system.

Interestingly, in the first experiment, none of the investigated unimodal feedback modalities significantly increased understanding. In fact, the vibrotactile feedback modality even led to a significant decrease in understanding. However, in the subsequent experiments, transparency communication through the combination of AR, light, and text, as well as retrospective on-device cues in experiment 2 and a conversational UI in experiment 4, all contributed to an increase in passengers' understanding. Experiment 4 further revealed a significant correlation between transparency and participants' understanding.

Therefore, the results of the second experiment align with the research conducted by Wintersberger et al. (2017), which stated that an AR modality improves participants' understanding of driving situations. Additionally, experiment 4 confirmed the findings of Schraagen et al. (2020) that textual transparency communication, especially when providing reasons or intentions, enhances system understanding.

In conclusion, the findings of these experiments demonstrate that providing transparency communication through UMDs is an effective approach for increasing passengers' understanding of AV. However, it is important to note that not every feedback modality was equally effective in achieving this outcome. This could also be due to their specific design and usage. The results emphasise the importance of carefully selecting and designing feedback modalities.

### 6.6.5 Attitude Towards AVs

Experiments 2 and 4 also looked at the influence of transparency communication on the participants' attitude towards using AVs. However, neither of these experiments demonstrated a significant increase in attitude. Although different feedback modalities were successful in enhancing the UX of first-time AV users, they did not have a significant impact on their attitude towards AVs. Interestingly, this lack of influence on attitude was observed for both regular driving situations and non-critical failure situations. It is worth noting that while there was no increase in attitude,

there was also no significant decrease. This suggests that experiencing non-critical failure situations does not have an apparent effect on passengers' overall attitude towards AVs.

This thesis follows, among others, the theory of Hassenzahl and Tractinsky (2006) that it is important to avoid a negative UX as this might lead to people discontinuing a product use which is especially important for first-time users in the context of AD. Transferring this to passengers' attitude towards AVs, the experiments showed that, at least for non-critical failure situations, no negative influence could be seen for first-time users.

An interesting side note is that the study of Colley, Krauss, Lanzer and Rukzio (2021) found out that unimodal feedback in the form of AR, light, or a HUD increases participants' acceptance of the AV. While the experiments of this thesis cannot show any influence on the attitude, transparency communication through UMDs seems to influence a metric close to it, the acceptance.

In conclusion, neither a positive nor a negative influence of transparency communication via UMDs on participants' attitude in different driving situations could be shown. Furthermore, experiencing non-critical failure situations does not seem to negatively influence passengers' attitude towards the AV. It is important to note that these conclusions are specific to the setups and conditions of the experiments conducted in this study and may not necessarily generalise to all scenarios and contexts.

# 6.6.6 Perceived Speed

Regarding the perceived speed of an autonomous ride, the results of experiment three show that different modalities can be used to audio-visually alter the perception of the same drive to make it feel faster or slower. Additionally, allowing participants to select a driving style that closely aligns with their own preferences resulted in increased perceived safety for slower driving styles and increased perceived control for both slower and faster driving styles, despite no actual modifications to the drive taking place.

Looking at adjacent research, Vasile et al. (2023) showed in their experiment that when the driving style of the AV is close to the passengers' perceived own driving style, an increase in perceived safety can be achieved. Interestingly this is only true for passengers' perceived driving style, not their actual one. Furthermore, although

not specifically explored in this study, aligning the AV's driving style with passengers' personal preference has been shown to enhance trust in AVs (Natarajan et al., 2022).

Regarding research published before experiment 3, the experiment was able to confirm the experiment of Basu et al. (2017) that passengers' prefer the AV to have a driving style closer to theirs. Furthermore, research of Yusof et al. (2016) was partly confirmed in regards to the personal driving style of the passenger not being assertive, as control and safety were increased in experiment 3 for the slower driving style but only control for the faster driving style.

In conclusion, experiment 3 revealed that different modalities can alter the perceived speed of an autonomous ride, creating the illusion of a faster or slower drive. Allowing participants to choose a driving style closer to their own led to increased perceived safety for slower driving styles and increased perceived control for both slower and faster driving styles, despite no actual modifications to the drive.

#### 6.6.7 Conclusion

This section has discussed the four main experiments of this thesis, outlining their results, interrelations, and significance in relation to existing research.

All experiments that tested for UX and perceived feeling of control were able to show a positive influence of transparency communication through UMDs on both metrics. They thereby mostly confirmed existing research and were confirmed by newer research. Furthermore, experiments 2 and 4 revealed a correlation between the UX and the perceived feeling of control and overall transparency. Experiment 2 also showed that retrospective feedback via on-device cues can be used to increase the UX and perceived control.

Regarding the perceived feeling of safety, only experiment 3, which focussed on perceived driving style adjustment, could significantly increase passengers' perceived safety. Therefore, speed and driving style perception might have a greater impact on perceived safety than transparency communication. However, this was not confirmed by adjacent research that found providing information through different feedback modalities increases the perceived feeling of safety.

In terms of participants' understanding of the AV system, experiments 2 and 4 led to a significant increase, with experiment 4 revealing a correlation between transparency and system understanding. The unimodal feedback modalities of

experiment 1 did not. The findings confirmed existing adjacent research.

Interestingly, the participants' attitudes towards AVs did not change in any experiment. Transparency communication did not influence the metric, neither in regular nor in non-critical failure driving situations.

Regarding the perceived speed of the AV, experiment 3 showed that different modalities could be used to alter participants' perception leading to an increased feeling of control, which might also be due to them being able to select their preferred driving style, and an increased feeling of safety.

To summarise, transparency communication via UMDs has a positive influence on passengers' UX, their perceived feeling of safety and control, and system understanding. It does not influence their attitude towards the AV, neither positively nor negatively. Furthermore, different feedback modalities also allow for a different speed and driving style perception, influencing perceived safety and control. While a general positive influence of UMDs on the different metrics could be shown through the experiments and adjacent research, not every feedback modality positively influenced every metric. This might be, for example, due to the modality itself or the experiment setups.

# 6.7 Summary of Findings and Contribution

This section provides a summary of the four experiment's main findings, discusses them in regard to the research questions RQ-1 and RQ-2 and highlights their main contribution.

The four main experiments of this thesis provide new insights on transparency communication through UMDs in AD regarding the primary metrics of UX, the perceived feeling of safety and control and system understanding. Furthermore, the alteration of the perceived speed of an AV was investigated, and correlations regarding different metrics were calculated. The main findings of these experiments are presented in Figure 6.28 and 6.29.

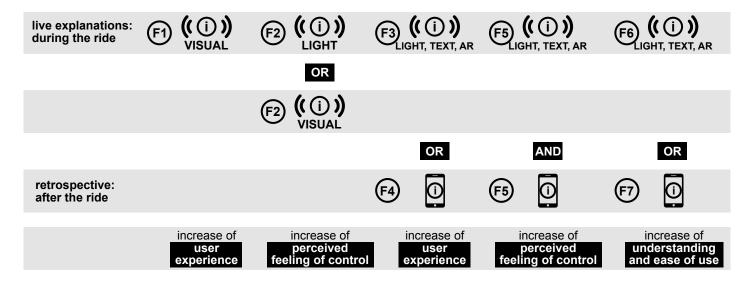


Figure 6.28: Contributions of experiment 1 and 2, showing their main findings F1 - F7.

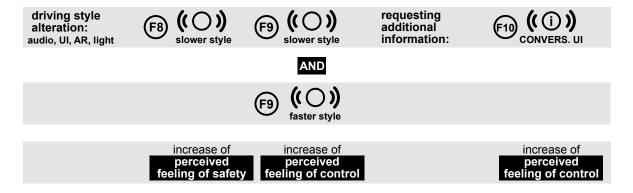


Figure 6.29: Contributions of experiment 3 and 4, showing their main findings F8 - F10.

### 6.7.1 Main Findings

The main findings of the experiments are:

- F1) Providing AV passengers with live information through a world in miniature visualisation significantly increases their UX.
- F2) Providing AV passengers with live information through a world in miniature visualisation or a light feedback modality significantly increases their perceived feeling of control.
- F3) Providing AV passengers with live information through a multimodal combination of light, text, and AR significantly increases their UX.
- F4) Providing AV passengers with explanations of the AV's actions after the ride through a smartphone app has a similar positive impact on the UX as providing real-time information. However, retrospective explanations do not prevent negative experiences during the ride. Additionally, offering retrospective feedback does not have any extra positive effect on the UX if live explanations were already provided.
- F5) Providing AV passengers with live explanations through a multimodal combination of light, text, and AR and retrospective feedback via a mobile application significantly increases the perceived feeling of control. Paraphrased: Even if live explanations were given, retrospective feedback still positively impacts the perceived feeling of control.
- F6) Providing AV passengers with live explanations significantly increases the understanding and ease of use of the AV.
- F7) Providing AV passengers with retrospective explanations significantly increases the understanding and ease of use of the AV if live explanations were not provided.
- F8) Allowing AV passengers to choose a personalised driving style altered through a multimodal combination of audio, an UI overlay, AR and light that makes the AV feel faster significantly increases their perceived feeling of safety.
- F9) Allowing AV passengers to choose a personalised driving style altered through a multimodal combination of audio, an UI overlay, AR and light that makes the AV feel slower significantly increases their perceived feeling of safety and control.
- F10) Providing AV passengers with the ability to request additional information during an autonomous ride through a conversational UI significantly increases their perceived feeling of control.

### 6.7.2 Research Question 1

RQ-1: How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?

Regarding RQ-1, the experiments have shown that transparency communication in AD through uni- and multimodal feedback modalities has a positive influence on the passengers' UX and their perceived feeling of control. Furthermore, their UX correlates with the system transparency and their perceived feeling of control. However, not every feedback modality was able to increase the UX or perceived control, which could, among other things, be due to the way the modalities were designed or how the experiments were set up.

In terms of system understanding, the experiments could partly show an increase through transparency communication using UMDs. While no unimodal modality led to an increase during an autonomous ride, the multimodal combination of AR, light, and text did, as well as using a smartphone app after the ride. Furthermore, experiment 4 found a correlation that showed a link between an increase in transparency and passengers' understanding.

Regarding the perceived feeling of safety, only experiment 3, which focussed on driving style alteration using different modalities, found a significant increase in perceived safety. This is rather allocated to the perceived speed difference and participants' ability to choose their preferred driving style than the transparency communication. The different transparency modalities in experiments 2 and 4 did not have a positive influence on the perceived feeling of safety, nor did it correlate with the system's transparency.

To summarise, providing transparency communication through UMDs has a positive influence on the passengers' UX, the perceived feeling of control and system understanding when they are first-time AV users. Providing the option to choose the preferred driving style and altering the perceived speed seems to increase passengers' perceived safety.

# 6.7.3 Research Question 2

RQ-2: How do failure situations affect the passengers' perception of transparency communication?

Regarding RQ-2, experiment 4 has revealed an information dilemma regarding transparency communication through UMDs in AD. While it confirmed the other experiments' results on the effectiveness of transparency communication regarding different metrics, it also showed that the same transparency communication could cause issues in non-critical failure situations. Despite significantly increasing passengers' perceived feeling of control, providing them with the option to request additional information about a driving situation did not have a mitigating effect, as it only pointed out in greater detail that the AV is unaware of its failure. Otherwise, the failure would not happen in the first place.

Therefore, the experiment's conclusion proposes that further research is needed on the topic and that an increase in additional information requests can indicate a non-critical failure situation. Furthermore, a human-in-the-loop design could be employed based on the number of information requests allowing passengers to give feedback on a current situation or connect them to a human service operator or teleoperator.

To summarise, providing the same transparency communication of regular driving situations in non-critical failure situations reveals the AV's limited knowledge of its failures creating an information dilemma. Different measures are needed to include passengers in this process and to detect failure situations early on, possibly through the number of information requests or a human-in-the-loop design.

#### 6.7.4 Conclusion

This chapter has presented and discussed the four main experiments of this thesis. They were based on an extensive literature review, focus groups and expert interviews and followed the UCD process. Thereby, the experiments gradually explored the use of different UMDs in AD and their influence on passengers' UX, their perceived feeling of safety and control, and their system understanding.

The experiments have shown the positive influence of transparency communication in AD through different UMDs on passengers' UX, their perceived feeling of control and system understanding. They furthermore showed that the perceived speed can be influenced using different modalities. This alteration of the perceived speed, combined with passengers being able to choose their preferred driving style, seems to increase the perceived feeling of safety. Furthermore, it has been shown that passengers' UX directly correlates with their perceived feeling of control and the system's

transparency.

However, transparency communication through different feedback modalities is not infallible. As experiment 4 has shown, transparency communication in non-critical failure situations can create an information dilemma and faces different challenges as it reveals the AV's limited knowledge of its failure. Therefore, a human-in-the-loop design could be favourable to detect failure situations early on.

Lastly, this chapter has presented the main findings of the four main experiments, providing contributions that can be used to design for a positive influence on the metrics above in AD, and answered the research questions RQ-1 and RQ-2.

Having found these significant positive influences of transparency communication through different UMDs on the passengers' UX, their perceived feeling of safety and control, and their system understanding raised another question: How can these results be made readily accessible and applicable to those interested in advancing the field of ADX? The following chapter will present the development of a card-based toolkit that aims to provide a solution to this question.

# Chapter 7

ADX.cards - The Autonomous Driving Experience Cards Toolkit

## 7.1 Introduction

With the research of the four experiments done, a new question arose. While publishing peer-reviewed research is undoubtedly important, making it available and accessible to the target groups seems equally important. This thesis has uncovered significant findings regarding transparency communication in the context of AD. The next objective is to determine how to effectively share these results and insights of adjacent research with UX, XAI, and HCI designers so that they can be used in their work.

This led to the third research question:

RQ-3: How can a framework be used to provide the research findings on transparency communication in autonomous driving to a broader, interdisciplinary audience for application in design-based disciplines?

The choice fell on creating a card-based design toolkit, as they are a popular and proven solution in the design space (Roy and Warren, 2019), more on that in Section 7.2. It is called ADX cards<sup>1</sup>.

