Master Thesis in the Master’s Degree Program

Audiovisuelle Medien: Interaktive Systeme/Games

Exploring User Experience in Autonomous Cars

Applying Lean UX to improve the Prototype of an Automotive 3D User Interface in Virtual Reality

Master Thesis in the Master’s Degree Program Audiovisuelle Medien: Interaktive Systeme/Games

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Kurzfassung

Das Mitfahren in einem autonomen Fahrzeug wird eine komplett neue Erfahrung werden, die viele neue Möglichkeiten für Benutzeroberflächen im Auto bietet. Augmented und Virtual Reality werden in Infotainmentsystemen eine immer größere Rolle spielen. Mit dieser Entwicklung werden 3D User Interfaces im Fahrzeug Einzug erhalten.

Die Thesis evaluiert den Prototyp eines 3D User Interfaces im Hinblick auf Usability und User Experience (UX) in einer virtuellen Testumgebung (VTE). Die VTE simuliert eine Fahrt durch die virtuelle Stadt und verschiedene gängige Anwendungsfälle von Interaktion im Fahrzeug können in VR erlebt und getestet werden. Beispielhaft für die Entwicklung neuer User Interfaces basiert der Designprozess der Thesis auf der Lean UX Methodik, um die ursprüngliche Version des Prototyps nach der ersten Evaluierung weiter zu verbessern.

Am Ende des Designprozesses wurde in einer zweiten Studie die Verbesserung des neu gestalteten Prototyps in Bezug auf die Benutzerfreundlichkeit bestätigt. Nützliche Best-Practices für das Entwerfen von 3D UIs im automobilen Kontext werden erörtert.

Abstract

The experience of being a passenger in an autonomous electric vehicle will be considerably different and creates many new possibilities for in-car user interfaces. Augmented and virtual reality technology will play an increasing role in infotainment systems and 3D user interfaces will find a way into the car. A literature review presents several approaches of VR based driving simulators for UX/UI evaluation to introduce virtual prototyping.

The thesis evaluates a prototype of an automotive 3D UI in terms of usability and UX within a virtual test environment (VTE). In the VTE a drive through the virtual city and several common use cases of in-car interaction can be experienced in head-mounted VR. Exemplary for the design process of in-car interfaces, Lean UX principles are applied to further improve the initial version of the prototype after the first evaluation.

At the end of the design process, a second user study confirmed the improvement of the redesigned 3D UI regarding the usability and several best practices for designing 3D UIs in the context of a self-driving car are discussed.

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Oliver Kausch

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List of Abbreviations

ADS	Advanced Driving Simulator
AR	Augmented Reality
DOF	Degrees of freedom (e.g. 6-DOF)
FPS	First person shooter
fps	Frames per second
HCI	Human-computer interaction
HM	Hand Menu
HMD	Head-mounted device
HMI	Human-machine interface
IPQ	Igroup Presence Questionnaire
IVAD	Immersive Video-based Automated Driving Simulator
LUI AR	Luxoft's Prototype of the automotive 3D User Interface, including the VTE
MMR	Mixed methods research
OEM	Original equipment manufacturer
P1/P2	Prototype 1/2 of the 3D UI
POI	Point-of-interest
UEQ	User Experience Questionnaire
UI	User Interface
US1	User Study 1 (Initial User Study)
US2	User Study 2 (Follow-up User Study)
UX	User Experience
UXD	User Experience Design
VE	Virtual Environment
VTE	Virtual Test Environment
VR	Virtual Reality

1. Introduction

The automotive industry is at the beginning of a paradigm shift from the mechanical to the digital car. The stable position of OEMs is challenged by start-ups that push innovations towards shared, self-driven, electric vehicles. (Ferràs-Hernández *et al.*, 2017) Current trends like data analytics, connectivity services, shared mobility, and autonomous vehicles will transform the car into a computer on wheels. With the rising number of sensors to make autonomous driving possible, cars will become connected devices and part of a large and complex network. The importance of software will highly increase and become a key competence in the automotive industry. New business models like “transport-as-a-service” (Arbib and Seba, 2017) will shift customers away from the ownership of a car. For the customer, a great user experience (UX) may become the main differentiating factor. The experience of being a passenger in an autonomous electric vehicle will be considerably different from being a driver. This development opens a new world of possibilities for in-car user interfaces. Technologies like AR and VR will play an increasing role in infotainment systems and 3-dimensional user interfaces (3D UIs) will find a way into the car.

With the increase of computing power and the accessibility of real-time rendering and animation software, the industry started to use driving simulators for HMI evaluation in early design stages. (Weir, 2010) Due to the high costs of advanced driving simulators, a low-cost driving simulator based on head-mounted virtual reality (VR) was proposed for UI prototyping (Schroeter and Gerber, 2018). A side-to-side evaluation of an HMI prototype in head-mounted VR and in a real car showed promising results for the early evaluation of automotive UIs in VR (Pettersson *et al.*, 2019).

This thesis evaluates the concept of an in-car 3D UI in a virtual test environment (VTE) in terms of usability and UX. Exemplary for the early design process of in-car user interfaces, the research project uses Lean UX principles to further improve the initial version of the 3D UI prototype. Best practices for designing 3D UIs are explored in the context of a self-driving car. The thesis presents an approach of using head-mounted VR for UX evaluations and usability testing within an iterative design process. At the end of the research project, a redesigned and improved version of the initial 3D UI provides a first glimpse on future interfaces of autonomous cars.

2. User Experience in Autonomous Cars

The rising importance of UX in the automotive industry goes hand in hand with the demand for new mobility concepts like electric vehicles and shared mobility. These new ecosystems must be designed human-centred, otherwise a lack of acceptance might arise. A new mindset must be established in the automotive industry to tackle these challenges. This chapter explains the concept of user experience (Hassenzahl, 2008) and defines the principles of Lean UX (Gothelf and Seiden, 2016) that were used during the research project to establish a human-centred design process.

2.1 Lean UX

Lean UX (Gothelf and Seiden, 2016) provides principles, and methods, which may help the automotive industry to shift to lean organisational structures and to develop and test new mobility solutions from a wide range of physical or digital products to service offerings. Lean principles remove waste from the UX design process and transform it into a fast, experimentation-based decision process. This leads to a concentration of resources on ideas that deliver the most value in terms of real business and user needs. The ambition is to meet the needs of the customer to its fullest with an outstanding user experience and high product satisfaction.

2.1.1 Components of Lean UX

Lean UX is built on the foundation of design thinking, agile software development principles, and the Lean Startup method. It provides principles to successfully merge these foundations together and make them work in organizational structures. Each foundation provides their own methods.

In design thinking, every member of the team, regardless of being a designer or not, is encouraged to use design methods to achieve their goals. This increases the collaboration across different roles in the team and each member gets a holistic perspective of the product. The holistic perspective helps every team member, for example from the perspective of an engineer, designer, or developer, to observe user needs and to explore ideas collectively. The collaboration across different roles leads to better ideas, which can be evaluated in an iterative process. (Gothelf and Seiden, 2016, pp. 5–6)

Agile software development as another foundation adds principles to organize teams and reduces the time between deliverables. The goal is a constant output of product/software iterations, which enables the team to learn and improve the product very fast. (Gothelf and Seiden, 2016, p. 6) The four core principles of agile development also apply to Lean UX:

1. *Individuals and interactions over processes and tools*
2. *Working software over comprehensive documentation*
3. *Customer collaboration over contract negotiation*
4. *Responding to change over following a plan*

(Beedle *et al.*, 2001)

The third foundation of Lean UX is the Lean Startup method by Ries (2011). He developed an iterative process called build-measure-learn feedback loop (see Figure 2.1). This cycle is applied to product development in short iterations. The team makes assumptions and evaluates these assumptions with the help of a prototype. The prototype is a minimal viable product (MVP). Building the MVP does not necessarily mean to write code and start with software development. It is also possible to fake the functionality in order to test the assumptions. After building, the team puts the MVP to the user test to get customer feedback. Measurements like UX questionnaires and usability engineering methods can be used for evaluation. Afterwards it is important to learn from the user test. The development team uses these learnings to create the next version of the prototype, a new advanced MVP. During this process, assumptions are evaluated very fast and can be dropped, if they proof to be incorrect. (Gothelf and Seiden, 2016, p. 7)

In summary, “Lean UX is the practice of bringing the true nature of a product to light faster, in a collaborative, cross-functional way that reduces the emphasis on thorough documentation while increasing the focus on building a shared understanding of the actual product experience being designed.” (Gothelf and Seiden, 2016, p. 7)

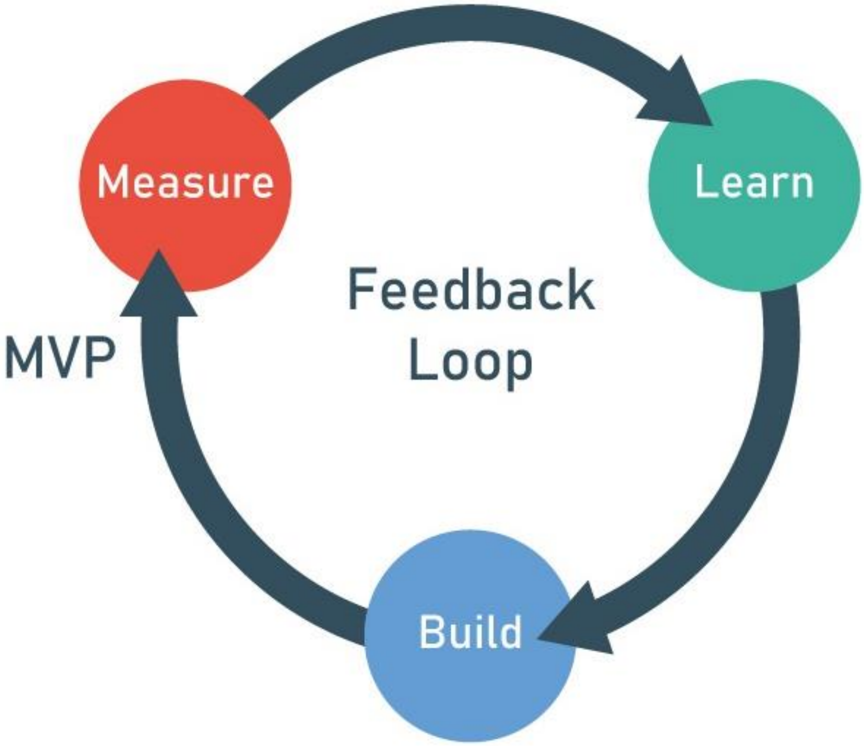

Figure 2.1: Lean Startup's feedback loop (build, measure, learn). Adapted from Ries (2011).

2.1.2 Applying Lean Principles

The organizational shift to Lean UX has many benefits for the development of interactive products including automotive user interfaces (UIs) and the in-car user experience. Through establishing small, cross-functional, and collaborative teams the efficiency increases. Fast iterations of the feedback loop during software and product development make it possible to consider user feedback and new knowledge at any stage of the development process. Features are always open to discussion and can be replaced. The most important and most valuable features have priority. The emerging product or software is easy to use, beautiful, and measurably successful. (Gothelf and Seiden, 2016, pp. 109–120)

Exemplary for applying Lean UX principles in the automotive industry, this research project used Lean Startup's build-measure-learn loop (feedback loop) for the improvement of an automotive user interface. The initial user study (US1) provided a baseline of the initial prototype (P1) and revealed usability issues at the beginning of the research project. After an iteration of the feedback loop, the second version of the prototype (P2) had to compete with the initial prototype. A second user study (US2) evaluated the second version to show an improvement of P2 over P1.

The Lean Startup method gave the project the fundamental structure. Almost two iterations of the feedback loop were conducted during the research as shown in figure 2.2. All phases of the research project are described below.

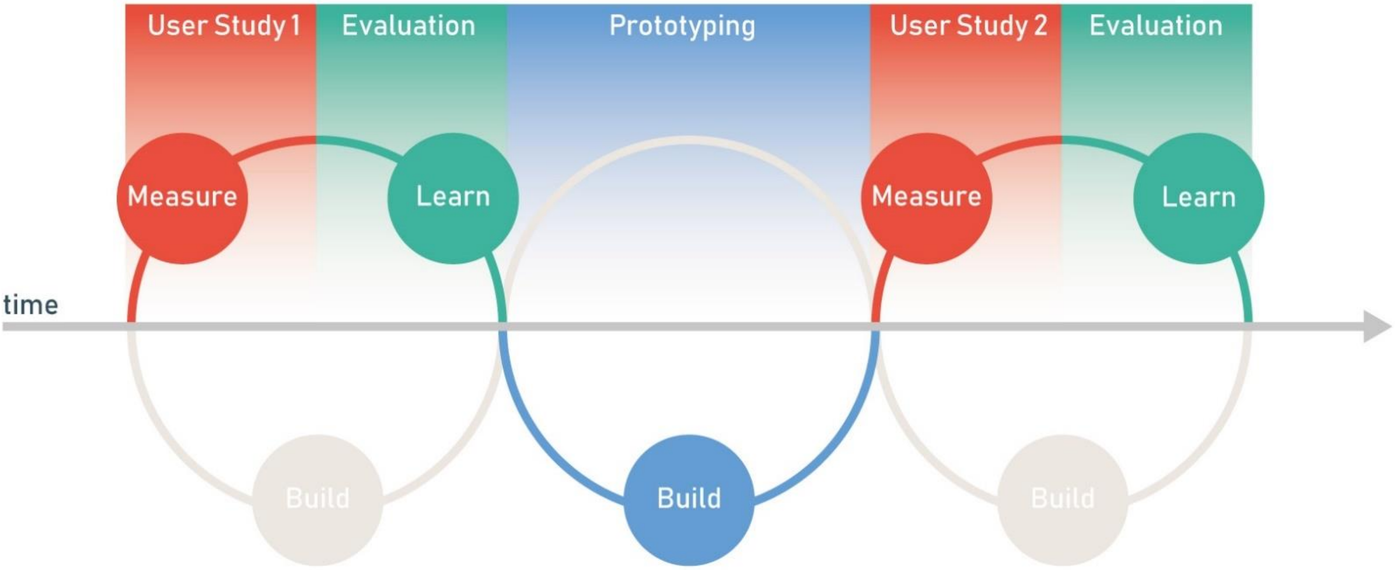

Figure 2.2: Feedback loop procedure during research.

All phases of the research project as shown in the timeline (Figure 2.2):

Measure:	*US1 measured the usability and UX of the initial version of the prototype (P1) to get a baseline for improvements.*
Learn:	*The data of US1 was interpreted, several findings lead to new assumptions.*
Build:	*A second version of the prototype (P2) was built.*
Measure:	*US2 measured the usability and UX of the second version of the prototype (P2).*
Learn:	*The results of US2 were compared to US1, new findings were discussed.*

2.2 Levels of Autonomous Driving

Driving a fully autonomous vehicle means being a passenger. The car takes over all aspects of the driving task. It observes and understands the environment in all weather and road conditions and takes notice of other traffic participants and acts accordingly. That means the car controls the steering and acceleration as well as deceleration and braking. It also navigates safely to the destination of choice.

The Society of Automotive Engineers (2014) defined six levels of driving automation for on-road vehicles. Starting from SAE level 0, where the human driver performs all tasks of driving, up to full driving automation defined in SAE level 5. In SAE level 5 the driver becomes a passenger and the vehicle handles the task of driving under all conditions without take-over requests. In case of a system failure, a fall-back system prevents dangerous situations and the system continuously monitors itself. The SAE levels of driving automation correspond roughly to the vehicle automation-degrees defined by the German Federal Highway Research Institute (BASt). Gasser and Westhoff (2012, p. 4) only defined five degrees of automation where the highest degree “full automation” conforms to SAE level 4. Compared to SAE level 5, BASt’s definition of “full automation” does include the system to send a take-over request to the passenger, if limits of the application are reached. If the passenger does not respond, the system will enable a minimal risk mode.

Talking about risk, trust in automated driving systems will play a major role in the future. This affects the user experience in autonomous vehicles and, vastly better, user experience can positively influence the trust of the passengers in the system (cf. Ekman *et al.*, 2016). Another key aspect of designing in-car user experiences will become minor, which is driver distraction. Distraction will become a feature in a positive manner. The car will become a gaming lounge, a mobile office or a living room. As a result, all types of new user interfaces and car interiors are imaginable. There is a need to explore the in-car user experience in this environment (SAE level 5) with all possibilities and constraints for an automotive user interface.

Level and Name	Description
Level 0 (L0) No Driving Automation	The human driver does all the driving.
Level 1 (L1) Driver Assistance	Vehicle is controlled by the driver, but some driving assist features may be included that can assist the human driver with either steering or braking/accelerating, but not both simultaneously.
Level 2 (L2) Partial Driving Automation	Vehicle has combined automated functions, like speed control and steering simultaneously, but the driver must remain engaged with the driving task and monitor the environment at all times.
Level 3 (L3) Conditional Driving Automation	An automated driving system on the vehicle can itself perform all aspects of the driving task under some circumstances. Driver is still necessity, but is not required to monitor the environment when the system is engaged. The driver is expected to be takeover-ready to take control of the vehicle at all times with notice.
Level 4 (L4) High Driving Automation	The vehicle can perform all driving functions under certain conditions. A user may have the option to control the vehicle.
Level 5 (L5) Full Driving Automation	The vehicle can perform all driving functions under all conditions. The human occupants never need to be involved in the driving task.

Table 2.1: Summary of SAE International driving automation levels. Reproduced from Campbell et al. (2018).

2.3 Creating a Meaningful User Experience

During the last decade there has been a shift from materialism to a post materialism society. Experiences have a higher value to the user or customer than material goods as van Boven and Gilovich (2003) showed in several studies.

In human-computer interaction (HCI), user experience (UX) is often used as synonym for usability. However, usability does not include all characteristics of an experience. Hassenzahl, M., Eckoldt, K., Thielsch, M. T. (2009) describe an experience as something in the users' imagination, which is strongly related to their feelings. Usability instead is objective and, in some cases, can be measured. For example, the efficiency of interacting with a product. Both terms, user experience (UX) and usability, will play an important role when evaluating the prototype of the automotive user interface (UI). Therefore, a precise definition is needed.

Hassenzahl (2008) "define[s] UX as a momentary, primarily evaluative feeling (good-bad) while interacting with a product or service." When a user interacts with a product, the most important part of UX are the feelings that arise when fulfilling his human needs for autonomy, competency, self-oriented stimulation, relatedness, and popularity. These feelings can change fast over time during the interaction, but they will be kept in mind even after the interaction with the product is finished.

When designing for a positive user experience, Hassenzahl (2008) separates "do-goals" and "be-goals". An interactive product should always meet the "do-goals". The achievement of "do-goals" lead to a good pragmatic quality of the interactive product. Important for a good pragmatic quality is that the product is functional, reliable, and usable. The user should find the product easy to learn, easy to use, and efficient when fulfilling tasks. These attributes represent the three basic levels of the UX pyramid (see figure 2.3) and they are objective characteristics, also often referred to as the usability of a product. Usability engineering offers the required methods (e.g. usability testing) and guidelines to create and evaluate an interactive product, which meets the "do-goals".

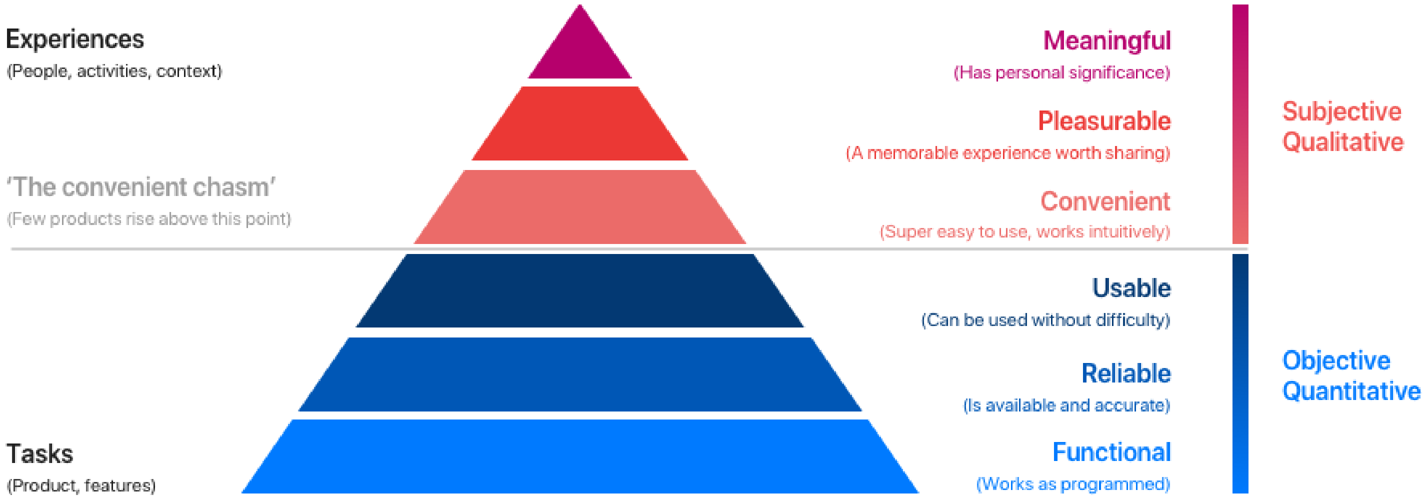

Figure 2.3: UXD hierarchy of needs model (Anderson, 2011). Reproduced from Ralph (2017).

A usable product is the foundation, but the positive UX is mainly achieved through “be-goals”, the fulfilment of human needs mentioned above. In the design process of a new interactive product, the “be-goals” have to be taken seriously. It is not enough to design a usable product and add a beautiful UI on top. The underlying human needs have to be addressed from the beginning. Hassenzahl (2008) gives the example of stimulation, which is induced by randomness. Randomness in an interactive product gives the user the possibility to explore the product from varying starting points and leads to surprises. This mechanism works well to stimulate the user, but it also has to be integrated into the design from the beginning. In the end, a positive UX is the result of a product, which is convenient, enjoyable and significant to the user.

2.4 Activities in Self-Driving Cars

Freeing the driver from the task of driving opens new possibilities for activities in the car. It is an opportunity to rethink the current interior design and seating positions. Laurier and Dant (2012) discussed the shift from expressing identity through driving to inhabiting a space that is caused by autonomous cars. They also identified a wide variety of activities occurring between passengers within the car. Many of them are related to conversations between passengers like all forms of storytelling, learning, caring, planning the week ahead, discussing troubles, and listening to the radio or music. In self-driving cars, Laurier and Dant (2012, p. 16) assume that there might be a shift towards activities like reading or working on a laptop. An exploratory study confirms this assumption. According to Ive *et al.* (2015), phone usage for reading and browsing the internet was mentioned by most study participants as main activity besides interacting with other passengers. Reading a book, tablet and laptop usage followed the above-noted activities. Regarding the seating position, some participants stated that they would prefer to face forward for safety reasons. Others liked the idea to have the possibility to face each other.

3. Virtual Reality in UX Research

This research project explores and evaluates the concept of an automotive user interface in a self-driving car. Many technologies needed for an implementation in a real car are not available or too expensive for prototyping. However, in early stages of the development and to explore user interface concepts, building a virtual prototype is an in-expensive and fast option to gain first user feedback. The virtual space is cost efficient and accessible and therefore great for prototyping and exploring new ideas and user experiences. This virtual space can be experienced by users in virtual reality.

3.1 Virtual Reality

According to Jerald’s (2016, pp. 9–10) definition, virtual reality is composed of a virtual, computer-generated environment and interaction, or communication between several entities. Different entities are the users, objects, and characters in the virtual environment (VE). Within the virtual world of a well-designed VR experience, the users easily understand how objects are controlled and how they can affect the environment and communicate with other entities. Communication between two entities can be such a natural thing as an object colliding with another object. Ideally, the users are fully immersed and perceive the virtual environment as real.

Milgram and Kishino (1994) classified mixed reality visual displays in the virtual continuum (VC). Virtual reality is at the right end of the virtual continuum, as shown in Figure 3.1. The virtual continuum represents the degree of virtuality of the experienced environment. At the left end of the scale, an environment consists solely real objects (real environment), at the right end, the environment is completely virtual (virtual reality). In between, different mixtures of real and virtual environments are located. They are called mixed reality. In mixed reality, real world and virtual world objects are presented in the same scene. For example, virtual objects are layered on top of the real world (augmented reality).

Currently the most common VR systems are head-mounted devices (HMD). A screen in front of each eye creates an immersive, stereoscopic experience. For development and rendering, real-time game engines render the virtual environment to the HMD and enable developers and designers to create VR applications.

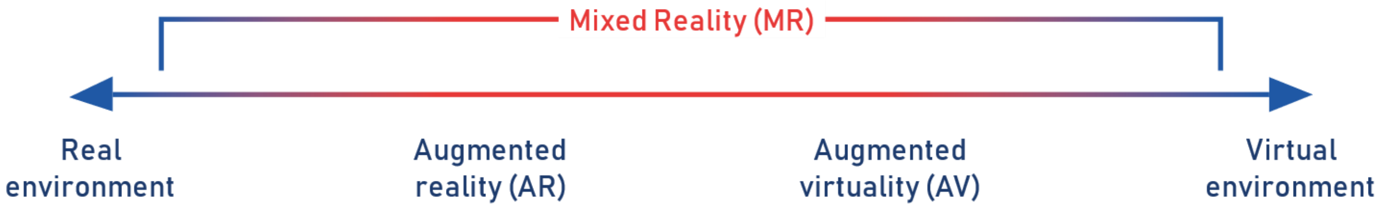

Figure 3.1: Virtuality continuum. Adapted from Milgram and Kishino (1994).

3.2 Immersion and Presence

Head-mounted virtual reality offers a high degree of immersion. According to Slater and Wilbur (1997), immersion is depending on the technology that surrounds the users and that delivers the stimuli needed for an illusion of reality. To achieve a high degree of immersion, the technology has to be inclusive, extensive, surrounding and vivid. Jerald (2016, p. 45) adds that the immersion rises, if the technology is also matching (e.g. head motion and the motion of the virtual camera), interactive, and has a plot (e.g. a consistent story and behaviour of the world). In contrast to presence, immersion is an objective measurement of the technology.

In 3D games and VR applications, users are most likely to experience presence. A user can experience a sense of being in the virtual environment during a VR experience. This feeling can also occur while consuming other types of media, like movies or video games, but the degree of immersion the respective technology offers, positively influences the potential to feel present. Jerald (2016, p. 46) describes presence as a psychological and physiological state, in which the user forgets about the real world and is fully involved in the virtual environment. In this state, the user perceives the interactions, characters and events similar to experiences in the real world and does not think about the technology. The feeling of presence is a form of illusion.

According to Jerald, several components influence the potential to feel present in the virtual environment. The first component is that the VE should feel like a physical environment. This is the case, when understandable, physical rules apply and “conflicting sensory inputs [are] supressed, including distracting stimuli from the hardware or the real environment” (Schubert *et al.*, 2001, p. 268). The illusion of being in a stable spatial place occurs when the user’s sensory perception is congruent to the presented stimuli and when those stimuli “behave as if [they] originated from real-world objects in 3D space” (Jerald, 2016, p. 47).

The second component described by Jerald (2016, p. 49) is the illusion of self-embodiment. Self-embodiment can be achieved by giving the users a virtual representation of their body in the VE. It is not important how realistic the representation of the body is; more important is that the virtual body matches the physical motion in a reasonable manner. Self-embodiment is not necessary to achieve the feeling of presence, but it can increase the level of presence in the VE.

The illusion of physical interaction describes another component that has an influence on presence. For example, sound effects or the rumble of a controller or another input/output device, which offers haptic feedback, can give the user an additional sense of feeling and touching the VE (Jerald, 2016, p. 49). Usoh *et al.* (1999) showed in a study that real walking through the VE as well as a higher connection between users and their virtual body (self-embodiment) increased the level of presence significantly. Another influence on the level of presence is social presence. Social presence is being able to communicate with other characters (or users) verbally and through body language. This increases the behavioural realism and “even tracking and rendering a few points on human players can be quite compelling” (Jerald, 2016, p. 49).

In summary, Presence has various levels and dimensions. It is hard to describe the feeling of being present in a VE. However, it can be assessed through questionnaires or physiological measurements like measuring the heart rate or skin resistance. It can be an important measurement when evaluating a virtual prototype in VR (LaViola *et al.*, 2017, p. 462), although it is unexplored how the feeling of presence influence the evaluation of a virtual user interface. In this research project, a questionnaire was used to evaluate the feeling of presence in the second user study (US2).

3.3 Driving Simulation in Virtual Reality

In the last years, several concepts of virtual reality driving simulators were presented. The focus of this chapter are concepts for head-mounted VR, because this technology has many benefits such as a high degree of immersion, the availability of good hand-, head-, and body-tracking technology, a high degree of flexibility regarding the lightweight setup, and the devices are affordable. Software packages like Unity or the Unreal Engine provide a set of tools to create immersive virtual environments and to prototype user interactions. Three different approaches of using VR for driving simulation are presented below.

3.3.1 Different Approaches

The Real-world Approach

Gerber *et al.* (2019) developed an Immersive Video-based Automated Driving (IVAD) Simulator for rapid prototyping and evaluation of in-car AR concepts in a 180-degree video-based environment. They recorded 180-degree videos of a drive through the city with a complex setup of cameras and sensors attached to a car. The videos and sensor data were then synchronized to get a rich and detailed environment for the driving simulation. In the first iteration, they tested the setup in an Advanced Driving Simulator (ADS) with three screens in front of the car for a 180-degree field of view, three screens as car mirrors and another screen on the dashboard. In the second iteration they replicated the same setup in Unity with a 3D car and a detailed 3D interior for the head-mounted VR version of IVAD. The videos are virtually projected on planes around the 3D car, synchronized and displayed in the car mirrors. Additionally, IVAD VR provides a toolset for rapid prototyping of automotive UIs and a Wizard of Oz interface that allows the researcher to control and change the UI during user testing.

Gerber *et al.* (2019) conducted a qualitative user study for each setup (IVAD ADS and IVAD VR). The participants perceived a surprisingly high immersion in IVAD VR, even though they felt disconnected from the environment, because many of them missed their body and hands. The feedback of participants indicated a familiarity with the environment and that the simulation makes it easy to imagine driving with an automated vehicle. The studies showed the possibility to switch seamlessly from the low-cost, portable VR solution to the high-fidelity ADS, which is a great advantage for the research process. From a design research perspective, IVAD VR is a great tool for gaining rich user feedback on different prototypes and for the exploration of ideas by changing and replacing objects in real-time.

The All-Virtual Approach

Compared to IVAD, which is based on a rich video-based environment, another concept for rapid HCI prototyping implements head-mounted VR in a computer-generated environment. The automated driving simulator, called AutoWSD, was developed for research on windshield displays, which utilize the whole windshield for the presentation of AR content. AutoWSD enables researchers to easily test different use cases and scenarios with little effort in user studies. The open-source framework is implemented in Unity and supports multimodal inputs, including gestural interaction, gaze-based interaction, and speech. Through framework components and modules such as the traffic, pedestrian, and vehicle component, it is easy to build own test scenarios. (Riegler *et al.*, 2019)

The In-car Approach

A challenge for driving simulators is to simulate the inertial forces and driving dynamics. Goedicke *et al.* (2018) presented their concept of a VR driving simulator, called VR-OOM, that is used in a car driven by a Wizard of Oz driver. The participant takes place in the passenger seat of a car and wears a VR headset. However, in the VE the participants find themselves in the driver's seat of a 3D car with a steering wheel. The virtual steering wheel and dashboard matches the position of the real physical dashboard and gaming steering wheel, which is mounted on the dashboard for haptic feedback. The car can be driven manually by the participants, where the Wizard driver mimics the users' steering inputs. In the autonomous mode the Wizard driver drives the car. The movement of the car is transferred into the VE so that the movement of the virtual car matches the real car. This setup provides a high degree of physical presence because the participant is exposed to the inertial forces and driving dynamics. When designing a scenario for VR-OOM, the virtual environment must match the constraints of the location and route where the car will be driven.