This chapter presents and discusses the theoretical background that led to the decision to create the card-based ADX toolkit. Then, the final toolkit is presented. This is followed by a section on the different design iterations developed and refined based on expert and workshop input. Subsequently, four independent case studies that used the ADX cards toolkit are presented. It is shown how the case studies interpreted and used the toolkit, what kind of solution they created and what results they obtained. Then, the toolkit and findings of the case studies are discussed, and a conclusion, including the final contribution, is presented.

<sup>&</sup>lt;sup>1</sup>https://adx.cards/

# 7.2 Theoretical Background

Card-based design toolkits are a common way in creatively inclined fields to stimulate creativity, help in (design-) workshops, teach non-professional users about a topic or help them overcome mental barriers<sup>2</sup> and are mostly used to support in early design stages (Möller, n.d.). In their study, Roy and Warren (2019) analysed 155 different card-based design toolkits designers can use. While the first toolkits started to come up in the 1950s, it took 40 years until the they were not only aimed at the expert but designed to be used in groups with non-professional users (Tudor et al., 1993). According to Roy and Warren (2019), card-based design toolkits began to sprout after the turn of the millennium. Their intended use was always focussed on something creativity-based, for example, stimulating ideas, designing modern websites, or including non-creative users in the design process. These card-based design toolkits are generally designed for one specific area, for example, helping to design learning games (Deng et al., 2014) or for the internet of things (Mora et al., 2017).

In their research, Roy and Warren (2019) highlight that card-based design toolkits have several advantages. They enable the creative merging of information and ideas by removing stringent orders, fostering shared understanding and communication within teams, offering tangible representations of information, providing useful and concise summaries of information, and serving as semi-structured tools that bridge the gap between blank Post-it notes and detailed manuals. However, card-based design toolkits also have several downsides that must be considered. These include potentially overwhelming users with excessive information, oversimplifying complex concepts due to space constraints, being challenging for users to grasp and utilise effectively, especially when they are not experts in the according field, and being difficult to modify or update once created.

Regarding the potential users, the study of Yoon et al. (2016) suggests that cardbased toolkits should provide guidelines on how to use them, even if they are designed to be used open-ended. Additionally, (Roy and Warren, 2019, p.15-18) suggest five types of cards a toolkit can have, based on the research of Möller (n.d.) and their own:

- Cards that provide prompts to stimulate creative thinking
- Cards that summarise good design practice know-how or information

<sup>&</sup>lt;sup>2</sup>see, for example,

https://www.enoshop.co.uk/product/oblique-strategies.html (Accessed: August 2023)

http://www.experienceandinteraction.com/tools/ (Accessed: August 2023)

https://innovation.tools/products/thinkpak-a-brainstorming-card-deck (Accessed: August 2023)

- Cards that summarise design methods
- Cards that provide concepts for specific design problems or domains
- Cards that provide checklists to aid specific design tasks

It is thereby important to highlight that card-based design toolkits should not be seen as the only perfect or always working solution. In the study of Bornoe et al. (2016), where they tested different toolkits (N=44), no influence of card-based design toolkits regarding usefulness or design quality could be found. According to them, the toolkits helped with ideation and keeping discussions alive. However, they could not make up for the lack of design knowledge in participants, leading to them having problems with comprehension. Thereby, one of the best designs was created by a group that did not have access to the toolkits.

In contrast, the study of Daly et al. (2012) (N=48) found that using a card-based toolkit that provided information on design heuristics helped to create better evolved, more unique and creative designs. This is also true for the study of Yilmaz et al. (2012), where designs that used heuristics cards were more complex, feature-rich, and creative.

Roy and Warren (2019) fittingly describe card-based design toolkits as helpful for generating new design ideas and aiding the design process in team settings. However, they also highlight that these toolkits might not be a one-fits-all solution for novice designers, which might need additional guidance or support.

To summarise, card-based design toolkits are a popular way to convey knowledge in design-based disciplines, including UX and often focus on one specific area. They can be used by experts and novice users alike, for example, in workshops. While they offer multiple benefits, such as a concise summary of information or fostering shared understanding, they also have some downsides to consider, like overwhelming users with too much information or being difficult to update once released. These toolkits should always provide some guidelines on how to use them and have the potential to induce creativity and make solutions more unique or feature-rich.

## 7.3 Toolkit

This section will describe the ADX cards toolkit and how it is designed to convey the knowledge gained from the four experiments and adjacent research and make it useable for solo designers as well as in design workshops. It will refer to the research discussed in the previous chapter and show how the ADX cards try to use the upsides of card-based toolkits to their benefit and apply a transmedia design approach to tackle their downsides. This section focusses on the finished toolkit. In the subsequent sections, the different design iterations that led to the finalised version will be presented.

#### 7.3.1 General Overview

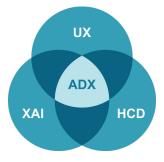


Figure 7.1: Focus areas of the ADX cards.

As the name ADX cards suggests, it is about experiences in AD. Therefore, the toolkit combines three main areas regarding AD, see Figure 7.1. (1) They are about XAI and thus making AI more transparent. Different cards of the toolkit will help the users to design this transparency. (2) The cards put the passenger of an AV at the centre of it all, following the UCD approach. In the final toolkit, this is referred to as human-centred design (HCD). (3) The cards help design new and positive experiences in AD regarding transparency communication through different feedback modalities.

The toolkit sees itself as a holistic solution to designing for transparency communication in AD, see Figure 7.2, and has three main goals. Thereby, the ADX cards can be used to address only one of the goals or all of them. Furthermore, the toolkit can be used, among other things, by oneself or in a group during a workshop or design phase.

1. Education: The toolkit allows oneself or others to gain knowledge about level 5 AD and its related areas of expertise, such as transparency, XAI, and UX. It does

not expect any prior knowledge before usage. It is built to guide users through the process of getting a first understanding of all relevant topics.

- 2. Designing solutions: This is the main goal of the toolkit. Following the research of this thesis, the ADX cards help the user to design for transparency communication for passengers of AVs by using different feedback modalities. The cards help designers create prototypes to increase the passengers' UX, understanding of the system and their perceived feeling of safety and control.
- 3. Evaluation: The toolkit supports users in developing fitting evaluation strategies to examine their concepts and prototypes and provides input on how to analyse and interpret the findings regarding AI transparency in AD.

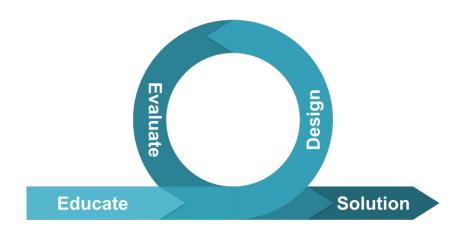


Figure 7.2: Goals of the ADX cards.

# 7.3.2 Transmedia Design Approach

As shown by Roy and Warren (2019) in the previous section, card-based design toolkits have several downsides, including overwhelming the user with too much information or oversimplifying complex concepts, being difficult to use for non-experts or hard to modify once created. In order to counteract these downsides, the ADX cards is a transmedia toolkit that combines physical cards with digital content; see Figure 7.3. Most physical cards feature a QR code on the back that allows users to scan it. They will then be redirected to the according page on the ADX cards website<sup>3</sup> where interactive material and more content can be found.

This design aims to counteract all the points of concern by Roy and Warren (2019). Starting with the physical cards, users will not be overwhelmed with too

<sup>&</sup>lt;sup>3</sup>https://adx.cards

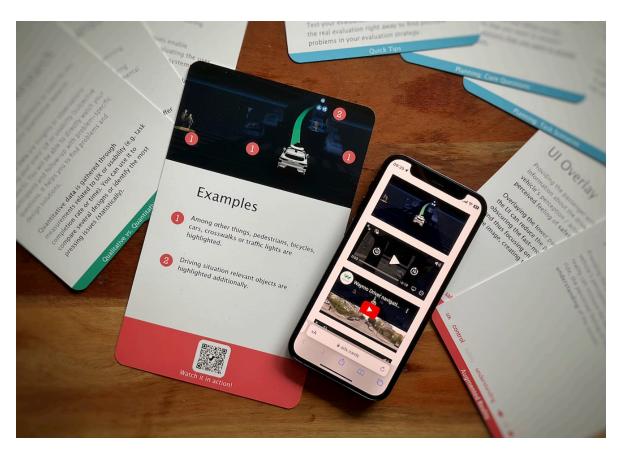


Figure 7.3: Physical ADX cards with interactive content on smartphone.

much information, as the card space is limited. At the same time, complex concepts are only introduced on the cards but not oversimplified as more information is available via the QR codes. Providing a designated education section in the toolkit aims to help everyone dive into the topic and make the toolkit easier to use for non-experts. The goal is to give users a relatively quick start with the physical cards, for example, in a workshop setting, and allow them to get more information via QR codes when needed. This also has another benefit: it allows users to get knowledge asynchronously, as everyone can scan QR codes when needed. Lastly, having digital content available helps to modify and extend the toolkit in the long run. While it is not possible to easily add new physical cards, the existing ones can be extended with new content and interactive examples online.

# 7.3.3 Usage Scenarios - User Stories

To better understand some application areas of the ADX cards, two short user stories can be found on the website<sup>4</sup>. While the main focus of the toolkit is to be used in workshop scenarios with multiple people, possibly multiple card sets, and in

<sup>&</sup>lt;sup>4</sup>https://adx.cards

combination with digital devices, the toolkit can be used in many ways. One can use it to solely inform oneself about the topic of transparency communication in AD or even only UCD related topics. Or the ADX cards can be used to create an evaluation strategy for empiric research regarding HCI and learn how to evaluate and interpret the results. In the following, the two user stories are presented.

Paula will write her Bachelor's thesis about HCI in autonomous driving and plans to perform empirical research. To educate herself on the topic and get a basic understanding of all relevant knowledge, her supervisor recommended the ADX.cards website to her. After browsing the website, she has a basic understanding and a good starting point of relevant theories. She was able to get some inspiration for her HCI designs. Furthermore, she isn't afraid to create an evaluation strategy anymore, as the complex topic and multiple buzzwords now make sense to her.

Sam is working at a car manufacturer and is planning to host a workshop. He and his colleagues should create new ideas for interior communication in their upcoming autonomous vehicle. The workshop will be attended by designers and engineers alike. Sam starts by handing out the knowledge cards to get everybody on the same page. Afterwards, Sam hands out the feedback modality cards to gain inspiration and to agree on one modality type. Then, the whole team uses the blank card to design their own feedback modality that they want to implement in a prototype.

# 7.3.4 Card Types

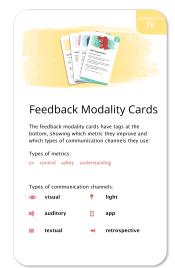
In order to achieve the three main goals previously mentioned and to help users better understand the structure of the ADX cards, different card types, or categories, have been created.

When using the physical cards, there are five types: Introduction Cards, Game Plan Cards, Knowledge Cards, Feedback Modality Cards and Evaluation Strategy Cards. When using the website, more on that in the next subsection, there are no Introduction Cards, as the start page of the website takes over that role. In the following, the different card types will be presented and discussed. For reference, images of the physical cards will be used, the website will be presented in the next subsection.











to add interactive material and more details to the physical cards. Knowledge Cards

Knowledge Cards
QR codes will provide you with further information on relevant knowledge.
Feedback Modality Cards

Feedback Modality Cards QR codes will provide you with multiple interactive examples of the different modalities to gain a better understanding and boost your creativity.

Evaluation Strategy Cards QR codes on the back will provide you with a detailed evaluation manual to help you build your evaluation strategy.













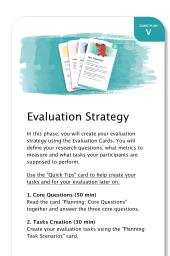


Figure 7.4: The ADX Introduction and Game Plan Cards.

#### **Introduction Cards**

There are seven *Introduction Cards*, and as the name suggests, they are supposed to introduce the user to the ADX cards; see Figure 7.4. They will learn about the areas the toolkit covers and its main goals; see the subchapters above.

Furthermore, the three main card types, *Knowledge*, *Feedback Modality*, and *Evaluation Strategy*, are explained and shown how they can be recognised in the card deck. Every card type has its colour and icon. These can be seen on the top right of every card and are also reflected in their general colour coding.

Next, it is explained to the user how the *Feedback Modality Cards* work. More on that, see below.

Then, the users are informed that the ADX cards are a transmedia toolkit, how the QR codes are intended to be used and with which cards they could start, depending on their background.

Lastly, users are informed that should they use the ADX cards in a workshop setting, they should continue to read the *Game Plan Cards* as they have been designed for workshops.

#### Game Plan Cards

There are five *Game Plan Cards*, and they are to be used when the ADX cards are used within a workshop setting; see Figure 7.4. The goal of a complete workshop run is to (1) dive into the topic of transparency communication in AD, (2) create a prototype concept, and (3) create an evaluation strategy. As mentioned earlier, doing only one or two of the above points is also possible.

In the first phase, the starting phase, the group picks a time manager to keep track of time. Then, they read the *Knowledge Cards* within the group and discuss them to get everyone on the same page. After that, the *Feedback Modality Cards* are divided among the participants. They are supposed to read them, look at the interactive examples to better understand them, and then present them to each other.

The second phase, the creation phase, is about creating a first prototype draft. First, participants must decide on a specific topic, which can be a driving situation, for example, transparency communication at crossroads, or a general problem like a reduced feeling of control for passengers. Then, participants perform a brainwriting pool exercise (Schlicksupp, 1975) to quickly gather ideas. Next, they prioritise the found ideas, split into subgroups of three people and choose one idea per subgroup. Using the *Feedback Modality Cards*, each subgroup designs its own feedback modality solution. Therefore, the ADX cards provide an empty *Feedback Modality Card* that

can be written on. Subsequently, the subgroups present their self-made *Feedback Modality Card* and first solution to the other subgroups and give feedback to each other.

In the third phase, the evaluation phase, the workshop group will create their first evaluation strategy draft. They will define research questions, metrics and tasks. Two dedicated cards within the *Evaluation Strategy Cards* have been created to help with this task: (1) the *Core Questions* card and (2) the *Task Scenarios* card. Both should be used by the participants to be guided through the evaluation strategy creation in combination with the other *Evaluation Strategy Cards*.

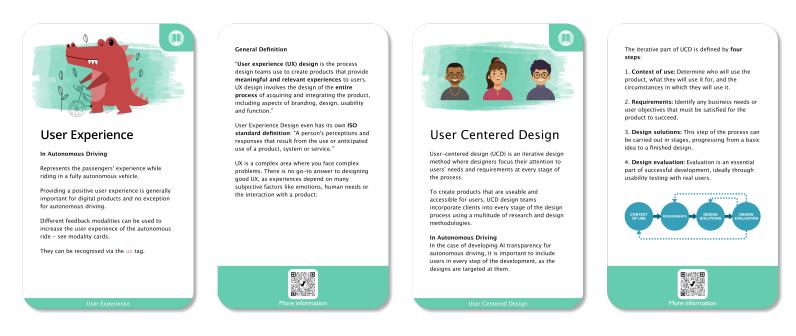


Figure 7.5: Two of the ADX Knowledge Cards, front and back.

#### **Knowledge Cards**

There are eleven *Knowledge Cards*, and their purpose is to introduce users of the ADX cards to the theoretical principles used within the toolkit. These cards have content on the front and the back. If applicable, the front always refers to the card's topic in AD and the back refers to the general definition. Furthermore, these cards now contain a QR code on the back, allowing users to get more information on the topic. As the amount of cards, front and back, is too much to put on a page, Figure 7.5 shows only an extract of cards. The full set can be found on the website<sup>5</sup>.

<sup>&</sup>lt;sup>5</sup>https://adx.cards/knowledge-cards.html

Next to the main metrics researched in this thesis, they also provide basic insights into usability and the SAE levels and introduce the users to the difference between qualitative and quantitative research. Furthermore, they introduce statistical comparison and significance of data and what kinds of prototypes can be used to create studies on transparency communication in AD.

#### Feedback Modality Cards



Figure 7.6: Two of the ADX Feedback Modality Cards, front and back.

There are seven Feedback Modality Cards, and their purpose is to give users proven modalities that can increase the UX, system understanding and perceived feeling of safety and control through transparency communication in AD. Furthermore, the toolkit contains empty Feedback Modality Cards that allow the user to create their own. The Feedback Modality Cards are the heart of the ADX cards toolkit and summarise the main findings of this thesis and adjacent research in an applicable manner.

On the front, each card provides a quick textual summary of what its modality improves in AD when used for transparency communication. At the bottom, tags quickly highlight the improved metric, and icons show which types of communication channels the modality uses; see Figure 7.6. On the back, the cards provide an example for the users to better understand how such a modality could look and be implemented. On the bottom, the QR code redirects users to the website, where more interactive examples in the form of videos are presented to understand better the modalities and how they could work. As the amount of cards, front and back, is too much to put on a page, Figure 7.6 shows only an extract of cards.

### **Evaluation Strategy Cards**



Figure 7.7: Two of the ADX Evaluation Strategy Cards, front and back.

There are nine Evaluation Strategy Cards, and their purpose is to help users design an evaluation strategy for their concepts and prototypes and to explain to them how to gather and evaluate the main metrics UX, system understanding, and perceived feeling of safety and control. Furthermore, there is a Quick Tips card, which contains a collection of useful tips regarding empirical evaluations.

Regarding the *Evaluation Strategy Cards* concerned with the main metrics, the front provides a short summary of how to evaluate them and the back how to interpret their results. The QR code at the bottom redirects users to the website, where they are provided with extensive information about the subject matter. Lastly, two cards are designed to help users define their core questions and tasks. As the amount of cards, front and back, is too much to put on a page, Figure 7.7 shows only an extract of cards.

#### 7.3.5 The Website

As mentioned, the ADX cards is a transmedia toolkit. Next to the physical cards, extended information and interactive examples are presented on the website<sup>6</sup>. Thereby, the website can also be used without the physical cards, as it provides the same structure and (extended) content but in a non-tangible form.

When users open the homepage, they are presented with a general introduction to the toolkit, how it will be used and advice on which cards to start with depending on their background. This homepage is the equivalent of the *Introduction Cards*. Users can select the other four card types in the top navigation menu: *Game Plan, Knowledge Cards, Feedback Modality Cards* and *Evaluation Strategy Cards*. While the *Game Plan* is a classic sequential website explaining the use in workshops, the other three links provide the user with a card-like overview screen of the different cards; see Figure 7.8. Each of the cards contains a very short summary of its content. This aesthetic was chosen to reflect the card-based approach of the toolkit even when not using the physical cards. When the user clicks on a card, it is opened as a new page. This is the same page that users get to see when they scan the QR code on the corresponding card. Thereby, it was made sure that the website is responsive and works well on mobile devices, as they are supposed to be used in conjunction with the physical cards during workshops.

<sup>&</sup>lt;sup>6</sup>https://adx.cards

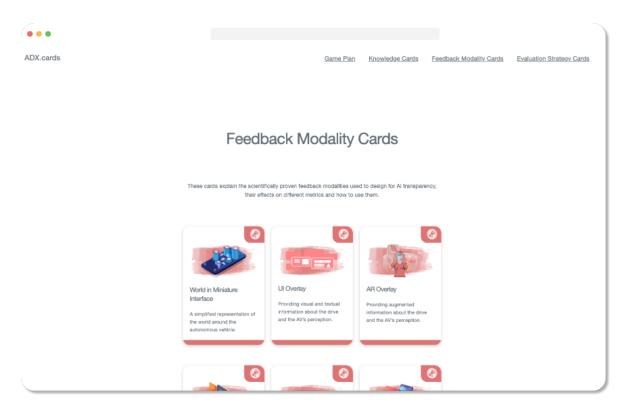


Figure 7.8: Screenshot of the adx.cards website showing the Feedback Modality Cards overview site.

# 7.4 Design Iterations

This section will describe the different design iterations that the ADX cards toolkit went through until its final state described in the previous section was reached. During the development, multiple UX experts were used as sparring partners to help gather feedback on the iterations, namely a professor for UX and two UX designers, both with research backgrounds and industry experience. All of the experts also had experience with card-based design toolkits.

Expert sparring and interviews served multiple purposes to strengthen the development and evaluation of transparency communication strategies for AD:

- Contextualization of Experimental Findings: While the experiments yielded quantitative and qualitative user data, expert insights allowed for deeper contextualization, relating findings to broader design, technological, and deployment considerations in the automotive field.
- Refinement of the ADX Toolkit: As the toolkit aimed for practical applicability in design-based disciplines, expert feedback was critical to ensure that the cards, categorizations, and recommendations were both theoretically grounded and practically useful.
- Expectation of Divergence: Given the multidisciplinary backgrounds of the experts, it was anticipated that not all feedback would converge. Diverging opinions were expected and valued as indicators of real-world complexity, helping refine the toolkit for broader applicability.

Overall, the rationale for conducting expert interviews was to enhance the relevance, validity, and applicability of the thesis' outputs, ensuring they resonate not only within academic circles but also in the emerging real-world practice of AD UX design.

# 7.4.1 First Concept

Compared to the final ADX toolkit, the first concept started out sparsely. It focused solely on different feedback modalities and their influence on the metrics UX, perceived safety and control, and system understanding. However, these cards are still the core of the finished framework, as will be shown later. The first scribbles and card designs describing the basic ideas of the *Feedback Modality Cards* can be seen in Figure 7.9.

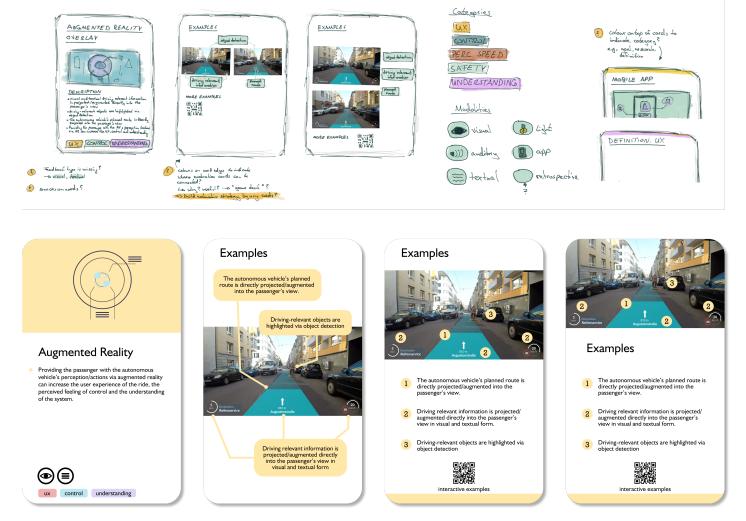


Figure 7.9: First conceptual scribbles and card designs of the AR feedback modality card of the ADX cards toolkit.

The idea was for every card to have two sides. The front will show the title of the feedback modality, an image representing it so that the card can be recognised faster during a workshop, and a text describing the feedback modality. Additionally, at the bottom of each card, the metrics improved by the modality are displayed as tags. The goal was to make it easy and fast to see which modality improves which metric. Therefore, icons were also designed to quickly highlight what type of communication channel the modalities use. AR, for example, uses visual and textual feedback.

On the back, each *Feedback Modality Card* would contain examples to make the description on the front easier to grasp for users. These examples would be taken from the experiments of this thesis or adjacent research. The back of the cards would also be the first indication of the hybrid ADX cards toolkit approach.

Users could scan a QR code and be redirected to the toolkit's website, where

examples would be provided as videos, and more information on the modality would be presented. This hybrid approach, mixing physical cards with additional digital content, makes up the core idea of the ADX cards toolkit and tries to counteract card-based design toolkit limitations (Roy and Warren, 2019) as mentioned in the previous chapter.

With the first basic card concept defined, seven Feedback Modality Cards were designed based on the four main experiments and adjacent research: Augmented Reality, World in Miniature, UI Overlay, Mobile App, Light, Conversational UI, and Anthropomorphic Voice Agent. The cards then went through three different graphical design iterations; see Figure 7.10. In these graphical iterations, the content of the cards did not change but only their appearance. In the first version, every card had the same theme colour, in version 2 and 3, every Feedback Modality Card was assigned its own colour. This would later prove to be problematic. Furthermore, the icons of the modalities changed as did the presentation of the tags and the QR codes.

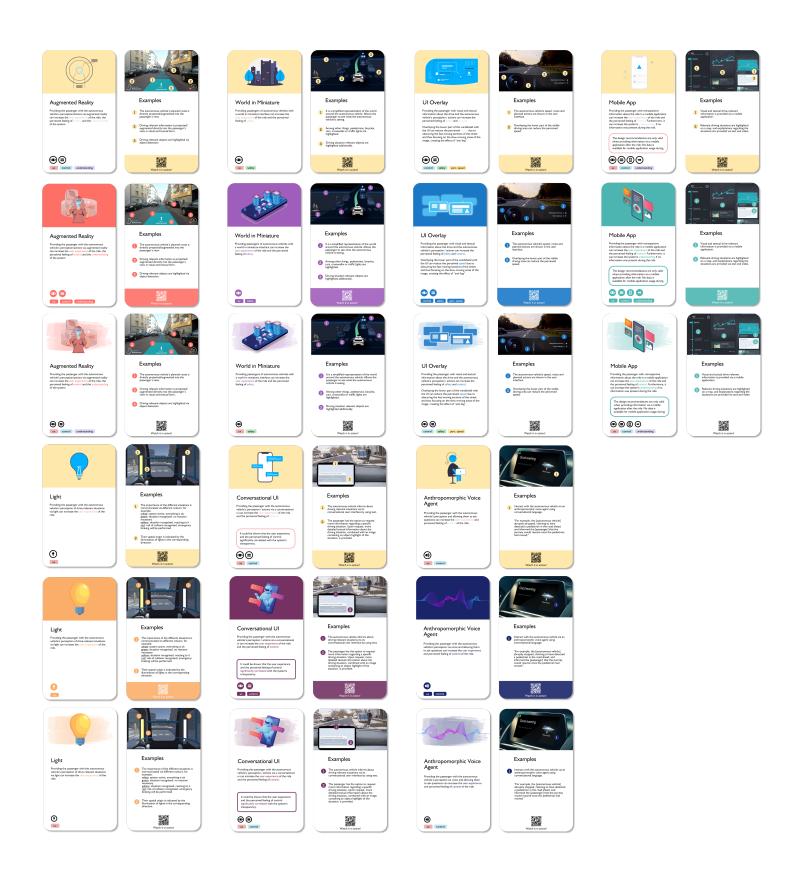


Figure 7.10: Three first graphical design iterations of the ADX cards.

#### **Expert Validation**

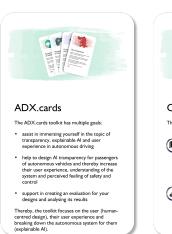
This first concept was then presented to one of the UX designer experts and discussed in a workshop. The expert did not have any previous knowledge about the toolkit. The workshop provided valuable input that was used for the second design iteration. The main takeaways were:

- 1. The user needs an introduction to the toolkit that tells them what it is and how it is used. In the current state, they would only be given seven cards with no introduction.
- 2. A first draft of the target audience was developed. The primary target group are designers and researchers, and the secondary target group are people who want to learn about the topic. Thereby, the toolkit should introduce all users to the topic; in a best-case scenario, they can develop a first concept with the toolkit.
- 3. Multiple goals for the toolkit were derived: (1) create understanding and transfer knowledge, (2) promote creativity (in groups) and help to create transparency communication concepts and prototypes, and (3) teach how to evaluate concepts and prototypes.
- 4. Regarding the application, the user could either use the proven modalities to design for a certain metric, for example, perceived safety, or use the *Feedback Modality Cards* as inspiration to design their own feedback modality.

### 7.4.2 Second Iteration

The Feedback Modality Cards were not reworked for the second iteration, but the third design variant was used; compare Figure 7.10. Instead, two new types of cards were created based on the feedback of the UX designer and the points developed during the workshop. (1) Instruction Cards, which should help to onboard the user, and (2) Definition / Evaluation cards, which should explain the four main metrics (UX, system understanding, and perceived feeling of safety and control) to the user and teach them how to evaluate them.