Goedicke *et al.* (2018) conducted a qualitative pilot study with six participants to verify the proof of concept. The participants showed natural responses to traffic events and they behaved as if they were in an autonomous car. Some participants intervened more often than others by grabbing the steering wheel to change the trajectory of the car slightly. One participant mentioned "…the driver [automated car] was parking very close to the other car and I noticed I was pressing my foot down. Just to brake." (Goedicke *et al.*, 2018, p. 8) This natural behaviour can be interpreted as a high degree of immersion and the feeling of presence. The authors of the study suggest using VR-OOM for a wide variety of use case that require on-road testing, such as autonomous vehicle design, exploration of human behaviour in autonomous vehicles, evaluation of critical and dangerous scenarios, and to design for entertainment and secondary activities.

Related Approaches

There are a few more concepts for driving simulation in VR, like the low-cost Automated Driving Simulator by Schroeter and Gerber (2018) that utilizes 180 degree video footage to create the immersive environment for head-mounted VR, or the "Concept for a Virtual Reality Driving Simulation in Combination with a Real Car" by Lê *et al.* (2017). Lungaro *et al.* (2018) developed a hyper-realistic testbed that is based on the video game GTA V and can be used for the design process and evaluation of future interfaces. They also provide a set of self-driving interfaces including heads-up displays and AR.

3.3.2 Evaluating UX in Virtual Reality

There is a consent in the research community, that head-mounted VR is a legitimate tool to assess user experience. In the article “Using virtual reality to assess user experience”, Rebelo *et al.* (2012) propose to utilize VR in user research studies and for the evaluation of human-product interaction. Several user research studies were conducted to gain insights on the users’ needs and expectations. These studies showed to be valuable in early stages of product development. In these studies, researchers and designers attempted to develop an understanding how users will integrate the interactive system into their daily life and routines. In the second use-case human-product interaction, VR user studies were conducted to assess the user experience and usability of an interactive product for product optimization.

In order to compare how head-mounted VR influences the participants’ behaviour and responses regarding the user experience of the same interactive in-vehicle system, Pettersson *et al.* (2019) conducted a user study in virtual reality and in the field in a Volvo S90. The VR system replicated the in-vehicle system and environment in all aspects, so that the field study was comparable to the VR study. The studies showed promising but not completely convincing results because the statements and observations regarding the user experience were very different in the field compared to VR. However, the authors also admit that a higher degree of realism of the VE, a higher resolution and refresh rate of the HMD, and more natural driving physics would raise the feeling of presence. The study concludes that the early evaluation of automotive user interfaces in VR to gain insights on users’ behaviour is promising.

4. 3D User Interfaces

All types of new user interfaces and infotainment systems are imaginable in autonomous cars to meet the passengers' needs. With AR/VR and motion tracking technology finding their way into the car, the use of 3-dimensional user interfaces (LaViola *et al.*, 2017) must be explored in depth. This research project explores a virtual prototype of a 3D UI that will be possible when AR/VR technology emerges into the car. The prototype implements holographic UI elements and gestural interaction into an autonomous single-seater car for urban environments. For a better understanding 3D user interfaces and common interaction techniques as well as some relevant design guidelines are introduced in the following chapters.

4.1 Introduction to 3D User Interfaces

The evolution of user interfaces is driven by technology. Around 1980 with the development of new input and output devices such as the mouse and first raster graphic displays, the graphical user interface (GUI) evolved. An area of research called human-computer interaction (HCI) emerged combining various areas of knowledge like cognitive science, linguistics, human factors, ethnography, sociology, graphic and product design. A similar development is happening in the last few years as technologies like VR and AR HMDs, 3D graphics, and motion-tracking technologies matured and became more powerful, affordable and precise. These technologies enable designers and developers to create 3D applications. The field of 3D user interfaces (3D UI) and 3D interactions is now an important, growing area of research. (LaViola *et al.*, 2017, p. 12)

LaViola *et al.* (2017, p. 8) define a 3D UI as a user interface "that involves 3D interaction". 3D interaction is human-computer interaction that is "performed directly in a real or virtual 3D spatial context" (LaViola *et al.*, 2017, p. 7). This definition includes software that translates 2D input into actions in a virtual 3D spatial context, however these applications are only a niche in 3D user interfaces. This research project solely concentrates on 3D UIs that use real 3D spatial input from a hand-tracking device. This includes hand gestures and direct interactions with virtual objects in a 3D spatial context. In this type of 3D UIs, a motion-tracking system tracks the movement of the user or parts of their body like their hands. Another common approach (Bowman, 2014) is to use controllers that are tracked by the system. The joysticks and buttons add input possibilities for discrete actions such as confirming a selection or firing a gun. In both approaches, the movement generates the input, which is directly translated into the virtual environment.

4.2 3D Interaction Techniques

Hardware and software components are essential to enable users to accomplish their tasks. Interaction techniques are methods that combine both components and translate hardware inputs into system actions. In 3D interaction, a few basic user interaction tasks were identified such as selection and manipulation, travel, and system control tasks that change the state of the system. The following 3D interaction techniques are structured according to these tasks.

4.2.1 Subset of Manipulation Tasks

One of the most common user tasks in 3D interaction is the manipulation and selection of objects. In the real world, a common understanding of manipulation is any interaction with a physical object that changes its position or size, such as grabbing a ball with one or two hands. It is the spatial manipulation of a rigid body, which preserves the shape of the objects.

According to LaViola *et al.* (2017, pp. 257–258) the canonical approach splits the manipulation task into a subset of tasks: The task of selecting an object (selection), moving an object from the initial position to the desired position (positioning), rotating an object around an axis or freely in 3D space (rotation), and scaling an object to change its size (scaling). Additionally, the type of application, object size, object shape, the distance between the user and the object, and the physical laws of the environment influences the manipulation task. Since rotation, scaling and some other user interaction tasks are not used in the automotive user interface, the following chapters provide only an overview of techniques relevant to the prototype.

4.2.2 Selection Techniques

“Selection is the task of acquiring or identifying a particular object or subset of objects from the entire set of objects available. Sometimes it is also called a target acquisition task.” (LaViola *et al.*, 2017, p. 258) The distance to the target object, the target size and the density of objects surrounding the target object influence the usability and user performance during the selection task. The selection of objects within arm’s reach or out of arm’s reach are two distinct tasks.

For the selection task within arm’s reach, there are a few grasping metaphors categorised in hand-based grasping and finger-based grasping techniques. However, the prototype does not implement grasping objects. There is no rigid object interaction with physics. Instead, direct interaction with virtual buttons, sliders, and menus within arm’s reach is used to change the state of the system and for the accomplishment of tasks. These UI elements are system control interfaces (see 4.2.5 System Control Interfaces).

Pointing Metaphors

Pointing metaphors (LaViola *et al.*, 2017, pp. 273–279) are often used for the selection of objects out of arm's reach. Pointing feels very natural to the users and is a powerful technique, because it requires only minimal arm and hand movement. The user performance is considerably better compared to grasping techniques if the input device provides reliable tracking data. Regarding the manipulation tasks positioning and rotation, pointing is almost unusable. Pointing restricts the repositioning of an object to a radial movement around the user. Changing the distance between the user and the object requires an additional input parameter. Due to these reasons, pointing is only considered for the selection of remote objects in this research. A frequently used solution are vector-based pointing techniques.

Vector-Based Pointing Techniques

Vector-based pointing (LaViola *et al.*, 2017, pp. 273–274) requires only one vector to be calculated and therefore is easy to implement and very common in current 3D UIs. Ray-casting, fishing reel and image-plane pointing are some examples for vector-based pointing techniques. Ray-casting calculates the pointing vector from a virtual ray that is attached to the user's hand or controller. Thus, the user can control the pointing vector with hand or controller movement. In some cases, it is not possible to get accurate tracking data of the hand.

A common solution is to use the orientation of the head instead of hand-tracking. A ray is casted into the viewing direction and the pointing vector is then controlled by the head movement and head rotation. This technique is called gaze-based ray-casting and is used in both versions of the prototype to select distant objects. In the prototype, the ray cast is visualised without a vector, implementing a gaze cursor in the centre of the field of view.

The issue that more than one object can intersect with the ray-cast is solved by the fishing reel technique, in which the user is able to choose between intersecting objects via an additional input mechanism. This input mechanism controls the length of the pointing vector.

4.2.3 Indirect Manipulation Techniques

Some virtual objects, especially large or remote objects, are impractical to manipulate with direct interaction. Indirect manipulation techniques allow the manipulation without direct interactions. There are some benefits, for example, remote objects can be manipulated without travelling and additional constraints can be implemented to reduce the degrees of freedom when reasonable to improve the user's efficiency and precision while accomplishing a manipulation task.

According to LaViola *et al.* (2017, p. 286) there are three types of indirect manipulation techniques. The control space metaphor separates the controls from the virtual environment into a physical space, where the user can control the manipulation of an object indirectly. In the proxy metaphor, the user directly interacts with a representation of the corresponding object in the VE. The manipulation is then translated onto the corresponding object. The representative object, called proxy, is within arm's reach and allows a more natural, direct interaction through grasping methods. The widget metaphor displays widgets around interactive objects in the VE. Users interact with widgets directly and the manipulation of these widgets is then transferred on the associated virtual objects.

Proxy Metaphors

Proxy metaphors use miniature representations of interactive objects within the VE for manipulation tasks. An effective approach is world in miniature. World in miniature (LaViola *et al.*, 2017, p. 292) scales the entire world down and makes it accessible within the users arm's reach. This works well for small and medium-sized VEs and allows the user to interact directly with objects in the miniature representation of the VE. The associated virtual objects are updated according to the interaction with their miniature representations. This technique does not only allow object manipulation, travelling through the VE is also a possible use case by moving the user's representation to another location, or by selecting a target location within the miniature world. In large virtual environments, the functionality to scale and scroll the miniature world should be implemented. This solves difficulties when interacting with very small representative objects in the miniature world.

4.2.4 Travel Techniques

In most VR applications, an important part of the experience is that users are able to navigate through the virtual environment. According to Jerald (2016, pp. 153–154), the combination of travel techniques and a good wayfinding system is necessary to achieve the goal of moving from one location to another. The cognitive process of navigation starts with wayfinding in the user’s mind. Wayfinding is the thinking that guides the movement. It is the important, non-physical part of navigation, in which users try to figure out their location, build a cognitive map of the virtual environment, and start to plan their path to the target location. The act of moving to the target location is referred to as travel technique. A distinction is made between active or passive travel techniques. The act of moving the user to the target is either actively achieved by themselves or the user is moved e.g. by a force. There are also several reasons for travelling, like exploration or search. When users explore the VE, they have no specific target location in their minds. Users often explore to build knowledge and to orient themselves in the VE. While searching on the other hand, a user is looking for a specific target location.

LaViola *et al.* (2017) categorise travel techniques into walking metaphors, steering metaphors, selection-based travel metaphors and manipulation-based travel metaphors. A selection-based travel metaphor is used in the prototype of this research project. Selection-based travel techniques simplify travelling by reducing it to solely setting the target location (target-based travel technique) or specifying the route (route-planning travel technique) through a selection method. The act of movement from the current position to the target position is controlled by the travel technique. Users are moved passively. In target-based travel techniques users do not have to worry about wayfinding. The target of travel has to be selected, and then the user is teleported to the target location. However, an empirical study (Bowman *et al.*, 1997) showed that due to teleportation the spatial orientation of the user decreased significantly. LaViola *et al.* (2017, p. 345) suggest a continuous movement from the start location to the target location. However, depending on the application, passive movement of users may cause cybersickness. A compromise between a decrease of spatial orientation and the occurrence of cybersickness is a fast transition between the start and target location. This “blink” mode gives the users the possibility to pick up enough spatial information to obtain their spatial orientation and the understanding of their location in the VE.

4.2.5 System Control Techniques

Selection, manipulation and travel are common interaction techniques eminently in 3D UIs. However, system controls are also important in immersive applications to “change the state of the system”, “the mode of interaction”, or to “request the system to perform a particular function” (LaViola *et al.*, 2017, p. 380). The difference between selection, manipulation, travel techniques and system control interfaces is that in system controls the user only commands the system to accomplish a certain task. The system itself takes care of the execution, in contrast to selection, manipulation, and travel techniques where users are also responsible for how the goal of the task is achieved. System controls are explicit actions that control the flow between different tasks of an application.

System controls (LaViola *et al.*, 2017, pp. 380–381) are widely explored in desktop or touch-based 2D UIs and many design patterns exist. An example is the WIMP (windows, icons, menus, and pointer) metaphor, which is commonplace in graphical user interfaces (GUI). Pull-down menus, text-based command lines, and tool palettes are often used in GUIs. In some cases, it does make sense to use these 2D techniques in AR/VR, such as mobile AR applications with touch-based input. In applications with a high degree of immersion, using WIMP might not be the best decision. A solution is to adapt 2D techniques to the interaction in virtual environments for better results. Additionally, system controls in 3D UIs can also make use of voice commands, gestural commands or tool belts.

Human Factor Guidelines

When designing 2D menus and elements for VR/AR applications, there are a few human factors (LaViola *et al.*, 2017, pp. 381–383) to keep in mind. First of all, the visibility of objects in the VE. System control elements like menus can overlap objects. It is important to scale them to an appropriate size by considering the screen resolution, and the reduction of readability. Semi-transparent elements are also an option. Second, focus switching can be an issue when control element and the area of main interaction is spatially separate. The consequence is an interruption of the flow of action. Collocated menus in the same spatial and substantial context are a way to reduce time-, and attention consuming switching. As in every UI, multimodal feedback is more important than ever in 3D UIs. Auditory feedback like the click of a button may be drowned out by ambient soundscapes or noise, and 2D graphics may be overseen due to a rich and detailed environment. It is also important to design menus functional with the right amount of breadth and depth. Users should be able to understand menu structures easily and know how to navigate fast to the desired function. Ergonomic issues can occur when buttons, menus or other UI elements are placed in an uncomfortable position in 3D space. System controls attached to the user's body should be useable with natural gestures and motions regarding the human anatomy.

Graphical Menus

The challenges with graphical menus in 3D UIs mentioned above require a careful adaption of 2D system control patterns. Adapted 2D menus (LaViola *et al.*, 2017, p. 387) are the most popular technique for system control in 3D UIs. They behave the same as their desktop or touch-based counterparts and can contain a large number of functions. Users are used to the principles of interacting with these menus, which is a great benefit. For the reason that the user travels through the VE, it does make sense to attach the menus to the user's head, to the controller or hands, or to a physical surface that is visible in the VE, to make the menu easily accessible.

A concept attaches the menu the user's hand and every finger controls a different menu item. Through finger tracking, it is possible for the system to interpret which menu item was selected. An approach is to use the non-dominant hand for menu selection and the dominant hand for selecting menu items. The hand-menu in the prototype implements a similar concept. The menu is attached to the non-dominant hand and the dominant hand is used for the selection of menu buttons. (LaViola *et al.*, 2017, p. 388)

The menu can also be attached to a physical surface and the movement of the physical surface is tracked and visualized in the VE. Users are able to pick it up and carry it with them through the environment. A great benefit is that it is intuitive and feels natural to shift it into the field of view when needed. Additionally, the physical device provides haptic feedback when pushing a virtual button layered over the surfaces. This approach lacks usability if controllers are needed for other interaction techniques in the same application. (LaViola *et al.*, 2017, p. 389)

For quick changes of tools or system states LaViola *et al.* (2017, pp. 390–391) suggest to use 1-DOF menus. 1-DOF menus enable users to switch between a small number of menu items with only one hand. A common technique is to attach the menu to the user's hand. The rotation of the hand switches through the items and the active item is the one which falls within the "selection basket". In this approach, switching through menu items can also be solved by a joystick or buttons of an input controller. It is also possible to use a physical tangible object as an input device for a 1-DOF menu. An example is the tangible skin cube by Lee and Woo (2010). By rotating the cubes in their hands, users can switch between menu items without looking at the menu.