Five Instruction Cards were created, see Figure 7.11 first row, that introduced the user to the general idea of the ADX cards toolkit, the two available card types (Definition / Evaluation Cards and Feedback Modality Cards), how the Feedback Modality Cards work, how to use the QR codes and where to begin.

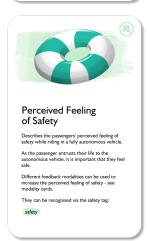
























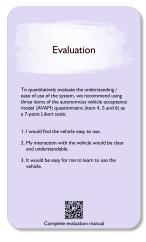






Figure 7.11: The five Instruction Cards and Definition / Evaluation Cards of the second iteration.

Furthermore, to help the user better understand the topic, five *Definition / Evaluation Cards* were created; see Figure 7.11 second and third row. On the front, they give the user basic information about the four main metrics, and a fifth card recommends using A/B testing between groups with and without transparency communication for examining any designs. On the back, the four cards regarding the metrics give a concise explanation of how to evaluate the metric, providing concrete questions or a reference to the UEQ-S. The fifth card displays a flow diagram that should help users decide which statistical test to use depending on their data.

Furthermore, this was the first iteration including a website. For quick prototyping, the tool Notion<sup>7</sup> was used, as it provides a gallery-like database view, perfect for displaying different cards; see Figure 7.12. A video walkthrough for better understanding is also available<sup>8</sup>. This first version of the website did not have a top-level navigation structure but only provided users with a homepage displaying different cards. Each card already provided more content than the physical ones, and the *Feedback Modality Cards* included interactive video examples. Users could filter the gallery view on the homepage according to the metric they want to improve or the feedback modality they want to use. For example, one could select UX and auditory feedback and would be provided with the Anthropomorphic Voice Agent card.

#### **Expert Validation**

This second concept was then presented to the UX professor and discussed in a workshop. At this point, the expert had no previous knowledge about the toolkit. The workshop gave important feedback that influenced the third design version. The main takeaways were:

- 1. The physical cards and especially the website need to emphasise better what the ADX toolkit is used for and by whom it is meant to be used.
- 2. The toolkit needs to provide its users with more guidance and help them understand when to use which cards. A general process could be described as a game plan to achieve this.
- 3. The toolkit should provide more cards that explain relevant theories and metrics to the users. In the current state, novice users would have difficulty using the toolkit as they lack any required knowledge in the areas of expertise and maybe

 $<sup>^7 \</sup>mathrm{https://notion.so}$  (Accessed: August 2023)

<sup>&</sup>lt;sup>8</sup>Walkthrough version 1: https://v1.adx.cards/ (Accessed: August 2023) Walkthrough version 2: https://v2.adx.cards/ (Accessed: August 2023)

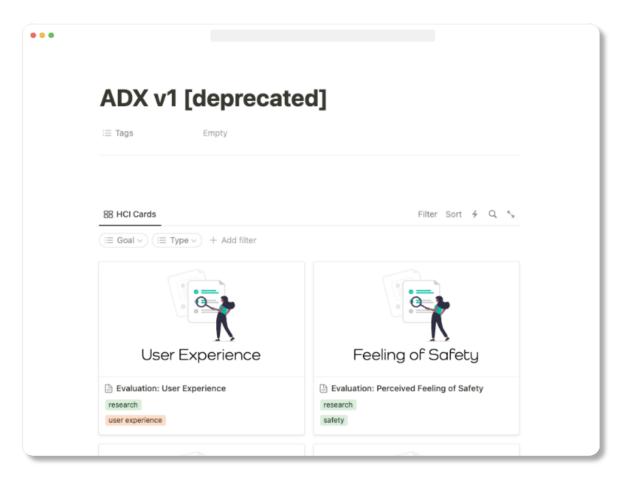


Figure 7.12: The first prototype draft of the website.

even understanding of required terms. The toolkit should help them with onboarding. The professor suggested to explain relevant concepts like SAE levels or UCD.

- 4. The *Definition / Evaluation Cards* should be separated into two groups, as information on evaluation is not needed when reading definitions and vice versa. Furthermore, this would give each card more space for the specific content.
- 5. It could help to create user stories for the main use cases and display them on the website to help potential users understand better how the toolkit can be used.

#### 7.4.3 Third Iteration

The third iteration was created based on the feedback of the UX professor and the developed ideas during the workshop. In the first version of the third iteration, there were now four card types: *Introduction Cards, Knowledge Cards, Feedback Modality Cards*, and *Evaluation Strategy Cards*. Aside from the workshop input, each card type was now assigned a specific colour to make it visually easy to separate. The first

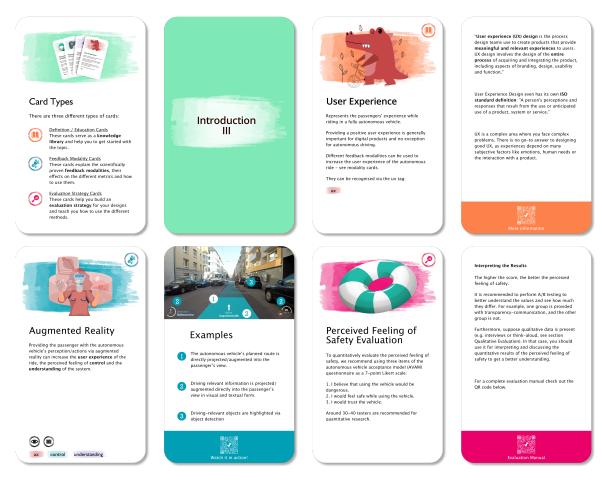


Figure 7.13: Extract of the first design variant of the third iteration using unified colours per card type. From left to right: Introduction Card, Knowledge Card, Feedback Modality Card, Evaluation Strategy Card.

design variant can be seen in Figure 7.13.

The *Definition / Evaluation* cards were now separated in two different groups. The *Knowledge Cards* present the user with input on ten different relevant topics in regards to transparency communication in AD: SAE levels, XAI, UX, usability, UCD, understanding of the system, perceived feeling of safety, perceived feeling of control, qualitative versus quantitative research, and statistical comparison. The *Evaluation Strategy Cards* present the user with information on how to evaluate the perceived feeling of safety and control, the understanding of the system and UX and usability qualitatively and quantitatively.

Another colour variant was then created for the card set; see Figure 7.14.

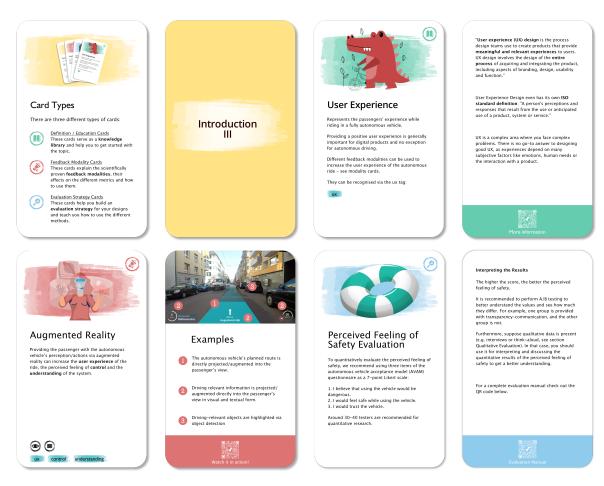


Figure 7.14: Extract of the second design variant of the third iteration using unified colours per card type. From left to right: Introduction Card, Knowledge Card, Feedback Modality Card, Evaluation Strategy Card.

Compared to the first variant, the colours were more muted and now already reflected the colours of the final toolkit. As with the first variant, every group of cards was assigned their own colour. At this stage, the fifth card type was added to the toolkit: *Game Plan Cards*. Design and content-wise, they nearly resembled the ones of the finished toolkit, compare Figure 7.4, and provided users with a step-by-step game plan of how to use the ADX cards in a workshop setting.

The Notion-based website prototype was updated accordingly and now featured the three main card types *Knowledge*, *Feedback Modality*, and *Evaluation Strategy*. Furthermore, the website included two user stories, which are the ones described in section 7.3.5, to make it more understandable for what applications the ADX toolkit can be used. The website prototype now also included the introduction on the homepage, basically similar to the one of the finished toolkit, providing users with onboarding to the toolkit and information surrounding it.

# 7.5 Workshop Validation

The third iteration of the ADX cards toolkit, described in the previous section, was tested in a two-part workshop setting with Master students from the Stuttgart Media University as part of their Experience Design lecture.

In the lecture, students pick a design brief and work on it throughout the semester. One design brief tasked the students with developing transparency communication for the passenger to feel safe in an AV and have a positive UX by understanding the ominous black box. It was targeted at first-time users of AVs. Part of the design brief was that the students would participate in two design workshops using the ADX toolkit to develop a first concept in the first workshop and an evaluation strategy in the second. The results of the two workshops found their way into the final toolkit iteration; see section 7.7.

# 7.5.1 First Workshop (Knowledge and Feedback Modality Cards)

Eight students (3 male, 5 female) with an average age of 25 (SD=2.20) participated in the workshop, which lasted about two hours. They were handed two physical card decks of the ADX cards and tasked with creating a first prototype concept for transparency communication in AD using the toolkit and following the game plan. After the workshop, the students filled out a self-developed 5-point Likert scale questionnaire, see Table 7.1, and a short interview openly discussing the Likert scale questions was conducted with the group. This subsection will report observations by the author during the workshop and the interview and questionnaire results.

#### **Obervations**

A summary of the observations during the workshop can be seen in Table 7.2. A general theme of the workshop was that the students did not always read or understand the Game Plan Cards correctly. This sometimes led to unintended behaviour. For example, instead of presenting the *Knowledge Cards* to each other, the students passed them around in a circle and read them themselves without discussing them. They also split up into two groups before it was intended by the *Game Plan Cards* and forgot to vote on their ideas generated during the Brainwriting.

Table 7.1: Self-defined 5-point Likert questionnaire for the first workshop evaluation.

Toolkit related questions	Value
The card-based toolkit helped me to get a better understanding of the topic.	4.57
The card-based toolkit helped me to design a feedback modality for	4.57
autonomous driving.	
The card-based toolkit helped me to get creative.	4.71
It was fun using the card-based toolkit together with other participants.	4.57
Having physical cards combined with interactive examples is useful.	4.71
Having created my own feedback modality card is a helpful starting point for	4.14
further development.	
•	
Content related questions	
The content is easy to understand.	4.86
The content is nicely presented.	4.86
The content is useful.	5.00
The cards contain enough information.	4.71
The cards contain too much information. (reverse-coded)	4.43
The interactive examples are helpful.	4.00
Workshop related questions	
The workshop duration was appropriate.	5.00
The workshop structure made sense.	5.00
I felt that I could contribute myself and my ideas.	4.57

The group chose to improve the metrics of system understanding and perceived feeling of safety. All students scanned the QR codes to inform themselves further on the metrics ("If we want to focus on understanding, let's scan the QR code and see if there's more."). The QR codes were also used out of curiosity to get more information ("Now I'm curious. I wonder why you can only use it [the mobile app feedback modality] after the ride."). It was interesting to see that to brainstorm ideas about feedback modality Cards that focus on the understanding of the system and the perceived feeling of control. Furthermore, they realised that no Feedback Modality Card exists that combines both understanding of the system and perceived safety, which led the students to think about creating a Feedback Modality Card that addresses both. In their case, they thought about combining the modalities of UI and AR.

Observing the participants during the workshop also revealed some areas for further clarification. For example, the students were confused why the mobile application *Feedback Modality Card* only works after the ride. They sometimes also took too much time per task on the *Game Plan* as no one kept track of time. Furthermore, it was seen that some students sorted cards of the same type on top of

each other with a little offset at the bottom. However, this did not allow them to read the card title anymore.

#### Questionnaire and Post-Interview

Table 7.1 displays the self-defined 5-point Likert scale questionnaire results. Participants rated all questions with 4 or higher, showing a general agreement with all statements. The highest rating of 5 was given for the workshop duration and structure and the usefulness of the content. The lowest value of 4 was given for the interactive examples. Overall, participants rated the whole experience with the ADX cards as positive. However, it must be said that the first workshop did not work with the Evaluation Strategy Cards. They were only used in the second workshop described later.

In the questionnaire, participants had the opportunity to provide textual feedback regarding the toolkit. Regarding positive feedback, they described the cards as visually appealing (2 mentions), pleasant to use (1) and great for sorting things clearly (1). Most of them mentioned the Brainwriting pool to collect ideas as useful (4). Furthermore, the online examples were seen as useful (2). The Brainwriting pool was appreciated most, and the visual feedback and examples are highlighted.

Regarding critical feedback, they agreed that the less content on the cards, the better (3) and wished for more interaction during the workshop (2). Furthermore, the toolkit only moderately helped to get a better understanding of the topic (1), additional online content should be displayed directly after scanning the QR code (1), and more attention should be paid to the time during the workshop (1).

Regarding negative feedback, one student wrote that one quickly reaches the point where things take on a life of their own, and the opinions of others become more important than the actual goal. However, according to the feedback, this seems to be more a problem with the team composition than with the ADX cards.

Lastly, an interview was conducted with the group, openly discussing the questions of the Likert scale questionnaire. Regarding the statement that the ADX cards helped the participants to get creative, two of them highlighted that this was mainly due to the Brainwriting exercise and not the toolkit itself.

In terms of creating a feedback modality, participants saw it as a good start ("I definitely feel more grounded now. Also, I didn't expect that we would have some concrete ideas at the end of the workshop.") Two of them mentioned that they don't know how to go from there scientifically. However, this would be part of the second

Table 7.2: Observations that were made during the first workshop grouped by type of finding.