Additional auditory feedback can provide hints about the currently selected menu item. In general, 1-DOF menus are easy to use and provide rapid access to different tools. The issue of focus switching is minimized, and menus attached to the hands or controllers are always accessible.

4.3 Design Guidelines for 3D User Interfaces

Interaction Techniques provide a set of methods on how users accomplish their tasks within the VE. The following design guidelines summarize important principles for designing 3D UIs, mainly based on the books from Jerald (2016) and LaViola *et al.* (2017). Some principles apply to user interfaces in general, others are important for the design process of 3D UIs in particular. These principles are based on common sense approaches and creative exploration. Some of the assumptions that were derived from the results of the initial user study are based on these guidelines.

Basic ergonomics rules also apply to 3D UIs. The ability to access a menu or other UI elements strongly depends on the placement in the VE. The human anatomy like the arm length and degrees of freedom regarding the rotation of joints like the wrist, elbow, and shoulder must be considered when designing the user interface. Providing an appropriate spatial reference frame (Jerald, 2016, p. 292) for UI elements is essential.

Alger (2017) presented several guidelines that apply to the virtual-world reference frame. He suggests placing UI elements in the area of 60 degrees wideness in the user's field of view. This assumption is based on the range of motion for head movement (by turning the head), which goes from minus 80 degree to plus 80 degree. The most comfortable range is between minus 30 degree to plus 30 degree. Alger also states that the distance of approx. 50 cm between the UI element and the user feels most comfortable for direct interaction (see Figure 4.1). Interactions that require the users to hold their arms up high in front of their bodies quickly results in fatigue and muscle ache. This also includes line of sight interaction methods. A solution is to consider using input devices that can be used from the side of the body or in the lap from a rested position (Jerald, 2016, p. 361).

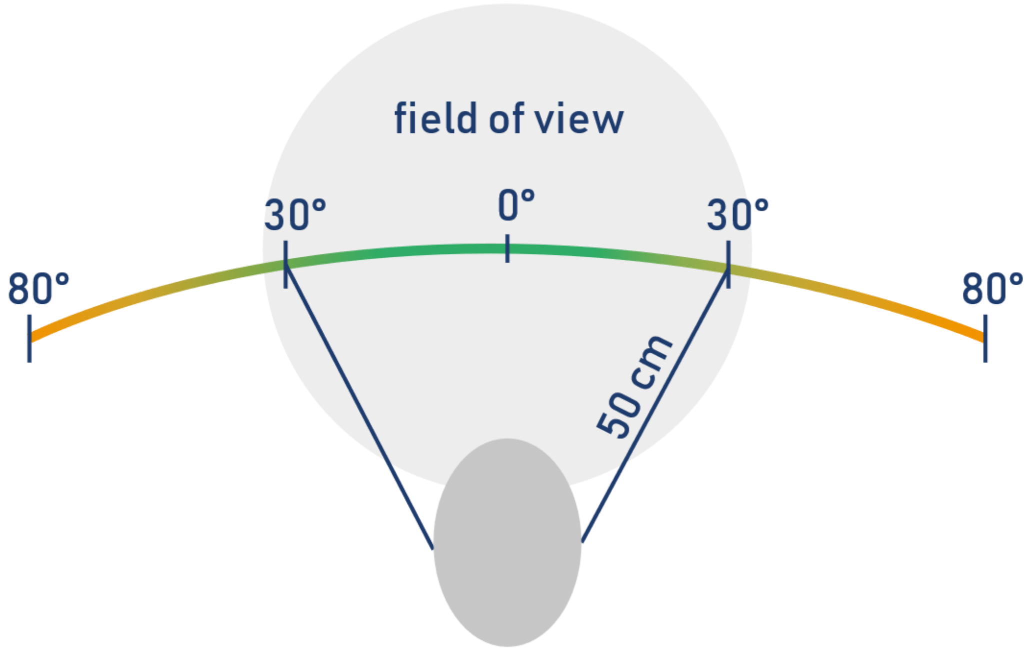

Figure 4.1: Interaction area of 60 degrees.

LaViola *et al.* (2017, p. 413) and Jerald (2016, p. 359) suggest to place system controls (e.g. menus) in the head- or body-reference frame. For example, they can be attached to body parts like the users' hands or to the controller. Thus, they are always easily accessible even if the user travels through the VE. According to Jerald (2016, p. 295), the non-dominant hand should maintain the reference frame of the attached UI elements so that the dominant hand can work efficiently without constraints. When using the head-reference frame, it is important to minimize visual cues in the field of view, except for a head-tracked pointer or gaze cursor (see 4.2.2 Selection Techniques) if needed for input (Jerald, 2016, p. 359). Additional information or UI elements should be placed in the torso-reference frame to avoid occlusion.

Although the spatial freedom encourages to design 3D menus, common design patterns or hybrid interfaces that combine 2D and 3D elements should be considered. The complexity of 3D interfaces is not always the best solution (LaViola *et al.*, 2017, p. 413). Common approaches are often straight forward, well-known and users are able to develop a mental model very quickly (Jerald, 2016, p. 355). Reducing the DOF of a menu by placing it on a 2D surface to simplify the selection process shows that constraints can be used deliberately to achieve a higher efficiency and accuracy (LaViola *et al.*, 2017, p. 450). From the visual point of view, it is important to show relations between different menu items through colours, shapes, textures, dimensions, positioning, text and symbols. Surfaces and textures also help to understand the orientation and position of the menu in 3D space. To avoid occlusion finding a good compromise between menu size, transparency, and readability is very important. Context-sensitive menus should also be considered to display only available and meaningful functions and to reduce the size of the menu.

Using several menus for interaction at the same time might cause focus switching (LaViola *et al.*, 2017, 382, 394). Focus switching occurs when related menus are not collocated. The flow of interaction is interrupted through switching between menus, interaction techniques, or different areas of interaction. This might also be caused by hybrid interfaces, where it is necessary to switch input devices or the context of interaction. Always avoid disturbing the flow of action of an interaction.

In the design process of 3D user interfaces based on hand tracking, Wigdor and Wixon (2011, pp. 97–103) pointed out that it is important to keep in mind that a tracking devices are one state input devices. They always track the movement of the user’s hands. Gestures that open a menu or enable a tool are prone to false positives. This is the case when a gesture was detected by accident and the user did not intent to perform this gesture, but rather did something else in the tracking area. The interface reacts by opening the menu or activating a tool and the user is confused by this reaction. This behaviour, called the “live mic” problem, should always be considered when designing 3D UIs with gestural input.

In general, it is important to make design decisions according to the specific system and user interface requirements. The usability of interfaces can benefit from Nielsen’s ten heuristics for user interface design (Nielsen, 1994). Wang *et al.* (2019) showed that the ten heuristics are also applicable to graphical menus in VR and that they are worth considering when designing 3D UIs.

5. Prototype

The virtual test environment and initial version of the 3D user interface was developed by the research and UX design team at Luxoft in Stuttgart, Germany. The concept is called LUI AR and had been showcased at several exhibitions, including CES 2019. In head-mounted VR, users can experience the virtual test environment and the 3D UI of an autonomous car. The car takes the users on a ride through the virtual city and common use cases of in-car interaction can be experienced.

For a better understanding, the virtual test environment must be considered separately from the in-car 3D user interface. When speaking of the virtual test environment, this includes the virtual city and car as well as the storyline and driving route. It is the virtual environment the user visits in VR and includes the input modalities like the virtual hands as a representation of the real hands and the gaze cursor as a vector-based pointing technique.

In the following, the 3D user interface (3D UI) is referred to as the prototype. It is placed in the virtual test environment, more precisely in the car interior, and utilises the input modalities for interaction. It consists of different applications in the car. All interactive elements in the virtual test environment are part of the 3D UI. Focus of this research project is the evaluation and improvement of the 3D UI in terms of usability and user experience.

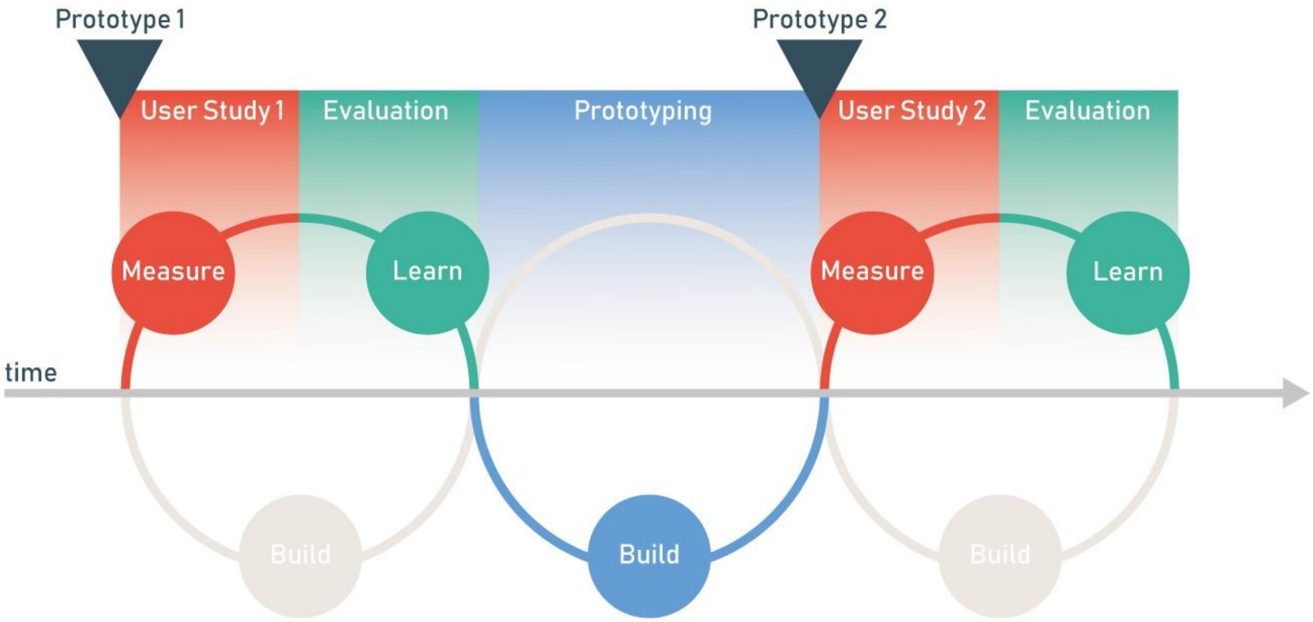

Figure 5.1: Timeline of research. Prototype 1 and 2 within the feedback loop procedure.

The markers in the timeline in figure 5.1 show both versions of the prototype. Prototype 1 (P1) is the initial version of the 3D UI at the beginning of the research project. Prototype 2 (P2) indicates the redesigned version of the 3D UI during this research project. Both versions are based on the following technical setup, virtual test environment, and same basic interaction techniques. In order to understand the differences between P1 and P2 the chapter Design Process explains the changes and improvements based on the findings (see 8. Results) and learnings of User Study 1 (US1).

5.1 Technical Setup

The prototype is built in Unreal Engine 4.21 for head-mounted virtual reality. The Unreal Engine is a game engine and real-time renderer. It provides tools to bring 3D models together, create materials, animations, and offers a development environment for visual scripting called Blueprints (Epic Games).

In the study setup, the prototype ran on the advanced model of the Razer Blade 15 gaming laptop with an integrated Nvidia GeForce RTX 2070 Max-Q graphics card. The graphics card achieved a constant frame rate of 60 fps on Oculus Rift S, which was the VR HMD of choice during the studies. A Leap Motion Controller was attached to the HMD to track the movement and position of the user’s hands. Hand-tracking allowed the user to interact directly with the 3D user interface. The Oculus Touch controllers were not required for interaction.

There are some technical constraints concerning the hand tracking. The Leap Motion Controller contains two cameras and three infrared LEDs. The cameras track the invisible infrared light. The interaction area in front of the controller is in average 135 degrees wide and deep, and tracks the hands up to a distance of 80 cm from the device as shown in figure 5.2. (Leap Motion, 2014) The tracked hands are rendered in the virtual environment to achieve self-embodiment (see 3.2 Immersion and Presence). In comparison to the field of view of the Oculus Rift S with approximately 110-degree wideness, the hands should always be visible when in the field of view. However, there are situations where the Leap Motion Controller loses the orientation of the hands and they cannot be tracked correctly. Since the cameras cannot see what is hidden behind an object, tracking failure can also occur when both hands overlap each other, or fingers are hidden for the cameras by the back of the hand, wrist or arm.

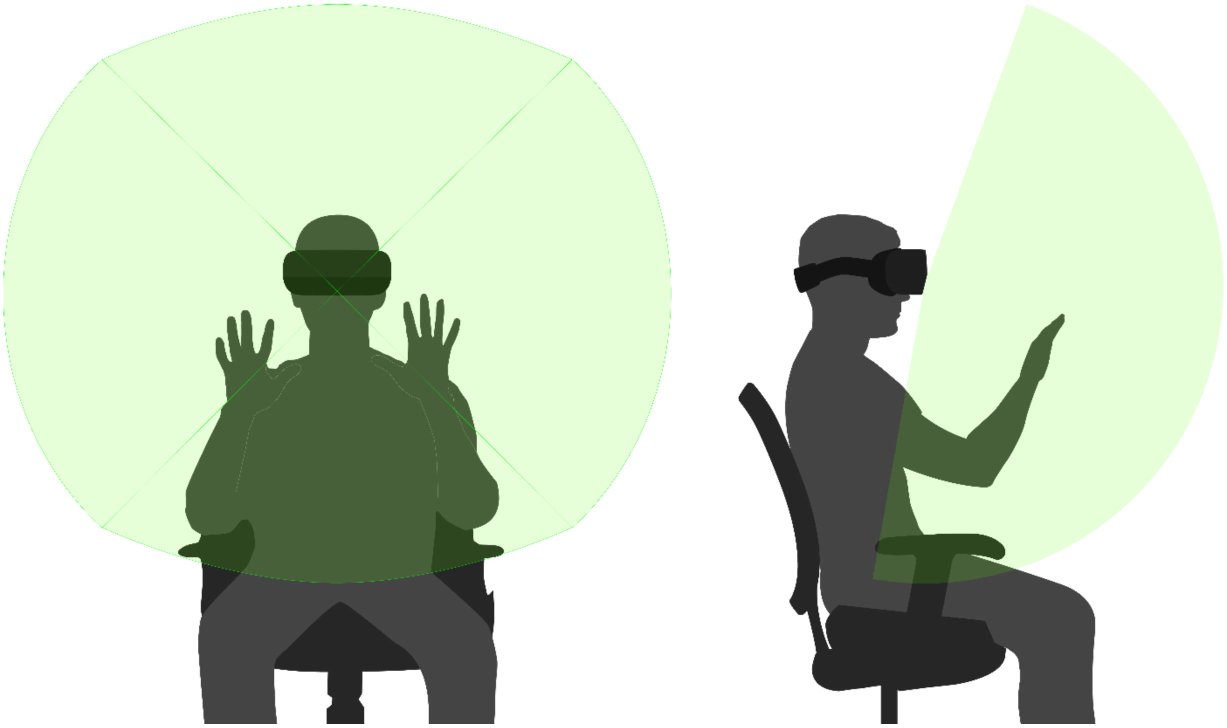

Figure 5.2: Tracking area of the Leap Motion controller. Reprinted from Leap Motion (2016).

5.2 Virtual Test Environment

The virtual test environment (VTE) acts as a sandbox for testing ideas. It contains of a futuristic city with a highway and a dense road network without traffic. Point of interests like a restaurant, museum, and a construction site enliven the virtual area. The VTE is suitable to simulate autonomous driving in an urban environment. Two different driving routes through the city are implemented, but custom routes can also be added with little effort. Therefore, other use cases than user interface testing are also imaginable in this environment. The current version provides a single-seater autonomous car with a clean interior. The dashboard neither has physical buttons and a steering wheel nor a touch screen. It leaves enough space to implement new 3D user interface concepts. For direct interaction with the UI the VTE provides a virtual representation of the hands. They create and support the feeling of self-embodiment in the virtual environment.