Interesting Findings	Problems	Interesting Situations	Clarification Needed
The participants passed the Knowledge Cards around in a circle and everyone read them for themselves. The Game Plan was not understood or read correctly.	They were not quite at one about the definition of safety.	"If we want to focus on understanding, let's scan the QR code and see if there's more."	Introduction Card: Write out ADX at the beginning
Before they read the Game Plan Cards further, they were thinking about whether they should form two groups (this only becomes relevant in Game Plan Card number 3).	Misunderstanding about which cards to introduce. The goal was to introduce the Feedback Modality Cards. One group thought it was about the Knowledge Cards.	The participants looked at which feedback modality cards fit understanding. They have orientated themselves using the tags and the cards and have directly looked only at cards that fit their focus of understanding and safety.	Participants were confused why the mobile app Feedback Modality card only works after the ride. It was not clear that no other research is available.
Everybody further informs themselves about understanding and safety via the QR Code.	"I don't yet fully understand why AR improves other metrics than other, similar cards."	One participant, after looking at the mobile app Feedback Modality Card: "Now I'm curious. I wonder why you can only use it after the ride." They then scanned the QR code to read up information online.	No one took the lead, for example, to see how much time is left per task.
They discuss how understanding is to be understood.	The participants read the instructions half-heartedly - not all of them added several ideas, some stopped after one idea.	"How could UI and AR be combined to achieve safety and understanding?".  They considered mixing modalities.	One participant looked for the Game Plan II Card. They could not see on the front which card number it was and had to turn all Game Plan Cards over to find the correct number on the back.
They formed two groups and looked at the Feedback Modality Cards in the two groups themselves. This differs from the Game Plan Card: everyone should read the same number of cards and present them to others.	They voted on ideas and had forgotten the idea prioritisation phase from the Game Plan Card.	"It would be good to create a card that addresses both [understanding and safety] because that's not on any of the existing cards together"	It should be emphasised that the Feedback Modality Card that the participants create and take with them is only meant to be an initial idea, not the finished concept.
They do not use the videos for their explanations of the examples.  QR codes are not used	Comprehension problem: after Brainwriting, they were no longer sure if their modality should fit their original goal of improving understanding and safety.		
during the idea generation phase.			

workshop.

Regarding the visual content presentation, one participant mentioned that she stacked the *Knowledge Cards* on top of each other to save space but would have needed the title to be at the top to find cards quickly then. She then suggested that a general area at the top of the card containing all tags and metrics for a quick overview would be helpful.

Regarding the workshop, all participants stated that they did not keep track of time and that someone should be responsible for that task in the group. They agreed with creating the same theoretical foundation for everyone at the beginning of the workshop and wished for the Game Plan to also be available on the website ("I had to check every now and then which step we were in and what came before and after. And to do that, I always had to find the right game plan card first.").

In conclusion, the ADX cards were positively received in the first workshop. However, not all cards were used, as the *Evaluation Strategy Cards* were supposed to be used in the second workshop. Observing the students during the usage and talking to them afterwards revealed interesting and useful insights that found their way into the final product, more on that in section 7.7.

## 7.5.2 Second Workshop (Evaluation Strategy Cards)

A couple of weeks later, the second workshop was held. By then, the students had time to further work on their concepts and were now at a stage where they had to define how to evaluate them. Therefore, the second workshop used the *Evaluation Strategy Cards* in combination with the instructions from the *Game Plan Cards*. This time, nine students took part in the workshop, which lasted again about two hours, and afterwards, the same questionnaire was filled out and post-interview conducted.

#### Observations

A summary of the observations during the workshop can be seen in Table 7.3. Compared to the workshop, fewer new observations were made.

It was interesting to see that students came to the workshop with an already-formulated research question. However, after using the *Core Questions* card in combination with the extended content on the website, they realised that their research question needed to be reworked and updated it accordingly.

Furthermore, it became clear that the instructions in the toolkit were not exact enough as the students thought that looking at the *Core Questions* and *Task Scenarios* 

students used the ADX website on

their mobile phones more than the

cards.

Evaluation Strategy Cards was pre-

empting and should not be done in

The students were unaware that they should use the cards in the workshop to decide which questionnaires to use. Participants did not know what an evaluation strategy is. This must be

the workshop.

better clarified.

Interesting Findings	Problems	Clarification Needed
They came to the workshop with an	Scanning the QR codes on Android	It was not immediately clear that the
already-defined research question.	smartphones often did not work.	three online Core Questions were the
They used the Evaluation Strategy		same as on the card.
Cards to check their research		
questions against the criteria and		
realised it was incorrect.		
Compared to workshop one, the	The group did not have a common	Participants thought looking at the

Table 7.3: Observations made during the second workshop grouped by type of finding.

understanding of a research question.

They have not found the Quick Tips

cards was pre-empting and would not be part of this workshop. Furthermore, the Core Questions card could not describe to the students well enough what an evaluation strategy is. The author then gave a verbal explanation during the workshop.

### Questionnaire and Post-Interview

Regarding the questionnaire results, it is evident that the above-mentioned problems impacted students' ratings; see Table 7.4. The general confusion on what to do and not understanding important core concepts like a research question seemed to have a negative impact.

Compared to the first workshop, almost all questions were rated worse, especially regarding the toolkit helping to understand the topic better, being fun to use with other participants and the appropriate workshop duration. As the participants did not always know the correct or next step, it felt to them that the workshop time was too short.

Regarding the general presentation of the content on the physical cards, the students still rated it as nicely presented and containing enough but not too much Interestingly, they still rated the content to be easy to understand despite multiple comprehension problems.

In terms of written feedback on the questionnaires, one student positively mentioned that the toolkit helped them get an overview of everything, as they could not participate in the first workshop. Furthermore, one student highlighted liking the compact content

on the cards and the cute pictures.

Regarding critical feedback, students stated that the physical cards were not as needed as in the first workshop (2 mentions). In contrast, others wished for more sets of cards (2). One student explicitly wrote "What is an evaluation strategy and why do you do it?" showing again that the toolkit could not answer that question sufficiently.

Regarding negative feedback, participants wrote that the workshop duration was too short for the intended steps (3).

Table 7.4: Results of the self-defined 5-point Likert questionnaire for the second workshop compared to the first. Only appropriate questions regarding the *Evaluation Strategy Cards* from the questionnaire were picked.

Toolkit related questions	WS1	WS2
The card-based toolkit helped me to get a better understanding of the topic.	4.57	2.86
It was fun using the card-based toolkit together with other participants.	4.57	2.86
		•
Content related questions		
The content is easy to understand.	4.86	4.00
The content is nicely presented.	4.86	4.86
The content is useful.	5.00	4.00
The cards contain enough information.	4.71	4.29
The cards contain too much information. (reverse-coded)	4.43	4.86
		,
Workshop related questions		
The workshop duration was appropriate.	5.00	2.43
The workshop structure made sense.	5.00	4.14
I felt that I could contribute myself and my ideas.	4.57	4.14

Lastly, the post-interview with the group was conducted. Here, it once more became clear that the *Evaluation Strategy Cards* were not able to get all needed information across ("For coordination, the evaluation cards are good, but not for conveying information.", "The cards were less helpful this time than the first time.").

Interestingly, even though the students used the website more than the physical cards this time, they still appreciated them, saying that it is "[...] cooler to have something tactile. To be able to push something across the table. To be able to add something. The website is valuable so others can read along too.".

Furthermore, the students once more highlighted the need for more card sets during a workshop ("I think each person would need a pack of cards.", "I think that the fun is somewhat diminished by the fact that not everyone has a card set. This way, you might not be able to see a card so well. It might not be as much fun if you have to bend over to see it.").

### 7.5.3 Conclusion

This section presented the application of the ADX toolkit in two workshops used by students to create transparency communication concepts in AD and to build an evaluation strategy for them. In the first workshop, all cards, except the *Evaluation Strategy Cards*, were used. Participants dove into the topic and built a general understanding, then designed initial concepts for transparency communication using the toolkit. In the second workshop, the *Evaluation Strategy Cards* were tested independently.

The results of the two workshops revealed notable discrepancies that highlight the importance of aligning the toolkit design with the participants' task complexity. The first workshop received highly positive feedback regarding understanding, usefulness, and enjoyment. Participants were able to creatively engage with the *Knowledge Cards* and *Feedback Modality Cards* with little facilitator support. In contrast, the second workshop showed significantly lower ratings, particularly in helping participants understand the topic and the appropriateness of the workshop's duration. Students struggled with the abstract task of developing evaluation strategies, requiring frequent verbal explanations, and experiencing confusion around core concepts.

These differences can be traced back to the toolkit's readiness for the respective tasks. The cards used in the first workshop provided sufficient scaffolding for ideation, even if deviations from the intended structure occurred. In contrast, the *Evaluation Strategy Cards* lacked the depth needed to independently guide participants, leading to heavier reliance on the website and support. Furthermore, technical friction during digital interactions (e.g., scanning QR codes) and the mismatch between perceived task complexity and available guidance contributed to lower satisfaction. Overall, the validation highlights that while the ADX.cards successfully support creative solution design, further development is needed to fully enable autonomous evaluation strategy creation.

The results of the two workshops were then incorporated into the final toolkit iteration. More on that in Section 7.7.

# 7.6 Expert Validation

Parallel to the two workshops, the ADX cards were also shown to the second UX expert previously mentioned. As with the other experts, she had no knowledge about the toolkit. This time, the cards and website were sent to her beforehand, and she was asked to look at the toolkit from an expert's point of view. This resembles a real-life approach where experts would find the toolkit and inform themselves about it without guidance. Afterwards, an interview was conducted with the expert, which will be discussed in the following. Furthermore, the expert used the toolkit in a lecture about future UXs. Her experiences were collected in a second interview, which will also be discussed below. The results of both interviews also found their way into the final iteration; see section 7.7.

To better structure the validation, the expert was interviewed twice. The rationale behind conducting two sessions, rather than a single interview, was to gather both an initial impression of the toolkit and a follow-up evaluation after hands-on engagement.

Initially, the goal was to discover whether the card-based approach, structure, and content could be intuitively understood by someone outside of the original development context. The first interview focused on gaining feedback about the clarity, structure, and immediate usefulness of the cards. The second interview aimed to evaluate how well the toolkit supports autonomous use over time and whether it could inspire critical reflection or spark concrete ideas for design and evaluation in autonomous driving. This two-step structure was intended to mirror both the first-contact experience and long-term applicability in a real-world context.

Both interviews were semi-structured and followed a basic outline, see Table 7.5, while still allowing for flexibility in questioning and follow-up discussions. For the first interview, the questions focused on the expert's unaffected opinion after having looked at the toolkit for the first time and by herself. For the second interview, the questions focussed on her usage of the toolkit.

#### 7.6.1 First Interview

At the beginning of the interview, the expert described her approach. She initially focused on the physical cards rather than the website as she was more interested in having a physical product. She compared the information on the cards with the website and felt no need for additional guidance at any point.

Interestingly, she had her own ideas on how to use the toolkit before even reading

Table 7.5: Semi-structured expert interview questions.

#### Interview 1

- 1) What is your overall understanding of the product?
- 2) Did you have the impression that you could have used the toolkit without the website?
- 3) In a corporate environment, could you imagine sending out the website before a workshop? Using it as a preliminary onboarding?
- 4) What went through your mind before you even saw the game plan?
- 5) What was your impression regarding participants or colleagues from other disciplines? Do you have the feeling that you can reach colleagues who do not come from the design field?
- 6) Have you looked at the interactive examples, and if so, what is your opinion?
- 7) Have you noticed any points where you, as an expert, would say something is missing or not quite correct?

#### Interview 2

- 1) How did it work out to not use the toolkit's game plan but come up with your own way of use?
- 2) Did participants use the haptic cards to argue?
- 3) Were there any difficulties using the toolkit's cards?
- 4) Has anything come up using the framework you did not expect?
- 5) Was there any feedback from students?

the *Introduction Cards*. While she found the provided instructions helpful, she would not have followed them so closely. The expert liked the organisation of the cards into different groups and saw potential for using them in workshops or interdisciplinary settings to facilitate discussions and generate ideas. Specifically, the *Evaluation Strategy Cards* could be useful in creative workshops for exploring product aspects or testing study designs. She furthermore supported the idea of having QR codes and their logic, highlighting that she likes the "byte-wise" approach where participants can get more input step by step and are never overloaded with information.

She then said that she believes the physical cards have an advantage in a workshop setting, with the physical entry point being great, as they are more engaging, interactive and simply fun. While she did not need the website, she found it useful for documentation and communication purposes.

The expert then continued to emphasise the physicality of the toolkit. In her eyes, the important part about the ADX cards in a workshop is that they are physically present in the room. They are lying in front of the participants, working as an anchor. Without reading the instructions at the beginning, she immediately connected the toolkit to a workshop setting in her domain.

Deviating from the *Game Plan Cards*, the first idea she had using the cards was to assign every participant one card at the beginning of the workshop and let them know that this is their role to keep and defend. She sees this as a way to sensitise them to their topic as they will probably bring it up repeatedly in discussions as it is *their* card.

Regarding the use case of the ADX cards, she stated that she sees the toolkit being used in early stages, for example, an ideation phase or in workshops, where it is about coming up with new ideas or concepts.

Lastly, when talking about possible outcomes of using the ADX cards, she said she could imagine using the cards to build first prototypes. While this was the toolkit's goal all along, this interview revealed that it had not been described at all at this point on the website, the *Introduction Cards* or *Game Plan Cards*. This very important miss found its way into the final iteration of the toolkit; see section 7.7. This operational blindness so far had not been apparent as there always was a verbal onboarding in the expert and student workshops.

To summarise, while the expert mostly had positive comments regarding the ADX cards, two points were interesting. First, before reading the *Game Plan Cards* she already had an idea of how to use the cards. Second, without the interview, the almost game-breaking omission of not talking about the goal of creating prototype concepts through the ADX cards would potentially not have been found.

#### 7.6.2 Second Interview

The expert then used the toolkit as one of multiple methodologies in a Master's UX lecture on future UXs where they applied the design fiction method to AD. The goal was, among others, to make students aware of how the future might look and what input modalities exist. Therefore, some of the ADX cards were used. The group progressed towards a concept throughout the lecture sessions and created multiple artefacts. These artefacts were reviewed and iteratively developed through group discussions and user testing.

In her case, she said that the ADX cards were used as knowledge input initially and recurrently as reminders on the topic. As she had stated in the first interview, she had her own idea of how to use the toolkit, not following the *Game Plan Cards*, as the students did not explicitly design for XAI in AD in this lecture. The student groups built different artefacts and gave each other feedback on them. For this feedback, the

expert said she always reminded the students of the ADX cards. Thereby, at the beginning of the lecture, everyone was assigned their own card that they would represent. And during feedback, they were asked if they could think of something specific to their card. Using this anchor technique, every student could contribute their own topic.