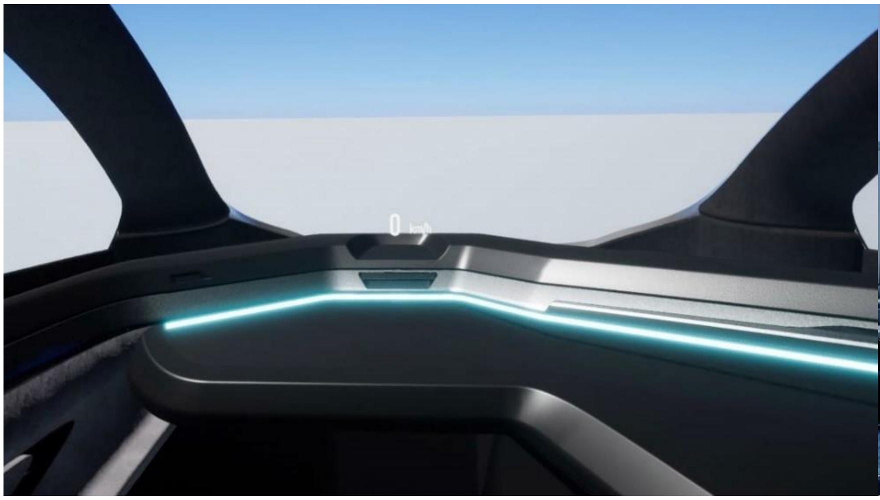

Figure 5.4: VTE car interior.

Figure 5.3: VTE futuristic city.

5.2.1 Interaction Techniques

Entering the prototype in VR, the user finds himself in the single-seater car. The entire 3D UI is projected in mid-air in the user’s field of view. In general, there are two different areas where UI elements are placed. The main menu is attached to the user’s left hand. By rotating the hand along the arm’s roll axis, the main menu (or hand menu) appears next to the hand and sticks to the hand movement. The right hand is used to push menu buttons and to open the applications. The main benefit of the hand menu (HM) is that the user has it always in a reachable position for interaction (see 4.2.5 System Control Techniques). However, the concept of a left-handed HM that must be used by the right hand might be a drawback for left-handers.

The second area for UI elements is above the dashboard and on the right side of the passenger. The area is about 140 degree wide and requires some upper body flexibility. Regarding the general flow of interactions, the HM controls the state (visible/invisible) of the respective application and the application itself is projected into the space above the dashboard. These applications stick to the physical dashboard and do not float through space for example when the user moves his head. The users must reach out with their hands to interact directly with the UI elements by touching the holograms.

Remote objects and menus cannot be accessed by direct interaction. Therefore, a gaze cursor is attached to the middle of the field of view and moves with the user’s head movement. To select a remote object the user must hover and hold the cursor above the object until a loading bar indicates the selection process. The cursor can be compared to a crosshair, a concept which is widely spread in FPS games. It is a vector-based pointing technique (see 4.2.2 Selection Techniques) and can also be used for travelling through the environment by looking at predefined waypoints (see 4.2.4 Travel Techniques).

5.2.2 Use Cases of the 3D User Interface

Most common use cases of in-car interaction can be experienced in the prototype. There is an application for Navigation which provides a 3D holographic map of the virtual city. Points of interest (POI) are marked in the map and can be explored by direct interaction. To take a ride through the city, users must select the restaurant POI to set it as travel destination. Opening the restaurant on the map loads a 3D virtual representation of the restaurant into the field of view of the user in the car, similar to Google Street View in VR (cf. Google Maps, 2012). Users are then able to navigate through the life-sized restaurant preview and can select a table to make a reservation. Pointing with the gaze cursor on a free table selects the table. A loading bar appears and on completion, the table is reserved. To navigate through the virtual restaurant representation, the user can jump back and forth between waypoints allocated in different locations. After a successful reservation the application closes and the car starts driving autonomously to the restaurant.

Other common use cases of the prototype are Climate controls, Media Player, and Ambient settings. The Climate application controls the airflow direction and the airflow strength. In the initial prototype these settings are controlled by two sliders. The vertical slider controls the strength and the horizontal slider changes the airflow direction from left to right or vice versa. A floating representation of a vent in front of the windshield indicates the current airflow direction and strength.

In the Media Player a song can be selected for playback and the songs can be sorted by genres. The media playback can be controlled by a play/pause button and volume slider. In the initial version of the Media application song covers are randomly spread above the dashboard. The genre buttons are placed on the bevel of the dashboard. The play/pause button and volume slider are permanently visible, regardless of which application is currently active.

The Ambient settings provide calming surroundings and entertainment in the car. When opening the Ambient application, the users must select a setting of choice in the HM. There are four settings to choose: An Asian Zen garden with a cherry tree, a jungle with a waterfall and many palm trees, a campfire, and a firework which is projected into the sky. Some Easter eggs encourage the users to interact with the different in-car environments. Additionally, the in-car lighting colour can be controlled by a slider in the HM.

5.2.3 Constraints for the User Studies

LUI AR as shown at several exhibitions has a linear storyline. At the beginning, the user enters the car, reserves a table at the restaurant, and the car starts driving autonomously. On the journey through the city the user experiences some scripted events.

For the user studies, the storyline was cut for several reasons. The participants should concentrate on the UI elements and interactions with the car. Therefore, participants needed enough time to explore the UI and it was important to reduce the risk of motion sickness during the studies. The driving route was adjusted and the highway around the city was added to the VTE. In the study procedure, the passenger had to book a table at the restaurant and tell the car to start driving. Then the car took the highway and drove an endless loop. That removed the time limit to explore the UI because the car never arrived at the restaurant. Additionally, the highway was the perfect place to test the in-car interactions without distraction and with a reduced risk of motion sickness.

5.3 Design Process

In advance of the chapter Results of user study 1, the design process describes the adaption of the prototype based on the assumptions made during the evaluation of US1 (see 8. Results). The prototyping is part of the Build-phase in the Lean feedback loop as shown in figure 5.5. In the following the assumptions of US1 are presented and the redesign of the prototype (P2) is documented in comparison to the initial version (P1).

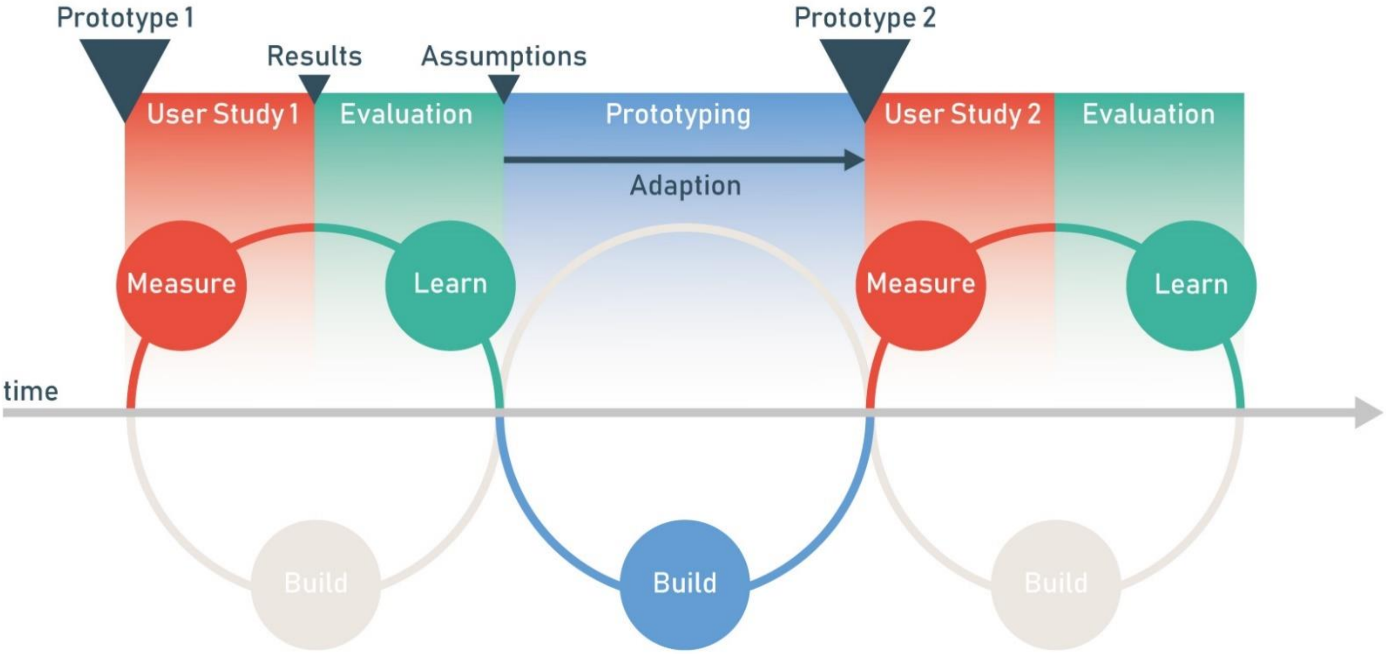

Figure 5.5: Design process within the feedback loop procedure.

5.3.1 Assumptions of User Study 1

During the evaluation of US1 four major usability topics were identified (see 6.3.2 Creating the Codebook). Many usability issues were related to the reachability and placement of UI elements, interaction techniques and menus, misleading affordances and design, and the misinterpretation of UI elements in their context. These topics were especially treated during the design process. The following assumptions were made based on major usability topics and the results of US1.

Usability Topic	*Assumptions*
Reachability and Placement	By replacing UI elements of Media and the Navigation map from the table to the right into the area of 60 degrees wideness in front of the user on the dashboard, the comfort of interaction (reachability) and visibility will highly increase. (Navigation, Media)
	By redesigning the Climate UI onto a curved plane/area surrounding the user in approx. 50 cm distance, the most comfortable position for direct interaction with UI elements will be reached. (Climate, Media)
	Even though the car drives autonomously many users will feel more comfortable in the car when UI elements do not restrict the view on the road, therefore replace these UI elements. (Climate)
Interaction Techniques and Menus	A flat hand menu structure with two levels of depth in every category of the menu will lead to a more consistent interaction. (Hand Menu)
	For the selection of remote objects in a spatial context, many users intuitively prefer pointing with the index finger. (Restaurant)
	An additional animation of the gaze cursor and highlighting selectable objects may help to draw the attention to this selection technique for a better understanding. (Restaurant)

Interpretation in Context	A context sensitive exit button in the hand menu to close an application, or to close and save the current settings of the related application, will remove false assumptions of the users that the settings will be lost by pressing the exit button. The states of the context sensitive exit button could be close, return, and set/save settings to cover all possibilities. (Hand Menu)
	The volume slider and play/pause button should be placed in the context of the Media Player and should not be permanently visible. Then, users will not expect that pressing the play button will launch the engine of the car. (Media)
	The “reserved” text above the tables in the restaurant application can be removed because the icons and colours speak for themselves. (Restaurant)
Misleading Affordances and Design	Changing the map POIs on the Navigation map to a flat design will prevent users from trying to grab and hold the map POI elements. (Navigation)
	The waypoints for navigating through the restaurant representation need a new distinct design to better explain the functionality of teleporting/travelling. (Restaurant)
Functionality	Pointing with the index finger to the sky might be more intuitive for the users than holding the flat hand into the sky to control the shooting direction of the firework. (Ambient)
	Implementing a new Media Player based on a common 2D design pattern with sorting by genre functionality and scrolling through different lists will meet the requests of the participants for an advanced version. (Media)

Table 5.1: Assumptions of User Study 1.

5.3.2 Prototyping and Redesign

This chapter describes the improvements and changes of the prototype in comparison to the initial version (P1). The prototype was completely redesigned, and many changes were made regarding the software architecture to increase the performance and make changes on the 3D UI much easier. The software architecture will be described in the next chapter in more detail.

Hand Menu

The HM was restructured for a more consistent interaction. The number of vertical levels was reduced from three to two. For more consistency, every application in the top level became a second level of depth with additional functionality. In P1 all applications were controlled by toggle buttons to open and close the application except for Ambient. The Ambient application had an additional depth of two vertical levels. Figure 5.6 shows the menu structure of P1 and P2 in comparison.

A tooltip was added to the HM (level 0). As soon as the right hand is detected by the tracking device, the tooltip appears in the middle of the HM and displays the name of the application that is nearest to the index finger. The compass animation follows the movement of the index finger and indicates the app-button, to which the tooltip is currently related (see Figure 5.7). In level 1 of P2, the tooltip is replaced by a context sensitive exit button that lets the user return to level 0 of the HM. It closes the application and saves the settings (Climate).

The Colour menu in the Ambient application that was the deepest menu of the HM in P1, was removed and the Colour slider was added to the Ambient menu at level 1. This decision is consistent with the new volume slider that is displayed in level 1 of the Media application in the new version of the prototype (P2) (see Figure 5.8 and 5.9). Some additional remote functionalities were added to the Media Player HM like skip, and play/pause.

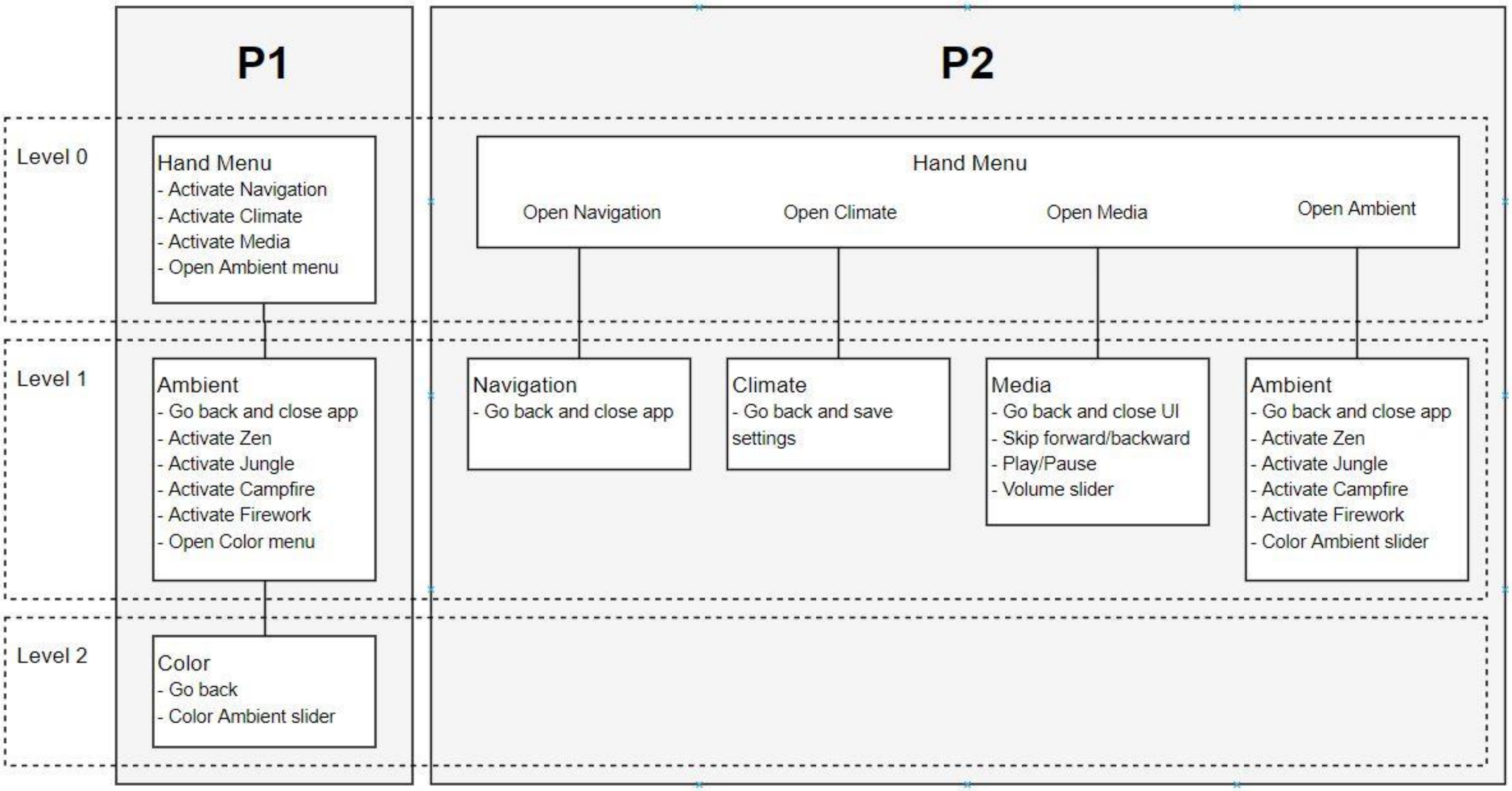

Figure 5.6: Hand menu depth and structure.