Generally speaking, she received positive feedback about the cards from the students. She observed that their physicality brought some variance into the lecture setting and worked well for her intended use. While the cards might not have been used as envisioned by the toolkit, it was interesting to see that they can be repurposed to help with adjacent topics. Once again, the physicality of the cards was highlighted as a positive aspect, this time not only by the expert but also her students.

To summarise, the expert applied the ADX cards toolkit in her UX lecture on future UXs. She modified the intended use of the ADX cards to fit her setting and goal of the lecture and focused on the physical cards. The students received the cards well, and their physicality introduced some variance to the lecture.

#### 7.6.3 Conclusion

In conclusion, showing the ADX cards to the UX expert without additional input led to valuable insights. Generally, the expert perceived the toolkit positively. Before even reading the *Game Plan Cards*, she already had her own vision of how to apply the cards, which she then did in her lecture. The first interview revealed that the ADX cards did not highlight the goal of creating first prototype concepts. An important issue which was fixed in the last iteration in the following section. Furthermore, the expert repeatedly highlighted that it is positive to have a physical card set present and that she instantly connected the cards to a workshop setting. The positive influence of the physicality of the cards was later confirmed by her students in the lecture.

## 7.7 Final Iteration

Based on the input gathered from the two workshops and the expert usage, the final iteration of the ADX cards was created; see Figure 7.15.

The *Introduction Cards* now better highlight the idea behind the creation of one's own *Feedback Modality Card* in a workshop. Furthermore, they and the *Game Plan Cards* now show their card number on the front to make it easier to find them.

The Game Plan Cards were also refined and now provide clearer steps of what to do. The role of a timekeeper was introduced. A dedicated person in the workshop who keeps track of the time per Game Plan task. Furthermore, the Brainwriting technique is now explained in greater detail. To understand every step and at the end of every Game Plan task, participants are provided with clearer instructions of what to do with the results of the previous step.

The *Education Cards* now feature a new card, physically and online, called Types of Prototypes. The card gives users a basic introduction to prototypes and what kind of prototypes can be created to evaluate transparency communication in AD.

In terms of *Feedback Modality Cards*, the mobile application card now explains better why it is only valid for retrospective feedback. Furthermore, the cards now have redesigned tags and icons to make them look more unified and easier to scan.

Regarding the *Evaluation Strategy Cards*, the use of the Quick Tips card is now better emphasised. Furthermore, the Core Questions card contains more information to make it better understandable, and it is made more clear what the goal of an evaluation strategy is and which cards should be used to create one.

Lastly, general design changes have been made. The QR codes are now displayed more distinct and bigger to make them scannable on Android devices. Furthermore, the title of every card is now also presented at the bottom of the card to make it easier to find if stacked on top of each other.

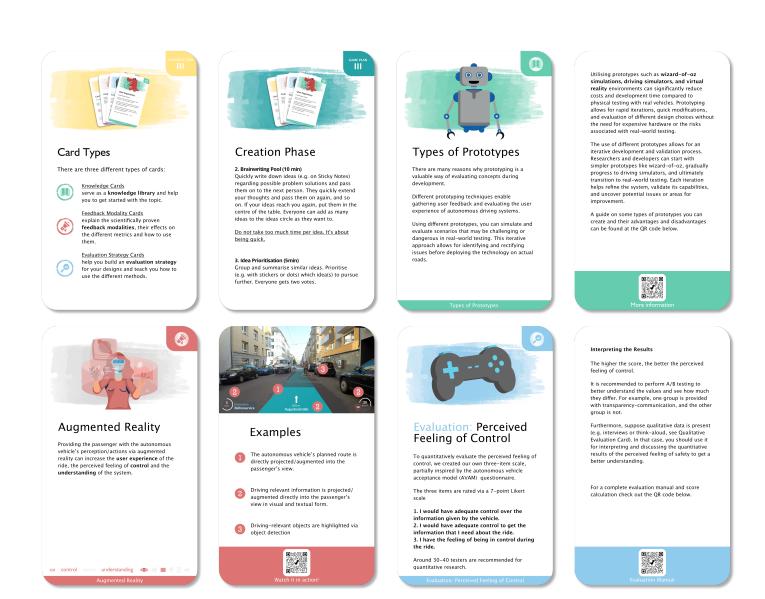


Figure 7.15: Extract of the final design of the ADX cards.

## 7.8 Case Studies

Next to being evaluated and validated with experts and in workshops, the ADX cards toolkit has also been applied independently by four students in their Bachelor's theses. These case studies were conducted to see what kind of solutions and evaluations students would create using the toolkit without any outside influence and if their results would compare to those of the four main experiments and adjacent research.

This section will shortly introduce each case study, its goals, the created feedback modalities and prototypes and the results. Then, all four case studies will be discussed in relation to the ADX cards toolkit and existing research. Regarding the collection and analysis of data, the students used the questionnaires<sup>9</sup> and statistical comparison manual<sup>10</sup> from the ADX cards website, which resembles the same approach as in the four main experiments.

## 7.8.1 Case Study 1

The first thesis looked at the application of the feedback modality light, sometimes extended with simple icons, to show the AV's intent and investigated their influence on the passengers' UX and perceived feeling of safety and control (Schneider, 2022). The final prototype setup can be seen in Figure 7.16.

The student created a prototype featuring a Matrix-LED display communicating intent to the passengers via light and sometimes icons. The feedback modality was placed beneath a monitor acting as the windshield. Participants (N=11) experienced a 3:50-minute-long drive through Stuttgart where different, regular driving situations occurred, like turning, stopping for pedestrians or bicycles, or passing a construction site.

Inspired by the colour coding of the light feedback modality from the ADX cards, white represented that the system is working and nothing is happening. Green represented that a situation or object that was irrelevant to the drive was detected. Orange represented that a situation or object was detected relevant to the drive. The prototype was evaluated with a mixed-method counterbalanced within-subjects design using the questionnaires for UX and perceived feeling of safety and control suggested by the ADX cards, and a short semi-structured interview afterwards.

Regarding the perceived feeling of control, providing passengers with transparency

<sup>&</sup>lt;sup>9</sup>https://adx.cards/evaluation-strategy-cards.html

<sup>&</sup>lt;sup>10</sup>https://adx.cards/knowledge-statistics.html



Figure 7.16: Prototype setup of the first case study (Schneider, 2022).

communication led to a significant increase when examined with a Wilcoxon Signed Rank test ( $M_{\text{no-feedback}}=3.21$ ,  $M_{\text{feedback}}=4.09$ , p<.05,  $\alpha$ =0.53). The same result could be seen for the perceived feeling of safety ( $M_{\text{no-feedback}}=3.76$ ,  $M_{\text{feedback}}=4.76$ , p<.05,  $\alpha$ =0.65). The passengers' UX was also significantly increased ( $PQ_{\text{no-feedback}}=0.30$ ,  $HQ_{\text{no-feedback}}=-0.96$ ,  $PQ_{\text{feedback}}=1.64$ ,  $HQ_{\text{feedback}}=0.59$ , p<.00001,  $\alpha$ =0.76).

In terms of qualitative feedback, three participants wished for more feedback about the vehicle. Seven described the information amount through the feedback modality as too little ("The display needs to show multi-dimensional Information[sic], it should provide info about the navigation/Route[sic] its[sic] taking." (Schneider, 2022, p.48)). This was emphasised again by five participants for driving relevant situations, where they wished for more details to understand the situation better.

Lastly, five participants wished for some sort of world in miniature visualisation ("The vehicle needs to show what it currently sees." (Schneider, 2022, p.48)).

In conclusion, the first case study created its own interpretation of the light feedback modality by using an altered colour scheme and sometimes adding descriptive icons to the colour. While the original feedback modality card only increased the UX and perceived feeling of control, the case study also tested for the perceived feeling of safety. The results confirmed the existing light feedback modality card. Further, they added an indication that it can also significantly increase the perceived feeling of safety. However, the small sample size of 11 must be considered regarding the validity of the findings. In terms of UX it was shown that not providing feedback led to a negative HQ which could be counteracted to an almost positive HQ through transparency communication via light.

## 7.8.2 Case Study 2





Figure 7.17: Prototype setup without and with feedback of the second case study (Albrecht, 2022).

The second thesis looked at the multimodal application of visual, textual, auditive, and AR feedback modalities for transparency communication in AD (Albrecht, 2022). It investigated their influence on the passengers' UX, the perceived feeling of safety and control, and the system understanding. The final prototype can be seen in Figure 7.17.

The student created a 3D prototype that was shown as a video to the participants on a TV, which acted as the windshield. Participants (N=17) experienced a 1-minute drive through dense traffic on a motorway, where three different driving situations occurred. (1) The AV is in the centre lane, and a car from the right lane suddenly

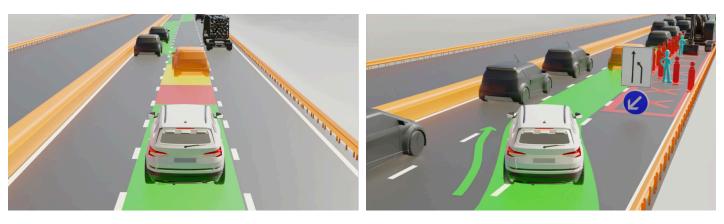


Figure 7.18: Different driving situations and visualisations of the second case study (Albrecht, 2022).

cuts in front of it, (2) a car in front is overtaken by the AV, and (3) the AV needs to change lanes to bypass a construction site.

Inspired by the ADX cards, the visual feedback modality was a world in miniature, see Figure 7.17, displaying what the AV sees and a coloured line highlighting objects or critical distances. The AR modality used the same coloured line for critical distances or lane changes. Furthermore, textual information was present on the windshield regarding driving information like speed and route information and driving situation relevant information (for example, "vehicle cutting in front from the right"). The auditive feedback was used in critical situations, announcing the situation through a warning beep followed by a short spoken text that specifies the situation further. The prototype was evaluated with a mixed-method counterbalanced within-subjects design using the questionnaires for UX, the perceived feeling of safety and control, and system understanding suggested by the ADX cards, the think-aloud method during the tests and a short semi-structured interview afterwards.

The transparency communication in the second case study was able to significantly increase all four metrics when examined with a Wilcoxon Signed Rank test, namely the perceived feeling of control ( $M_{\text{no-feedback}}=2.78$ ,  $M_{\text{feedback}}=5.35$ , p<.05,  $\alpha$ =0.78), the perceived feeling of safety ( $M_{\text{no-feedback}}=4.86$ ,  $M_{\text{feedback}}=6.08$ , p<.05,  $\alpha$ =0.88), the system understanding ( $M_{\text{no-feedback}}=3.59$ ,  $M_{\text{feedback}}=5.51$ , p<.05,  $\alpha$ =0.73), and the UX ( $PQ_{\text{no-feedback}}=0.65$ ,  $HQ_{\text{no-feedback}}=0.91$ ,  $PQ_{\text{feedback}}=2.15$ ,  $HQ_{\text{feedback}}=2.16$  p<.05,  $\alpha$ =0.77).

Regarding think-aloud feedback for the no-feedback prototype during the ride, nine participants got slightly scared when the car from the right suddenly cut in front of them. Three said that they do not trust the AV and want to take control, four wished for an auditive or visual notification for driving situations, and one felt at the mercy of the AV without any control. These points were further confirmed in the post-interview, where 15 participants stated that they did not feel informed enough, highlighting that they want to know the *why* behind the AV's actions, confirming research of Walch et al. (2015).

Regarding the post-interview for the prototype with live feedback, eight participants described the auditive feedback as helpful, four stated that the projected route gave them an increased feeling of safety, and four said that the announced driving manoeuvres felt helpful. During the test, it was observed that six participants still got a bit scared when the car cut in front of them.

In conclusion, the second case study created its own interpretation of the visual, UI and AR feedback modalities and added auditive feedback on top. Here, the world in miniature was extended with the line-elements known from the AR card. The combination of the three ADX cards states that all four metrics investigated by the case study should be significantly improved, which could be confirmed. Interestingly, the perceived feeling of control increased substantially, highlighting again the importance of giving passengers the impression of having control and the effectiveness of different feedback modalities to create this feeling.

# 7.8.3 Case Study 3

The third thesis looked at the multimodal use of UI, light, AR, and voice assistant feedback modalities for transparency communication (Saibel, 2023). In a study, it investigated their influence on the passengers' UX and their perceived feeling of safety. The final prototype can be seen in Figure 7.19.

The student created a video-based prototype for their experiment with the TV acting as the windshield. Inspired by the ADX cards, they added a UI overlay containing basic information like speed, temperature and street names. Additionally, they used AR to highlight driving relevant objects through a coloured rectangle, with green highlighting recognised objects, orange highlighting driving situation relevant objects and red highlighting critical situation objects. Furthermore, they added light to the sides of the windshield using the same colours as the AR. Lastly, a voice assistant announces driving relevant AV reactions (for example, "overtaking initiated"). These modalities were experienced by participants (N=20) in a 9:17-minute-long drive where multiple regular driving situations happened, for example, taking a turn or overtaking a bicyclist. Furthermore, one scripted critical





Figure 7.19: Different driving situations and visualisations of the third case study (Saibel, 2023).

situation happened where a ball was rolling onto the street, and a person was running behind it to stop it. The prototype was evaluated using a mixed-method counterbalanced within-subjects design using the questionnaires for UX and perceived feeling of safety suggested by the ADX cards.

The transparency communication in the third study led to a significant increase for both the UX (PQ<sub>no-feedback</sub>=-0.29, HQ<sub>no-feedback</sub>=-0.23, PQ<sub>feedback</sub>=2.28, HQ<sub>feedback</sub>=1.44 p<.05,  $\alpha$ =0.78) and the perceived feeling of safety (M<sub>no-feedback</sub>=3.32, M<sub>feedback</sub>=6.00, p<.05,  $\alpha$ =0.89).

In conclusion, the third case study again created its own interpretation of the different feedback modalities. The two metrics investigated by the case study were both significantly increased. Like the previous case studies, it confirmed the research results provided by the ADX cards.