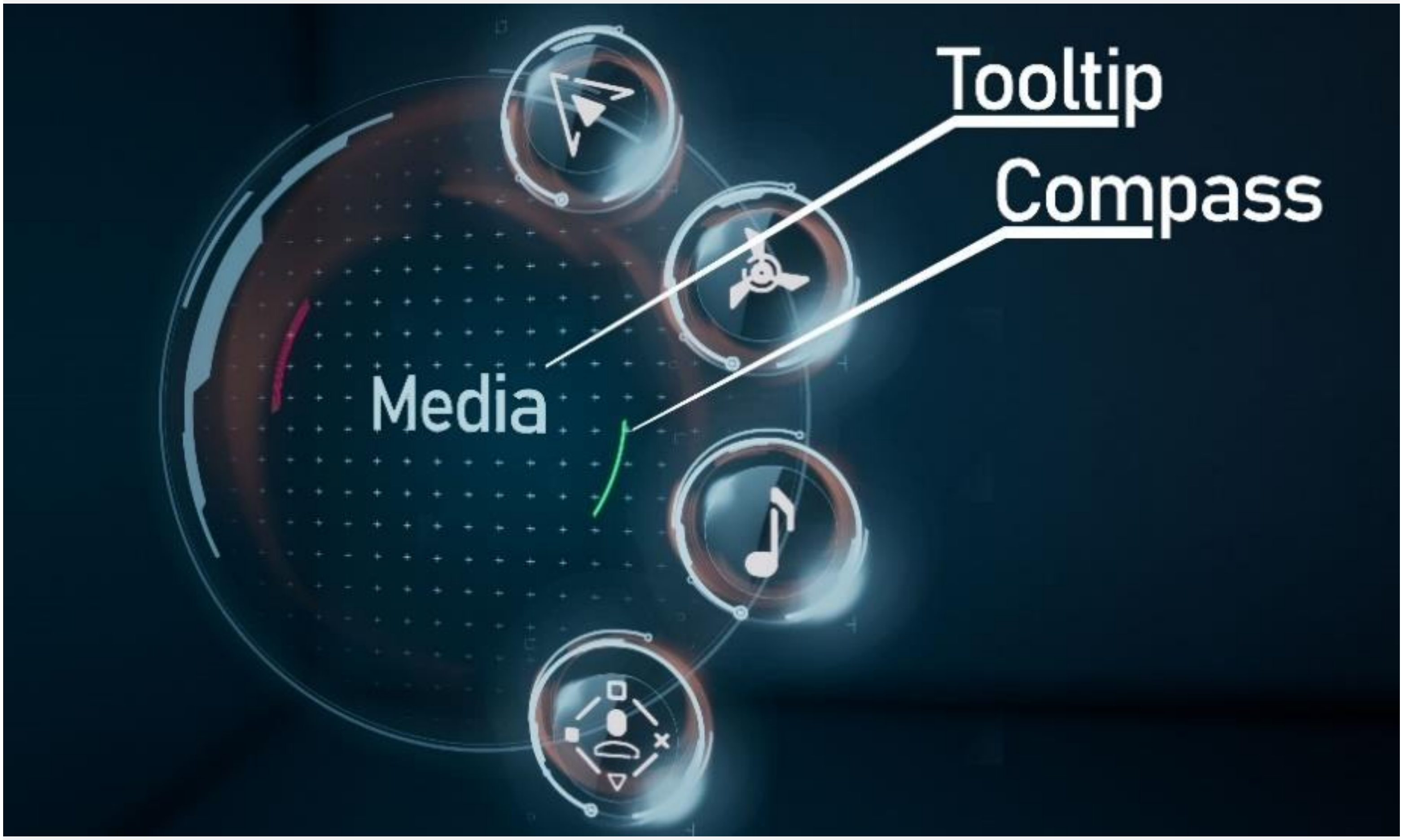

Figure 5.7: Rendering of the hand menu at level 0 (P2).

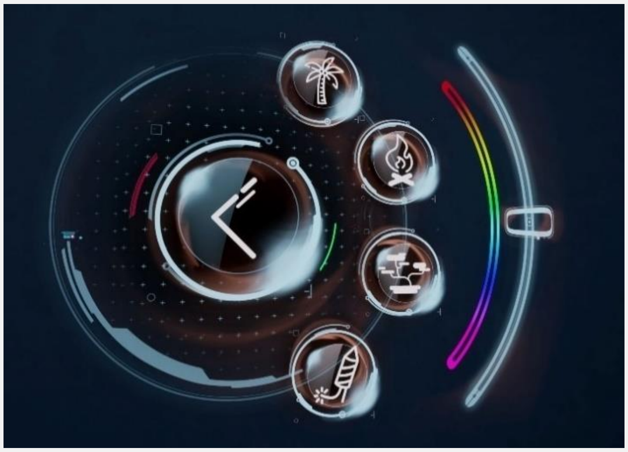

Figure 5.9: HM at Ambient state with Colour slider (P2).

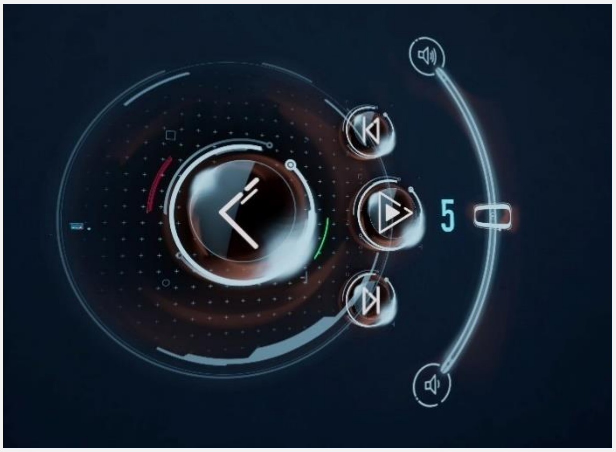

Figure 5.8: HM at Media state with Volume slider (P2).

Navigation

In P1 the navigation map was hard to spot and uncomfortable to reach for the users. Therefore, the placement was adjusted so that the navigation map is spawned above the dashboard in front of the users. It is slightly tilted towards the users for an easier interaction.

The design of the map elements was changed from rigid 3D spheres to flat UI elements with the aim to remove the affordance to pick them up. Holding the index finger into the UI element to load the map element remained the same. However, the loading bar was enlarged to give the users more noticeable feedback.

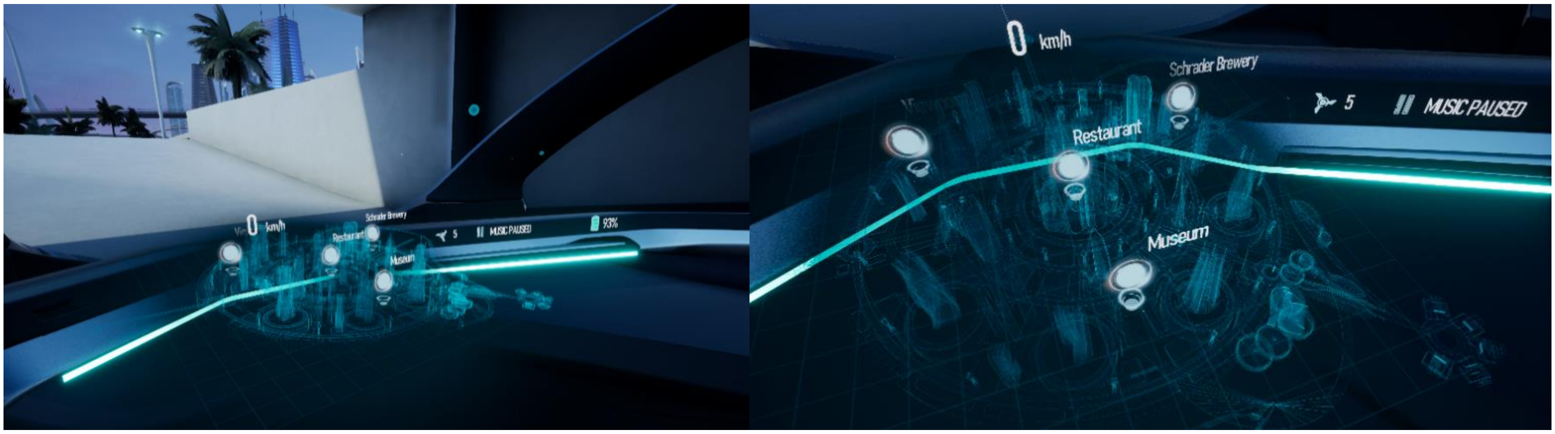

Figure 5.10: Navigation map in the car (P2).

Restaurant

In the Restaurant application, the biggest improvement is the context sensitive HM that guides the user to accomplish the reservation of a table. The Hand Menu displays only the tooltips and buttons that are relevant to the user’s current situation. The task to reserve a table starts with the call for action “reserve a table” in the HM. After pushing the button, the tables indicate with red cross or blue plus symbols, whether they are available or not. Additionally, the tooltip of the HM calls on the user to “look at a table”. After the selection of a table via gaze cursor, the HM displays a button to “submit” the reservation. This guidance of the users did not exist in the first prototype. There were no tooltips and the HM only showed a “reserve table” and “close” button. It also was not possible to select and then deselect a table for reservation.

The other changes to the Restaurant application were design decisions. The waypoints were improved with a larger trigger box for an easier selection and the design changed to look like pins on a map. The “reserved” text above the tables was removed in P2, because the red cross, blue plus and green hook symbols are unmistakable.

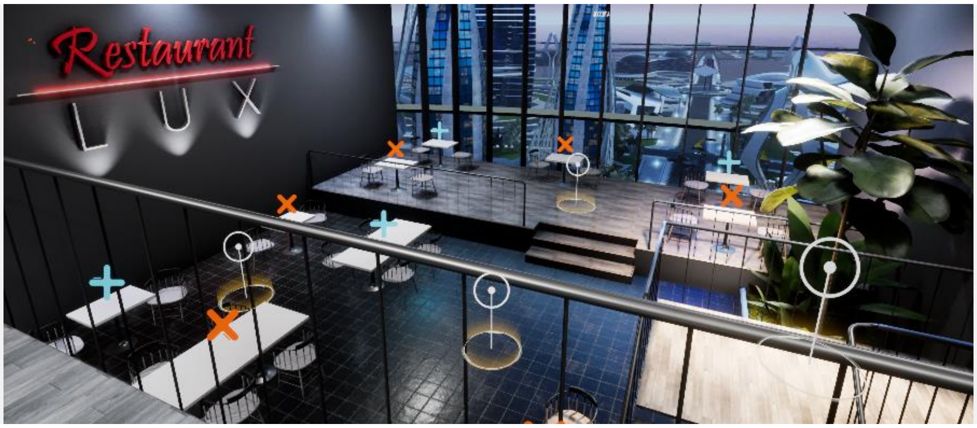

Figure 5.11: The Restaurant with waypoints and reservation icons above the tables (P2).

Climate

The redesign of the Climate UI explores the interaction within arm's reach on a curved plane in front of the user. A draggable button can be moved over the surface of the curved plane. The plane is limited to a 70-degree angle and therefore fits into the field of view completely. The curved shape around the user's position makes it easy to reach every point on the surface. By dragging the button over the surface, the strength and direction of the airflow is adjusted. In P1 two sliders for strength and airflow direction were used, but they proved to be hard to reach for the users.

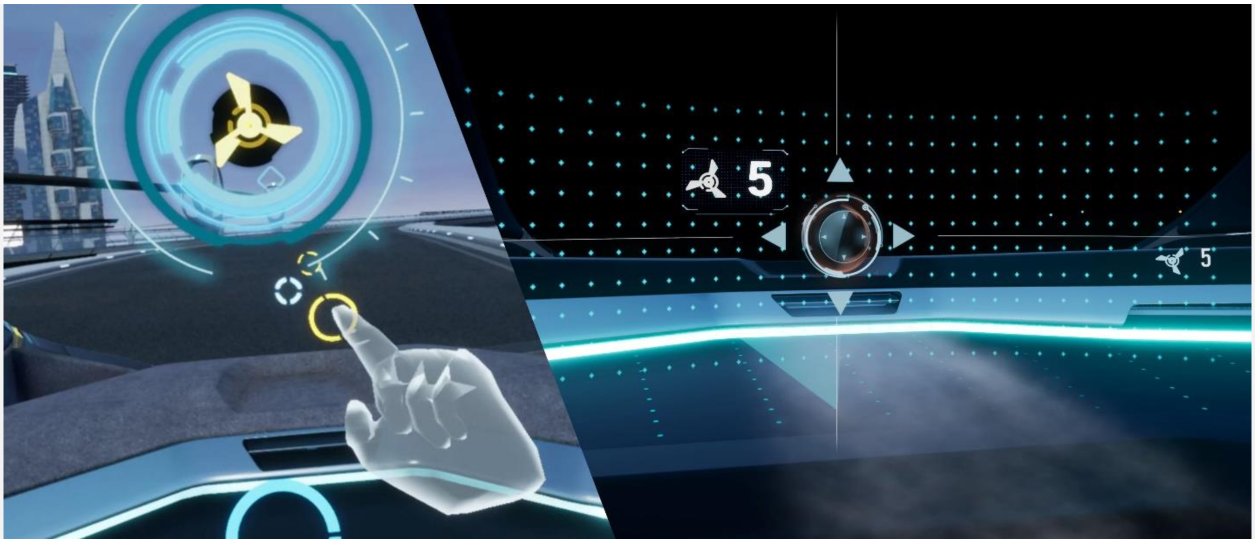

Figure 5.12: Climate UI of P1 with yellow and blue sliders (left), and P2 with draggable button (right).

The particles that indicate the airflow in P2 are placed directly above the dashboard and stick to the horizontal movement of the draggable button to create a connection between the button position and the direction of the airflow. Additionally, an arrow projected on the dashboard indicates the airflow direction. The HM displays a “SET” button (context sensitive exit button) to save the current strength, direction, and to close the Climate UI.

Media Player

The biggest adjustments were made in the Media application. Media of P1 contained a bunch of song covers floating above the dashboard (see Figure 5.14). They were clickable to start playing the song and it was possible to sort them by genre. The genre buttons were placed on the bevel of the dashboard and when pushing one of those buttons, the respective covers were sorted in the space above the button. There was no possibility to go back from the genre to the unsorted view. In US1 the observation was made that many users did not take notice of the genre buttons. The play/pause button and the volume slider on the dashboard was always displayed, even when the Media Player application was closed.

Figure 5.14: Media Player of P1.

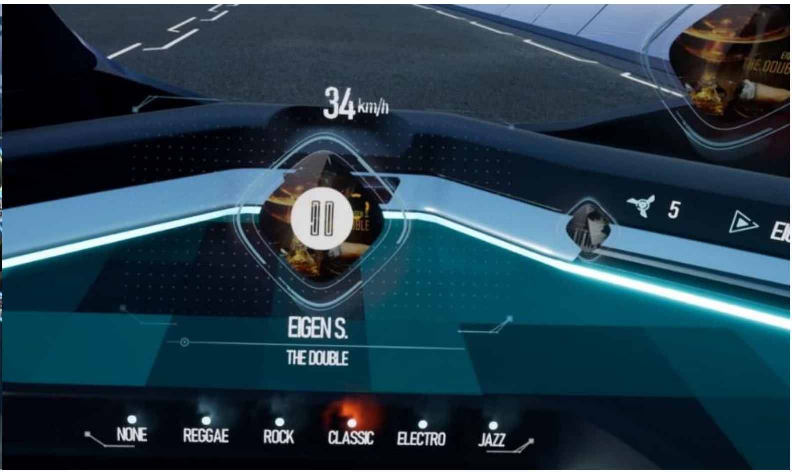

Figure 5.13: Media Player of P2.