## 7.8.4 Case Study 4

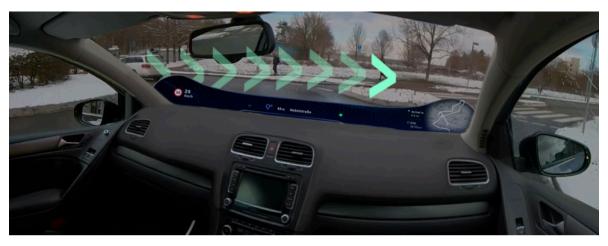




Figure 7.20: Different driving situations and visualisations of the fourth case study (Tews, 2023).

The fourth thesis combined the AR, UI, and light modalities for transparency communication (Tews, 2023). It examined how they influence AV passengers' UX and perceived feeling of safety and control. Figure 7.20 shows the final prototype.

Compared to the other three case studies, this one used an immersive prototype. Participants (N=15) experienced a 12-minute-long autonomous drive recorded with a 360-degree camera in a VR headset. Regular driving situations occurred during the drive, like pedestrians using crosswalks or red traffic lights. For further immersion the steering wheel was removed from the video.

Inspired by the ADX cards, the AR highlighted driving relevant objects via

coloured rectangles or triangles and displayed anticipated driving direction changes. Thereby, green was used for non-driving relevant detections, and red for driving-relevant situations. The light modality was installed in the foot compartment and used the same colour coding as the AR. Lastly, the UI overlay displayed driving relevant information like the current speed and a map. The study used a mixed-method counterbalanced within-subjects design and the questionnaires for UX, and the perceived feeling of safety and control suggested by the ADX cards. Furthermore, the think-aloud method was used during the tests.

As with the other case studies, the used modalities were able to significantly increase all tested metrics when examined with a Wilcoxon Signed Rank test, namely the UX (PQ<sub>no-feedback</sub>=0.22, HQ<sub>no-feedback</sub>=-0.73, PQ<sub>feedback</sub>=2.00, HQ<sub>feedback</sub>=0.85 p<.05,  $\alpha$ =0.71), the perceived feeling of safety (M<sub>no-feedback</sub>=3.53, M<sub>feedback</sub>=4.89, p<.05,  $\alpha$ =0.86) and control (M<sub>no-feedback</sub>=1.82, M<sub>feedback</sub>=4.18, p<.05,  $\alpha$ =0.75).

In terms of think-aloud feedback, four participants verbally liked the pedestrian detection at crosswalks, three the warning designs, three the UI overlay and two the AR. Regarding negative feedback, four mentioned that they dislike not being in control, four wanted to have more control, and five wished to be able to request more information when they want to.

In conclusion, the fourth case study, like the ones before, created its own interpretation of the feedback modalities and confirmed the research of the ADX cards. Again, participants confirmed the importance of control in AD, and the increased perceived control through the multimodal feedback modalities was substantial.

#### 7.8.5 Discussion

The four case studies used different uni- and multimodal feedback modalities and their influence on this thesis' four main metrics UX, the perceived feeling of safety and control, and system understanding. Thereby, the students chose their own goals and approach in their theses. They used the ADX cards toolkit independently for the whole process. To dive into the topic, create their own transparency communications and prototypes, build their evaluation strategies and apply the cards' information to analyse their data. Thereby, no outside influence was applied in terms of using the toolkit.

The first interesting observation was that while having the same overall goal, the

students chose different approaches to present and evaluate their transparency communication with prototypes. They used recorded real-life driving scenarios, 3D animation and immersive 360-degree VR videos. This highlights an important aspect that the ADX cards want to achieve: enabling creativity. This was further confirmed by how the students applied the *Feedback Modality Cards*. While following the general information of the cards, all of them created their own variations of the modalities, making it an exploratory process.

Furthermore, the theses' introduction, theoretical background and prototype chapters show that the *Knowledge Cards* helped the students dive into the topic and gain a first understanding that they could use as a starting point for further research. Additionally, using the *Evaluation Strategy Cards*, all of them were able to create their own evaluation strategies and understand how to analyse the data to get meaningful results. The amount of information provided by the cards seemed to be sufficient.

One thing that the author did not expect was that all four case studies were able to significantly increase the metrics by creating transparency communication through different feedback modalities. While the small number of participants in the different studies certainly has to be considered while looking at the results, they are interesting nonetheless. This reproducibility creates two interesting aspects to discuss.

First, while all students created their variations of the feedback modalities, they still could reproduce the cards' results. This makes the modalities more generally valid as not only their exact designs from the four main experiments but also variants of them lead to the same results. Furthermore, the modalities seem to be combinable in different ways to fulfil multiple metrics.

Second, this reproducibility shows the effectiveness of the modalities. While one could argue that their effect is only happening as it is the first time passengers witness them, studies focussed on long-term use would have to look into this. However, as the goal of this transparency communication was to increase the metrics for first-time users of AVs, the case studies show that the different feedback modalities all significantly increased them.

Looking at the feedback from the participants, the importance of perceived control and the problem of losing direct control was repeatedly shown. The case studies designed for the perceived control metric were all able to confirm the significant increase using transparency communication.

As with the main experiments, the perceived safety was also significantly increased but generally higher in the no-feedback base versions than the perceived control. For the case studies, this could be due to the same reasons as with the main experiments, that participants experienced the autonomous rides in different simulators, not being exposed to real driving threads.

Regarding UX and system understanding, the studies also confirmed the positive effect and importance of transparency communication.

### 7.8.6 Conclusion

This section has presented four case studies where the ADX cards were used in the context of Bachelor's theses. The students used the toolkit without external influences. They used the cards to dive into the topic, create variations of existing feedback modalities for transparency communication, and evaluate their prototypes. All four case studies were able to reproduce the findings of the four main experiments of this thesis' and adjacent research, confirming the content of the Feedback Modality Cards. Furthermore, the case studies showed that variations of existing feedback modalities can lead to the same result. The case studies, therefore, confirm that the ADX cards provide useful and applicable guidance when designing for transparency communication in AD and, simultaneously, allow for a degree of creativity and freedom while still providing the same value.

## 7.9 Conclusion

This chapter has presented the ADX cards, the main creative contribution of this thesis, following RQ-3: How can a framework be used to provide the research findings on transparency communication in autonomous driving to a broader, interdisciplinary audience for application in design-based disciplines?

The cards aim to convey the knowledge gathered in research experiments to designers and assist them in creating and evaluating transparency communication in AD for first-time passengers. The goal is to increase passengers' UX, perceived feeling of safety and control, and system understanding. Thereby, the ADX cards are grounded in the four main experiments of this thesis and adjacent research, covering transparency communication via different feedback modalities and their influence on passengers.

The development of the toolkit was motivated by a distinct research gap identified during the literature review, where existing work primarily focused on system performance or reaction times rather than human experience, and no structured method existed to transfer this research knowledge into design-based disciplines. Building upon user-centred design principles, the ADX cards were envisioned as an accessible medium for both education and application.

The toolkit was developed following an iterative UCD approach, combining theoretical foundations of transparency communication, system understanding, and perceived safety and control with practical design iterations. These iterations were evaluated through expert feedback, workshops, and four independent case studies. This first validation suggests that the toolkit can fulfil its intended purpose, helping users dive into the topic, design new feedback modalities, and structure evaluation strategies. In particular, the reproduction of Feedback Modality Card outcomes through design variations offers a first indication of content validity.

Reflecting on the design of the toolkit, a key finding was the importance of allowing creativity while maintaining guidance. Users appreciated the cards' flexibility in supporting a wide range of design approaches rather than prescribing rigid solutions. This aligns with the findings from the case studies, which demonstrated that the cards enabled personalised, creative solutions while maintaining a consistent focus on the key metrics of UX, system understanding, and perceived feeling of safety and control.

However, it must be noted that while first evaluations show promise, further independent studies would be beneficial to investigate long-term applicability and generalisability. Especially for scaling into broader interdisciplinary educational contexts or industrial settings, more systematic validation should be performed.

Overall, the ADX cards address the lack of practical frameworks translating academic research on transparency communication in AD into applicable, user-centred design tools. They provide an innovative, holistic contribution to the field, fostering creative and structured engagement with the core findings of this thesis.

The next chapter will conclude this thesis and provide a final overview of the research questions, the findings, and the contributions to knowledge.

Chapter 8

Conclusion

This thesis investigated the influence of transparency communication in AD through different feedback modalities on first-time passengers' UX, their perceived feeling of safety and control, and system understanding. Therefore, four experiments investigated different feedback modalities and their combinations in different driving simulators and driving situations, varying from regular to critical to failure situations. Starting with basic research, focussed on single modalities in different, isolated types of driving situations, the experiments progressed to more complex modality combinations and longer, more extensive autonomous drives. Finishing with an experiment on non-critical failure situations and discovering new challenges for transparency communication that have arisen as a result. Finally, the gathered knowledge from the four experiments and adjacent research was made available to those interested in advancing the field of autonomous driving experience through a card-based design toolkit, the ADX cards. The toolkit was developed iteratively, discussed and validated through workshops and with experts and used independently in four case studies to see if its results could be reproduced. Thereby, the thesis was driven by three main RQs which will be discussed in the following section.

# 8.1 Research Questions

## 8.1.1 Research Question 1

RQ-1: How do uni- and multimodal feedback modalities for transparency communication in autonomous driving affect first-time passengers' user experience, understanding and perceived feeling of safety and control?

To answer this question, experiments 1 to 3 were carried out. The first experiment investigated using unimodal feedback modalities in different driving situations. The availability of transparency communication through light or visualisation led to a significant increase in the first-time passengers' UX. Furthermore, light feedback communication also significantly increases the perceived feeling of control. Thereby, participants preferred softer, less intrusive feedback modalities for proactive driving situations and more prominent ones for reactive driving situations.

The second experiment then investigated multimodal feedback modalities for transparency communication during the ride and retrospective on-device cues after the ride. The live feedback during the ride consisted of the feedback modalities light, text and AR. Retrospective transparency communication happened through a smartphone app. Providing passengers with live and retrospective information significantly increased their UX, perceived feeling of control, and understanding of the

system. While live and retrospective feedback increased the perceived feeling of control, retrospective feedback only increased the UX and system understanding if no feedback was present during the ride, showing an interesting alternative to live feedback.

The third experiment then investigated if it is possible to influence the perceived speed of passengers in AVs via feedback modalities and if it has an additional influence together with transparency communication on their perceived feeling of safety and control. The experiment showed that participants could experience the same drive as faster or slower and closer to their own driving style. A defensive driving style significantly increased their perceived safety and control. In contrast, a more offensive driving style only significantly increased their perceived control. Providing passengers with the ability to allegedly influence the driving style, which is changed through audio-visual modifications only, seems to have a positive effect on first-time users when combined with transparency communication.

To summarise, experiments 1 to 3 showed that transparency communication in AD through uni- and multimodal feedback modalities could significantly positively influence the passengers' UX, perceived feeling of safety and control, and system understanding and might be able to counteract some problems of AD like loss of control.

## 8.1.2 Research Question 2

RQ-2: How do failure situations affect the passengers' perception of transparency communication?

While the AVs in experiments 1 to 3 were driving perfectly and never making any mistakes, the fourth experiment then investigated the second RQ regarding the influence of AV non-critical failures on the transparency communication. While it confirmed the other three experiments regarding the positive influence of transparency communication on passengers in regular driving situations, it also showed that non-critical failure situations require a different approach to transparency communication. The otherwise positive influence of feedback modalities reached its limitations when passengers were made aware of AV system limitation in non-critical failures. Providing them with additional information that highlights the AV's inability to understand the situation could even negatively influence their UX. This creates an information dilemma regarding transparency communication as it has a positive influence in regular driving situations but can create the opposite effect when non-critical failures happen. Therefore, a new approach is required to detect

non-critical failures to adopt the transparency communication. This could, for example, be achieved through detecting increased requests for additional information by passengers or implementing a human-in-the-loop design.

## 8.1.3 Research Question 3

RQ-3: How can a framework be used to provide the research findings on transparency communication in autonomous driving to a broader, interdisciplinary audience for application in design-based disciplines?

With new knowledge generated, the question arose of how to make that knowledge available to the audience that can directly profit from it, namely UX designers, researchers or users that want to dive into the topic of transparency communication in AD. The question was how to put this knowledge and the knowledge of adjacent research into a framework and make it available and applicable in everyday use. Therefore, the card-based design toolkit ADX cards was developed through multiple iterations of workshops and expert discussions and validations.

The core of the toolkit is based on the four main experiments of this thesis, the Feedback Modality Cards, and extended with introductory content, the Knowledge Cards, and information and guidance about evaluating new and existing concepts, the Evaluation Strategy Cards. These groups of cards also reflect the toolkit's three main holistic goals of helping users dive into the topic, create their own transparency communication solutions and help them evaluate their concepts and prototypes. Furthermore, the ADX cards are described as a transmedia toolkit, combining physical cards with dynamic, expandable online content. This way, the toolkit uses the benefits of having haptic cards and tries to counteract the downside by adding interactive online content.

After four iterations, the ADX cards were used independently in four different case studies where students used the toolkit as a starting point to dive into the topic, created their own transparency communication prototypes and evaluation strategies, and learned about evaluating and interpreting their data. Thereby, all four case studies could reproduce and confirm the results the ADX cards are built on. Furthermore, it was shown that the toolkit allowed for a degree of freedom regarding creativity while still producing the same intended results. The solutions of the case studies were all following the general information of the ADX cards but were all designed and implemented in their own way and interpretation. This was interesting, as variations of the feedback modalities still reproduced their results.

# 8.2 Contribution to Knowledge

Prior work in transparency communication mostly focussed on improving take-over quality in SAE Level 2/3 contexts. This thesis expanded the scope towards first-time UX, perceived control, system understanding, and managing transparency during non-critical failures in fully autonomous (Level 5) vehicles — thus advancing both theoretical and applied knowledge in the field.