In order to require less upper body flexibility from the users, a new concept (see Figure 5.13) was developed for the Media Player in P2. The cover flow pattern was adapted to 3D interaction. The cover flow is placed in front of the user and the song covers are displayed in a horizontal array. An area with swipe functionality was implemented to switch between the songs by swiping with the index finger. Each active cover is scaled up and a play/pause button fades in. By tapping the play/pause button for the first time the song starts playing. The genre buttons are placed beneath the swipe area and by selecting a genre the covers are rearranged in the array. Every functionality is easily accessible, and the cover flow structure can save a huge number of songs, radio stations, or personal playlists. The whole concept is scalable.

In Media, the HM is designed as a remote controller. It allows the users to switch between songs, start or stop the playback, and to adjust the volume (see Figure 5.9). In P2, there is no permanent play/pause button and volume slider on the dashboard of the car. When the user closes the Media Player UI by pushing the exit button in the HM, the current song continues to play.

Ambient

As mentioned above in the Hand Menu section, the HM of the Ambient application was restructured and reduced to one level of depth. The Colour slider is always accessible within the Ambient application and the different Ambient scenes are activated and closed by toggle buttons (see Figure 5.9).

Gaze Cursor

The gaze cursor was retained for the selection of remote objects in the VE and Restaurant. In P1 participants did not understand the interaction technique of the vector-based gaze selection, therefore the gaze cursor was redesigned in P2. The cursor reacts to interactive objects. This is indicated by the contraction of the cursor and an orange “piece of cake”-shaped gradient above the cursor starts blinking to get the users attention.

Status Bar

In P2 a status bar behind the dashboard of the car was added. The status bar provides information about the current battery status of the electric vehicle, the current song and interpret, as well as the strength of the Climate airflow. It is a nice little feature to enhance the experience in the car.

5.3.3 Software Architecture

The second version of the prototype was vastly improved regarding the software architecture of the Unreal Blueprints. Major changes were made to increase the performance of the VTE. The reduction of fps drops may reduce the occurrence of motion sickness. The new architecture with generic classes speeds up the Lean feedback loop for future iterations and projects, because it makes changes on UI elements fast and simple.

All user interface elements are children of the generic Blueprint class UIElement that implements the interface InterfaceUI to distribute the hand-tracking data to all children. The ButtonGeneric and SliderGeneric classes define UI elements more precise and add button and slider functionalities. The Application class adds to the inherited functions the functionality to use, activate, and animate the applications. It also takes care of the current App- and Animation-State and implements the interface InterfaceApp. All these Blueprint classes and child-classes are generic Blueprints as shown in Figure 5.15. They are also usable in other projects and are not LUI AR specific. Therefore, this structure is distributed to all future Unreal projects at Luxoft as a basic framework and can be further improved and extended. The great benefit with generic classes is that designers are now able to create children of a generic class (e.g. ButtonGeneric) and easily set the style (e.g. button colour, texture, etc.) and other attributes in the Details pane of the child-class in Unreal without scripting.

All Blueprint classes below the Generic Blueprints are LUI AR specific and cannot be used in other projects. They describe the behaviour, style, and structure of the UI element or menu in detail. Children of the GenreButton class exist multiple times for each genre button that is placed in the VE. Each one contains its own information and style saved in the attributes.

The applications (Navigation, Climate, Media, Ambient) are actors of the parent class Application within the Unreal Editor. They inherit all basic functions from the Application class. These actors are containers and can be filled with different types of actor components. These actor components might also have their own parent class. In case of the Media application, the Media actor is a container for GenreButton components, media player graphics, and the Swiper component. The Swiper component within the Media actor inherits the swiping functionality from the Swiper Blueprint class and therefore adds swiping to the Media Player.

Outside this structure, there are controllers that keep track of the current state of the story (Storyteller), create save games (SavegameConroller), attach the UI elements to the car interior and user’s hand at the beginning of the game (AttachmentController), or open/close applications and save their current state (LUIAppController) (see Figure 5.15).

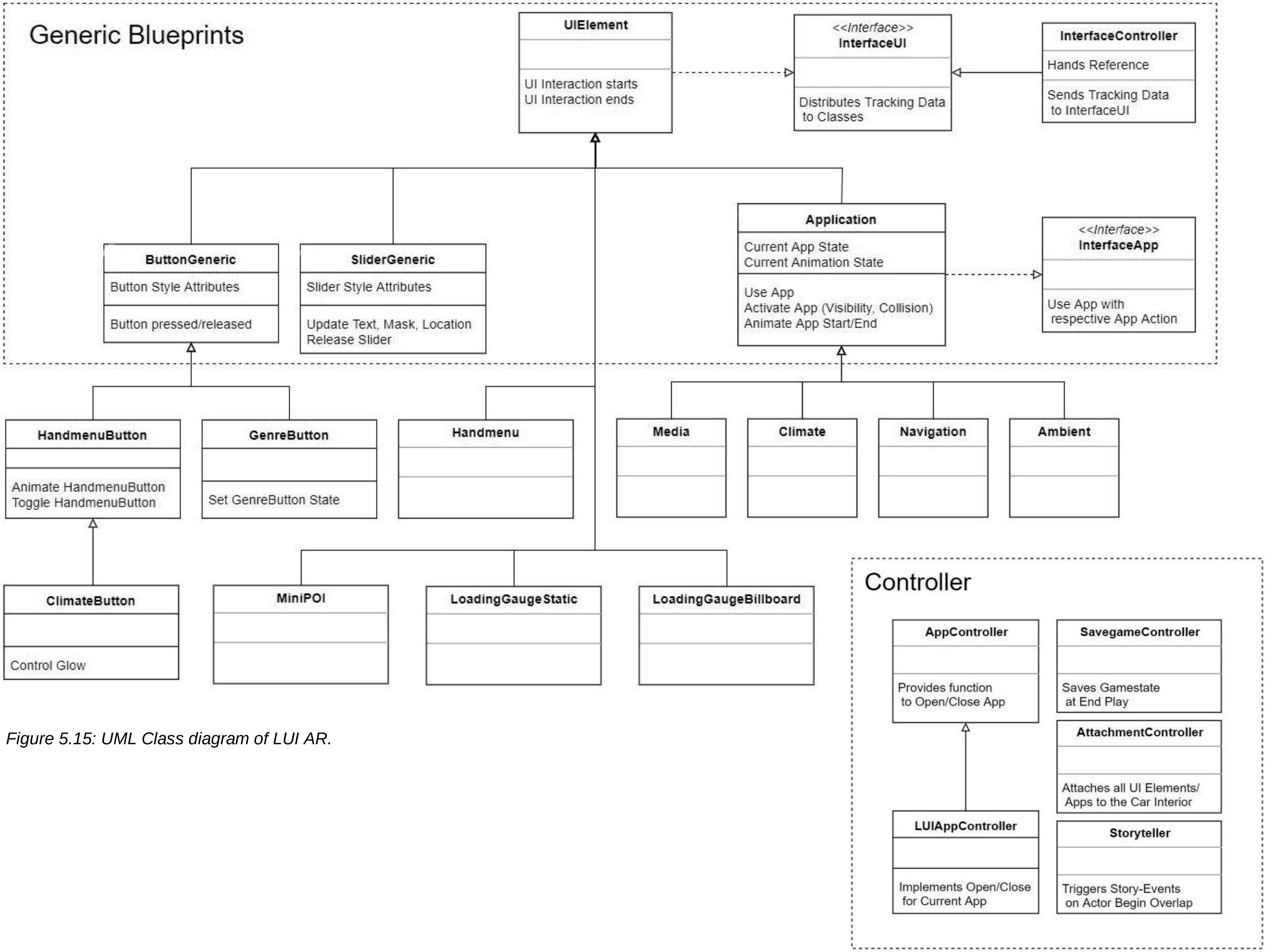

Figure 5.15: UML Class diagram of LUI AR.

6. Methods

This chapter introduces the research methods that were applied in both studies. The initial user study (US1) and the follow-up user study (US2) followed the same mixed methods approach (Bryman, 2006), combining qualitative and quantitative methods to strengthen the study’s conclusion. The general study design was qualitatively driven, sequentially and independent.

6.1 Mixed Methods

6.1.1 Advantages of Mixed Methods

A mixed methods research design (MMR) enables researchers to combine qualitative and quantitative research methods to gain deeper or broader insights and to strengthen the study’s conclusion. Bryman (2006, pp. 105–107) describes many reasons, also called rationales, to perform a mixed methods study. Some of them emphasize the decision to design the user studies according to a mixed methods approach, in order to expand and strengthen the results of this research project.

Relevant reasons for an MMR study design (Bryman, 2006) are that quantitative questionnaires are susceptible to misinterpretation or a lack of sobriety of the participants. The combination of quantitative questionnaires and qualitative methods lets the researcher observe, interpret and value the results according to her/his estimation. This might offset the weakness of each method. Additionally, the quantitative questionnaires can give explanation to the results of the qualitative methods and the integrity of the findings may be enhanced.

Since this is an applied research project, two approaches may be more useful two draw assumptions for the improvement of the prototype, than using only a qualitative method. There is a chance that the results of the qualitative methods can be tested by the quantitative questionnaires. The assumptions for a new version of the prototype might be confirmed through a quantitative questionnaire and further, new discoveries may be made. These reasons correspond to the rationales offset, explanation, credibility, utility, and confirm and discover by Bryman (2006, p. 106).

6.1.2 Design Guidelines

Schoonenboom and Johnson (2017) explained seven primary and ten secondary dimensions, that are able to guide the researcher during the design process of a mixed methods approach. Some of the primary dimensions relevant to this research are discussed in the following.

The theoretical drive of an MMR can be qualitatively driven, quantitatively driven, or equal status (Schoonenboom and Johnson, 2017). Qualitative data is the most important data in usability studies with a small number of participants. The data helps to gain insights in the mind of the participants while using the interactive system. Qualitative methods in usability studies offer direct user feedback. This feedback can be analysed and then used for the improvement of the product.

Another primary dimension is timing, simultaneity and dependence. The quantitative and qualitative data can be raised sequentially or simultaneously. Sequentially means that the participants must provide the quantitative data before the researcher gathers the qualitative data, or vice versa. Dependency is the second aspect of timing. According to Schoonenboom and Johnson (2017, pp. 113–115), it should be regarded separately to simultaneity. A study is independent, if the execution of the second component is not influenced by the results of the first component. In contrast to a study design, where the result of the first component influences the second component or different components are applied depending on the result of the first component.

Schoonenboom and Johnson (2017, p. 115) also discuss the point of integration. Several points of integration exist. The “results point of integration” might be the most applicable to this research project. Point of integration describes, where the qualitative and quantitative data is merged during the general evaluation of the studies. The use of a joint display is possible to show the results of the qualitative and quantitative methods and then draw a conclusion through an integrative statement. Morse and Niehaus (2016) first identified this concept.

Complexity is an additional important dimension in the discussion. The number of components is not the only influence on the dimension complexity. Complexity also raises, when different data sets have a high degree of dependency. Considering all dimensions discussed by Schoonenboom and Johnson (2017) perfectly guides researchers through the construction of a mixed methods research design.

6.1.3 Applied Mixed Methods Design

This study followed a qualitative dominant mixed methods approach. The focus was on qualitative user statements and observations during the conduction of the user study. The concurrent think-aloud method was applied during the VR experience, and a retrospective think-aloud was conducted less or more detailed at the end of the user study.

Quantitative data was gathered with the User Experience Questionnaire (UEQ). In US2 the research design emerged, because the Igroup Presence Questionnaire (IPQ) was added as a tool to assess the feeling of presence. This decision was made due to curiosity and to give a clue, whether the head-mounted VR setup for prototyping can be compared to other immersive technical setups like driving simulators. In order to get unbiased questionnaire results, the questionnaires had to be filled in before talking about usability issues in the retrospective think-aloud and interview.

In summary, the design of the user studies conducted during this research project were qualitatively driven, sequentially and independent. All methods are explained in the following chapters.

6.2 Think-Aloud

“Thinking aloud may be the single most valuable usability engineering method. Basically, a thinking-aloud test involves having a test subject use the system while continuously thinking out loud.” (Lewis, 1982, cited in Nielsen, 2009, p. 195) According to Nielsen (2009) the method is not good for performance measuring, but it helps to gather a wealth of qualitative data. The researcher must be careful interpreting the data. Users’ theories about the problem itself and suggestions for improvement must be well thought through before applying to the UI. In combination, the statements and observation of the participants deliver a strong understanding of the cognitive process responsible for users’ behaviour. When applying the method, the researcher must be as neutral as possible. Questions like “What do you think about it right now?”, and “Did it behave as expected?” will lead to unbiased answers by the users.

There are two think-aloud methods. In the concurrent think-aloud the users verbalize their thoughts while using the product and in the retrospective think-aloud after finishing the interaction with the product. Van den Haak and Jong (2003) compared the two methods in a study. They found out that both methods reveal the same amount and type of usability problems and therefore are interchangeable. The study also showed that participants who verbalized their thoughts afterwards performed better during the test.

Before the participants entered VR, the researcher encouraged them to talk about problems directly as they occur. Due to the fact, that VR can be a bit overwhelming, it was not expected to get that much information from the concurrent think-aloud and the researcher desisted from reminding the participants to think out loud. However, some participants gave lots of information about misconceptions and interface elements.

Additionally, a retrospective think-aloud was conducted after the test to get enough information from each participant. Depending on the amount of information gathered in the concurrent think-aloud, the retrospective think-aloud was conducted more or less detailed. The participants and the researcher watched the screen recording of the test session together. The participants commented on their behaviour, and some usability issues were discussed. The researcher also asked questions about observations made during the VR experience to get deeper insights.

6.3 Coding in Qualitative Research

6.3.1 Coding Guidelines

Usability studies produce a huge amount of qualitative data, which needs to be analysed, categorised and interpreted. In qualitative research, coding techniques are used to figure out relevant parts of data through an exploratory problem-solving approach. Saldaña (2009, pp. 8–10) describes it as the first step towards analysing and interpreting the data to answer the research question. Codes are used to link different parts of data together, which indicate similar assumptions, statements, or observations relevant to the research. This is the first step to categorise or classify the qualitative data. There are no specific rules for coding, but coding is an iterative process. During the first cycle of coding, it is very important to compare, improve, relabel, merge or drop codes when necessary. Coding is an ongoing process, which then leads to more abstract categories or classifications. In general, the process of coding and re-coding leads from the reality of data to an abstract generalisation of data in the form of themes and concepts. It enables the researcher to evaluate, compare and interpret the qualitative data.

Saldaña (2009, pp. 16–21) summarises some best practices on the procedure of coding. Starting with a first pre-coding by highlighting, underlining, or colourising of quotes and important passages. These markers are used for a deeper inspection later in the process. While in the process of coding, it is important to keep the research question in mind to prevent shifting away from the topic. In a study with multiple participants, he suggests assessing participants in a chronological order. The data of the second participant will influence the coding of the first participant, but the process of parallel recoding is desired. The codebook helps to keep track of all codes and their respective meaning with a description, references, and categories. It is a very important evolving document and gets bigger during the process of coding. According to MacQueen et al. (2008, cited in Saldaña, 2009, p. 21) a codebook includes "the code, a brief definition, a full definition, guidelines for when to use the code, and examples". After categorising or classifying the codes, Rubin and Rubin (1995, cited in Saldaña, 2009, p. 9) suggest refining the codes within a category first, before comparing different categories with each other.