Through a structured series of four experiments across different simulators — VR, physical driving simulator, and WoZ setups — this thesis systematically explored the effects of transparency communication on UX, perceived safety and control, and system understanding in Level 5 autonomy. Moreover, the creation of the ADX cards toolkit operationalised these research findings into an actionable, interdisciplinary framework making theoretical insights available for everyday application by UX practitioners, researchers, and students in automotive and HCI domains.

The reproducibility and applicability of the research findings were further demonstrated in four independent case studies, where students using the ADX cards successfully created new transparency communication prototypes and evaluation strategies that aligned with the intended theoretical results (Albrecht (2022); Saibel (2023); Schneider (2022); Tews (2023)). This validation underscores not only the practical effectiveness of the toolkit but also its ability to foster creativity while maintaining underlying design robustness. Hence, the contribution is twofold: (1) advancing theoretical knowledge about transparency communication effects in SAE Level 5 AD, especially in first-time user and failure contexts, and (2) providing an empirically validated, interdisciplinary toolkit to translate research into practical, reproducible design interventions.

The findings of this thesis and their contributions are summarised in Table 8.1.

# 8.3 Limitations and Future Work

This section critically reflects on the methodological and theoretical limitations of the conducted research and outlines promising directions for future work. While this thesis contributes to the growing body of knowledge around transparency communication in AD, it also revealed several areas where further research is needed to increase ecological validity, strengthen internal consistency, and explore long-term user trajectories.

The subsequent subsections address these dimensions in detail. They include reflections on the challenges of using different simulator setups and the need for streamlined testing conditions, the potential of real-world WoZ studies, and the

Table 8.1: The contributions of this thesis are summarised as statements, referencing the according experiments.

Contribution Statement	Experiments
Live transparency communication through world in miniature, AR	1, 2, 4
overlay, conversational UI, or light modalities can increase first-time	
passengers' UX.	
Transparency communication through retrospective on-device cues	2
can increase first-time passengers' UX.	
Live transparency communication through world in miniature or UI	1, 3
overlay modalities can increase first-time passengers' perceived feeling	
of safety.	
Live transparency communication through UI overlay, AR overlay,	1, 2, 3, 4
conversational UI, or light modalities can increase first-time	
passengers' perceived feeling of control.	
Transparency communication through retrospective on-device cues	2
can increase first-time passengers' perceived feeling of control.	
Live transparency communication through AR overlay modalities can	2
increase first-time passengers' system understanding	
Transparency communication through retrospective on-device cues	2
can increase first-time passengers' system understanding.	
Audio-visual modifications can make an autonomous drive feel faster	3
or slower and closer to first-time passengers' own driving style.	
Providing design-based professionals and novices with knowledge on	ADX
transparency communication through a transmedia card-based toolkit	
enables them to dive into the topic, create their own solutions and	
evaluate and interpret them.	

importance of multi-item scale validation to improve construct reliability. Moreover, future work should not only investigate novel modality combinations and driving situations but also consider long-term studies, user diversity, and the integration of personalised onboarding strategies. Structural equation modelling and the measurement of presence are proposed as methods to better understand mediation effects and participant engagement. Finally, the ADX.cards toolkit would benefit from further independent validation and broader application contexts to ensure its effectiveness across diverse design scenarios.

# 8.3.1 Extending the Use of Real-World Driving

Using simulators allows for replicability and control over the setting and has confirmed relative validity (compare, for example, Engström et al. (2005); Mayhew et al. (2011); Mullen et al. (2011)). Furthermore, they allow participants to be put in critical driving situations without the risk of harm. However, simulators can only provide a certain amount of immersion. An indication of this can be seen in the

experiment results, where the perceived feeling of safety is always rated relatively high compared to the perceived feeling of control, as no physical threads were present during the experiments. Future research could emphasise real-world driving, for example, through WoZ studies, to provide participants with a higher degree of immersion (compare, for example, Detjen et al. (2020)). However, in terms of driving situations, this would create its own challenges, as ethically, participants could not be exposed to critical driving situations but only regular ones.

## 8.3.2 Streamlining Simulator Use

While employing three distinct simulator types (VR, physical, and WoZ) increased the ecological validity of the findings — especially the WoZ setup due to its real-world immersion and g-forces — this introduced variability that is difficult to fully control. Future work may benefit from streamlining simulator use or explicitly investigating simulator-type effects in isolation to strengthen internal validity.

## 8.3.3 Using More Modalities, Designs and Combinations

This thesis has investigated multiple feedback modalities and some of their multimodal combinations. However, their application is far from complete. Future work could look at different design variations of already tested modalities and see if the results can be reproduced or even new knowledge can be generated. The tested modalities could be combined in different ways. This would lead to many possible combinations that can still be researched. Additionally, new modalities could be added to the scope, for example, more on-device cues like smart wearables. Furthermore, a bigger emphasis could be placed on retrospective transparency communication, looking into other modalities for information transmission after the fact.

# 8.3.4 Further Investigation of Critical and Non-Critical Driving Situations

While this thesis focused on different types of driving situations, most of which are non-critical, future research could delve deeper into critical and non-critical driving scenarios. Exploring more driving situations could provide more valuable insights into how different feedback modalities influence different metrics through transparency communication. Additionally, investigating more non-critical driving situations would allow for a comprehensive understanding of how feedback modalities could be optimised for everyday driving experiences, contributing to the development of more effective transparency communication.

## 8.3.5 Using Long-Term Studies

Long-term studies could bring valuable insights by examining the influence of transparency communication on the main metrics beyond initial usage. While this thesis focussed on first-time users, long-term studies would allow assessing the performance and user perceptions of transparency communication over an extended period. This would provide a more comprehensive understanding of the long-term impact on UX, perceived feeling of safety and control, and system understanding, which could lead to new design implications of transparency communication for long-term users. Additionally, these studies could uncover any potential issues or limitations that may not have been apparent during short-term evaluations, ensuring the development of more robust and reliable transparency communication.

## 8.3.6 Extending the Investigated Metrics

While this thesis focused on investigating its main metrics UX, perceived feeling of safety and control, and system understanding, several other metrics could be explored to gain a more comprehensive understanding of transparency communication in AD and its influence. For example, future work could investigate the impact on mental workload or cognitive performance. Additionally, metrics such as trust in the system and user preferences combined with long-term studies could provide further insights into user attitudes and perceptions. Expanding the range of metrics would provide a more nuanced understanding of transparency communication and guide future iterations in their design and implementation.

#### 8.3.7 Further Evaluation of the ADX Cards

Further evaluation of the ADX cards is necessary to assess their effectiveness, usability and general validity in a wider range of contexts. While the cards have been tested in two workshops and four case studies, showing that results can be reproduced, expanding the evaluation to include more diverse user groups and settings would provide a more comprehensive understanding of their potential. Conducting additional workshops and case studies would allow for iterative improvements based on user feedback and real-world applications. Furthermore, analysing the data collected from these evaluations would provide valuable insights into the strengths and limitations of the ADX cards, enabling to refine the toolkit and identifying areas for enhancement. Therefore, it would be important that the toolkit would be evaluated by researchers other than the author to remove any potential influence.

## 8.3.8 Using More Diverse User Groups

To enhance the generalisability and applicability of the findings, future work should consider incorporating more diverse user groups in evaluating transparency communication in AD. While this thesis primarily focused on relatively young participants with average ages ranging from 24 to 28, including participants from a wider age range would provide insights into how different age groups perceive and interact with these systems. Additionally, considering factors such as gender, driving experience, and cultural backgrounds would contribute to a more comprehensive understanding across various user demographics. By including a more diverse range of participants, future work could identify potential age-related or demographic-specific challenges and tailor the design and implementation of driver assistance systems to better meet the needs and preferences of different user groups, providing a more personalised UX.

# 8.3.9 Strengthening Construct Validity Through Multi-Item Scales

Some constructs such as transparency and or control (in one experiment) were measured using single-item scales. While this allowed for pragmatic inclusion during studies, future research should consider validated, multi-item scales where possible to strengthen construct validity and allow for reliability testing (e.g. via Cronbach's Alpha). In later experiments, the perceived feeling of control was assessed using a three-item self-defined scale, inspired by the AVAM structure, but further refinement and validation would be beneficial.

# 8.3.10 Transparency Alone Is Not Enough

Additionally, while correlations between transparency, UX, and perceived control were identified, the underlying causal structure remains unclear. Findings from Experiment 4 suggest a possible mediation effect — namely, that transparency alone is insufficient to increase UX unless it concurrently increases the perceived feeling of control. This feedback loop highlights the potential of integrating structural equation modeling or mediation analysis in future work to model these relationships explicitly. In particular, structural equation modeling would allow for modeling indirect effects (e.g. transparency increasing UX via perceived control), simultaneously accounting for multiple interdependent variables, and controlling for measurement error across constructs. Given the central role of control as a potential mediator identified in Experiment 4, these advanced methods could help unravel the directional structure underlying transparency communication, perceived agency, and UX in AD.

## 8.3.11 Exploring Habituation and Long-Term UX Trajectories

Finally, while this thesis focused deliberately on first-time passengers, future work should examine how repeated exposure to AD changes information needs, expectations and the impact of UMDs. Understanding long-term habituation or preference adaptation may help create dynamically responsive systems that tailor transparency to individual user journeys over time.

# 8.3.12 Presence as a Mediator of Ecological Validity and Participant Engagement

The concept of presence—the subjective experience of "being there" within a virtual environment—is pivotal in evaluating the ecological validity of simulations used in AD research. High levels of presence can enhance the realism of the simulation, leading participants to respond more authentically, thereby increasing the ecological validity of the study Deniaud et al. (2015). Moreover, presence is closely linked to participant engagement; a stronger sense of presence can result in higher engagement levels, which are crucial for obtaining reliable and valid data Lessiter et al. (2001). To accurately assess presence, validated instruments such as the ITC-Sense of Presence Inventory (ITC-SOPI) can be employed, which measures dimensions including spatial presence, engagement, ecological validity, and negative effects Lessiter et al. (2001). Incorporating such measures in future studies can provide deeper insights into the participant experience and the effectiveness of the simulation in replicating real-world scenarios.

## 8.3.13 Personalisation and Onboarding

While this thesis provides a comprehensive examination of transparency communication for first-time passengers in AVs, future work could expand upon this by investigating the role of personalised onboarding strategies. Studies in adjacent domains have shown that personalised introductions to complex systems can significantly improve user understanding and trust (Ehsan and Riedl, 2020; Langer et al., 2021). Applying this to SAE Level 5 AD, onboarding could involve interactive explanations or adaptive feedback based on user profiles (e.g. prior experience, anxiety levels, or age). This direction is further supported by findings from human-centred XAI research, which emphasise the need to align explanations with individual user mental models to improve system understanding and perceived control (Eiband et al., 2018; Liao and Varshney, 2021). Incorporating such onboarding methods may help reduce the steep learning curve associated with fully automated systems, especially when real-time feedback is limited or non-existent. Therefore,

future studies could explore onboarding not just as an introductory phase but as an ongoing, adaptive dialogue between user and vehicle, potentially enhancing long-term user acceptance and safety perceptions.

#### 8.4 The Future of the Field

#### 8.4.1 Building Trust in Autonomous Systems

Trust will remain a central construct in the future of AD. The absence of a human driver requires new design strategies that allow users to develop situational awareness and feel confident in the system's abilities (Ekman et al., 2021). As trust is inherently multidimensional, future research should continue to distinguish between cognitive trust (e.g. competence) and affective trust (e.g. perceived benevolence), and focus on supporting both. This could involve dynamic trust calibration (Okamura and Yamada, 2020), where feedback adapts in real-time based on the passenger's behaviour and level of familiarity with the system.

## 8.4.2 Scientific Validity and Relatable AI

The scientific validity of AI systems in the automotive domain depends on how transparent, accountable, and predictable they are—not only to engineers but also to the end-users. Future research should consider the psychological and cognitive validity of explanations, extending beyond system logic to address user understanding. Accountability mechanisms must also include traceability, providing explainable justifications for decisions in a human-understandable format (Amershi et al., 2019). Moreover, future systems should move beyond interpretability as a technical property and develop interfaces that foster relatability, wherein passengers intuitively comprehend the intentions and confidence of the system.

# 8.4.3 Quality of Experience and Societal Integration

While UX in AD has focused on core interactions, the field must broaden towards Quality of Experience (QoE), encompassing aspects such as comfort, social context, and long-term habituation (Detjen, Geisler and Schneegass, 2021). Especially relevant is the development of onboarding and educational mechanisms. For example, a 'driving licence' for AVs could provide passengers with system knowledge and interaction strategies, boosting their feeling of preparedness and control. Such onboarding could be tailored to age, gender, and prior exposure, recognising the generational and socio-cultural diversity in mobility preferences (Buckley et al., 2018).

#### 8.4.4 Designing for Children and Other Vulnerable Groups

The future will require systems that are inclusive and adaptable across all demographics. Children, for instance, may become early adopters as passengers in autonomous family vehicles. Research should investigate child-specific transparency strategies and educational interventions, considering their unique cognitive and emotional models of trust and understanding (Lee and Mirman, 2018). Moreover, future systems should enable passive and active learning, embedding moments of familiarisation into everyday mobility interactions.

#### 8.4.5 Synthesis

Ultimately, the future of the field lies in integrating adaptive transparency, verifiable trust metrics, and educational scaffolding to support a diverse user base. As vehicles grow in autonomy, so too must their ability to communicate, relate and educate. As this thesis has shown, the experience of first-time users is shaped not merely by what is explained, but how and when it is explained—and how much control passengers are afforded in interpreting or engaging with that information.

## 8.5 Conclusions

To summarise, this thesis investigated the influence of transparency communication in AD through uni- and multimodal feedback modalities and its implications on first-time passengers' UX, perceived feeling of safety and control, and system understanding. The investigation was done through an extensive literature review and four main experiments, which confirmed the positive effect of transparency communication, with the last one shedding light on the impact of non-critical failure situations. Then, a card-based toolkit was developed to make the generated knowledge accessible and applicable and initially verified in workshops and with experts. Subsequently, the toolkit was used in four case studies, which were able to replicate existing results. Thereby, this thesis has created a theoretical and applicable contribution to transparency communication in AD.

# Appendix A

All data acquired and prototypes created can be found under the following link:

https://adx.cards/appendix.html

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