6.3.2 Creating the Codebook

The recordings of all participants were transcribed during the evaluation procedure. Not only important statements during the study were transcribed, it was also very important to capture the user interactions and remarkable behaviour of each participant in the transcript. Setting the statements and the user behaviour in relation was very valuable for the analysis of the usability. Afterwards, every statement and behaviour related to the usability of the prototype was coded with a short description, according the descriptive coding method (Saldaña, 2009, pp. 70–73). A list of codes, the codebook, was created concurrently. The number of affected participants of each code gave an impression of the importance of the code. Categories identified major usability topics for further research and improvements of the prototype. The following categories were identified and provide the usability topics for the evaluation (see 8. Results):

Reachability and Placement	Reachability (Pheasant and Haslegrave, 2004, pp. 94–98) is about ensuring that users can reach, touch and control every interactive element of the 3-dimensional user interface. This is deeply connected to the placement of UI elements in 3D space surrounding the users, so that users do not oversee relevant information.

Interaction Techniques and Menus	LaViola *et al.* (2017, p. 7) defined interaction techniques as methods, which enable the users to accomplish a task via the UI. Important for the accomplishment of a task is the input/output device and the software. The software translates the input into an action inside the system and displays the result of the action. This category describes usability issues related to interaction techniques of the prototype and the interaction via different types of menus.
Misleading Affordances and Design	Misleading affordances (LaViola *et al.*, 2017, p. 99) of interactive UI elements are caused by the design in combination with the individual experience of the user. A good affordance leaves no doubt how to interact with the UI element and what will be achieved.
Interpretation in Context	The interpretation and understanding of UI elements is not only dependent on their design, it also depends on the surrounding context (spatial context, context of the application). The users interpret the functionality of an UI element in relation to the context.
Cover Flow Design Pattern	Usability issues regarding the new cover flow in prototype 2 are part of this category.
Functionality	Usability issues regarding the functionality of UI elements. For example, unfulfilled user expectations or unexpected behaviour of UI elements.

Table 6.1: Major usability topics/categories identified in the codebook.

6.4 User Experience Questionnaire (UEQ)

According to Thomaschewski *et al.* (2018) the User Experience Questionnaire (UEQ) covers three important factors of the pragmatic quality (PQ), two factors of hedonic quality (HQ) and additionally the attractiveness of a product. The pragmatic quality gives answers about the overall usability. The relevant factors for pragmatic quality are perspicuity, efficiency, and dependability. All of them are relevant for the evaluation of the initial prototype. Hedonic quality in UEQ includes the two factors stimulation and novelty. Schrepp *et al.* (2016) compared UEQ to five other questionnaires, including AttrakDiff2. “In 2003, the AttrakDiff2 questionnaire was the first questionnaire to measure user experience with the approach to describe user experience by factors of pragmatic quality and hedonic quality." (Thomaschewski *et al.*, 2018, p. 440)

Nevertheless, the advantage of the UEQ over AttrakDiff2 lies in the fact that the UEQ covers the three factors perspicuity, efficiency, dependability in its entirety. In contrast, AttrakDiff2 only covers these three factors partly as shown in table 6.2. In this study, the complete coverage of pragmatic quality was important because the usability will play a huge role when it comes to further improving the prototype. Therefore, the decision had been made to use UEQ for the evaluation.

The User Experience Questionnaire (UEQ) is made up of 26 semantic differentials. A semantic differential contains two contrary adjectives, for example boring and exciting. On a seven-point scale in-between the pair of contrary adjectives, the participant describes his perception of the product. UEQ rates the user experience of a product in six different scales, which are Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation and Novelty. Attractiveness describes the visual perception of a product. Perspicuity, Efficiency and Dependability can be grouped into pragmatic quality, and Stimulation and Novelty into hedonic quality. The pragmatic quality describes the usability, the task related quality of a product. Whereas hedonic quality describes the non-task related quality, which includes the feelings of the user towards the product.

In the user study, the questionnaire was handed to the participants in German to ensure that they understand the differentials correctly. They had to fill in the questionnaire directly after the VR experience to avoid a distortion of the results.

Dimension	**UEQ**	**AttrakDiff2**
General score	--	--
Attractiveness	completely	completely
Efficiency	completely	partly
Perspicuity	completely	partly
Dependability	completely	partly
Stimulation	completely	completely
Novelty	completely	--
Identity	--	completely

Table 6.2: Overview of the different questionnaires and their dimensions. Adapted from Schrepp et al. (2016).

6.5 Presence Questionnaire (IPQ)

Schubert *et al.* (2001) developed the Igroup Presence Questionnaire through a factor analysis. In two survey studies on presence and immersion experiences, they evaluated 75 items in order to factorise the results. In the evaluation of the first study, three presence factors were identified. The factor spatial presence (SP), which is explained by the phrase “the sense of being there”, and the factor involvement (INV), whose items describe awareness and attention processes, are two factors of presence. Additionally, the realness (REAL) factor also was considered part of presence factors. The factors identified as immersion or interaction factors described stimulations of the virtual environment, the interface, or the interaction with both. They were considered to simplify getting into the state of presence, but presence cannot be measured by factors of immersion or interaction.

The second study confirmed the results of the first study in terms of the prediction, that a spatial and attentional constructive component are experienced during the cognitive process leading to presence. The factors spatial presence (SP) and involvement (INV) were almost identical to the results of the first study.

After the second study, Schubert *et al.* (2001) included all items from the presence factors (25 items), which were selected for the second study, in a confirmatory factor analysis. As a result, five items on SP, four items on INV, and three items on REAL remained. These items form the Igroup Presence Questionnaire (IPQ). In the recent version of the IPQ, an additional item for REAL was added. The IPQ consists of 14 items to measure and evaluate the feeling of presence.

7. User Studies

Both studies followed the same procedure to gain comparable results for both versions of the prototype. However, some slight changes were made, and the objectives of each study were different. This chapter explains the objectives of each study, the applied procedure during user testing, and gives some insights into the demographics of the participants.

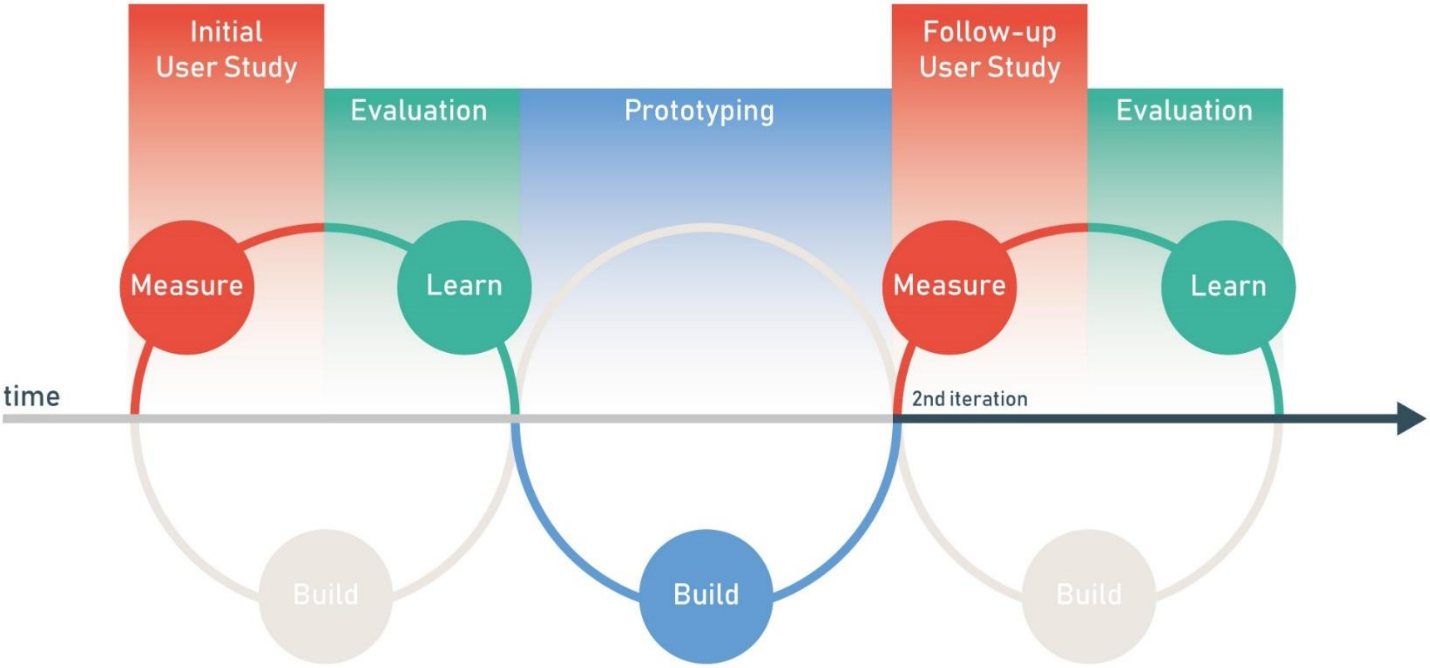

Figure 7.1: Conduction of the user studies in the timeline, and start of the second iteration.

7.1 Study Objectives

7.1.1 Objectives of User Study 1

The initial user study (US1) was conducted right at the beginning of this research project to get a baseline of the prototype. According to Lean Startup, conducting US1 was the first measurement in the build-measure-learn feedback loop. It was interesting to figure out, if users are capable of using the UI without the guidance of a presenter. Another important objective of user study 1 was to discover usability problems. The results helped to fix usability issues and to identify topics for further research. Additionally, US1 surveyed the overall user experience.

The focus of the initial user study (US1) was on exploring the following questions:

1. *Do participants master the 3D user interface of the autonomous car intuitively without guidance?*
2. *What major usability issues of LUI AR can be identified and are they suitable for further explorations?*
3. *How does P1 perform in terms of the overall user experience (UEQ)?*

7.1.2 Objectives of User Study 2

The follow-up study (US2) was conducted at the beginning of the second iteration of the build-measure-learn cycle. Figure 7.1 shows the phases the research project passed through until US2 was carried out. The outcome of the first iteration of measure, learn, and build (in this order) is the second version of the prototype (P2). During the design process, assumptions were derived from findings of US1 (see 5.3.1 Assumptions of User Study 1). These assumptions were addressed in the development of P2 with the aim to improve the 3D UI in terms of UX and usability. After finishing P2, the second iteration of the cycle started with the measure-phase: The conduction of US2.

Several categories of major usability issues were identified during US1 (see 6.3.2 Creating the Codebook). US2 evaluated these topics and verified, that the adjustments led to a decrease of major usability issues. The overall user experience was assessed to verify, if the assumptions of US1 led to an improvement in the UEQ scales. Furthermore, it was expected that US2 reveals unknown usability issues and topics for future work. The objectives of US2 provided a basis for the discussion of the progression and improvement of the prototype during the design process. The comparison of both studies was essential for the contribution to the research on automotive 3D user interfaces with learnings and best practices.

The following questions should provide the basis for the discussion:

1. *Is there a decrease of usability issues regarding the identified categories "reachability and placement", "interaction techniques and menus", "misleading affordances and design", and "interpretation in context"?*
2. *What usability issues can be identified that did not occur in US1, and do they have to be addressed in future work?*
3. *How does P2 perform in terms of overall user experience and is there a significant difference compared to the user experience of P1?*

7.2 Participants

An automotive UI should be easy to use for a broad target group. Autonomous driving even expands the target group from drivers to passengers without driver's licence, people with disabilities, teenagers and the elderly. Since autonomous driving below level 5 requires a driver's licence, the desired target group was limited to people above the age of 18. No further limitations were made for participating in the studies.

The participants of both studies had no prior knowledge of the prototype. The lack of knowledge and expectations were the most important aspects of recruiting participants. The participants were unbiased and the assessment of the prototype from a neutral point of view was possible. The researcher was able to evaluate the participants' interactions with the user interface regarding the usability and UX.

Head-mounted Virtual Reality can be quite intense and immersive, especially when experiencing VR for the first time. This may cause higher ratings in the categories attractiveness and hedonic quality of the UEQ. The novelty of VR influences the rating of the hedonic quality as it is a part of it and participants experiencing VR for the first time tend to give higher ratings in this scale. Therefore, participants with some prior VR experience are a plus.

The initial user study was conducted at the office of Luxoft. Eight co-workers from different departments were recruited. A participant knew some facts about the project before but did not experience the prototype on his own. Three participants had some experience and five had no experience with VR at all. The test group contained five male and three female participants. Three participants were in the age range of 25-34, and five in the range of 35-50. The participants had their backgrounds in various professions. Three participants were software developer; two were recruiter, two were designer, and another participant was a coordinator. The demographic questionnaire showed that all participants were right-handed. This was not intended, and it would have been interesting to see left-handed participants using the user interface.

Regarding user study 2, the demographics of the participants slightly changed due to the fact, that participants were recruited at Stuttgart Media University and through personal connections. Nine participants participated in the study. Six participants were males and three females, eight in the age range of 25-34 and one participant in the range of 18-24. The professional background varied. The test group contained five master students from different study programs (Film/TV, Sound Engineering, and Interactive Systems), two social workers, a software developer and a project coordinator. Two participants were left-handed. The study took place at Stuttgart Media University.

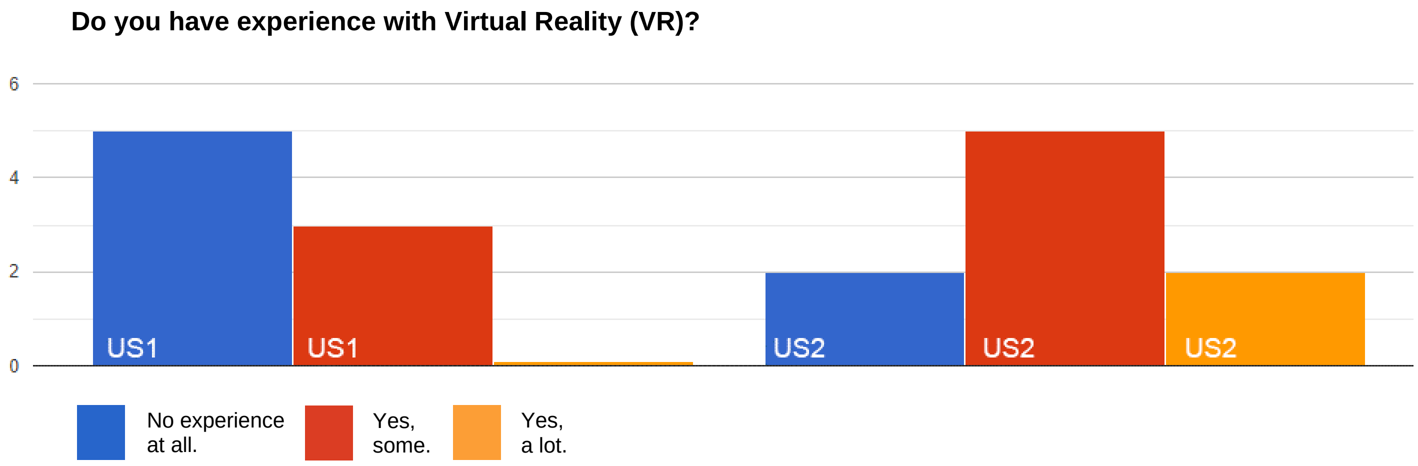

Figure 7.2: Participants' experience with VR.

The main differentiating factor between both studies were the prior experience with VR. In US2, only two participants had no prior experience with VR. Two stated they use VR quite a lot and the other five participants had experienced VR for a few times. In US1, the test group was of a higher age and only three out of eight participants had at least some experience with VR. Corresponding to the prior experience with VR, participants of US1 had less experience with gestural user interfaces used in technologies like Nintendo Wii, Xbox Kinect, Microsoft HoloLens and Leap Motion.

7.3 Procedure and User Tasks

Both user studies were conducted within three days each and followed almost the same procedure described in this chapter.

The day before the initial study (US1) started, a test run was held with an additional participant. The results of this test run were not considered in the final evaluation of the study, because the participant was a co-worker and advisor to the researcher during the preparations of the study. The test iteration run smoothly and only some user tasks had to be adjusted to focus on a more explorative approach. Objective of the tasks was to encourage the participants to explore all aspects of the UI and interaction, and to foster their curiosity.

At the beginning of the study, the participants were welcomed in a meeting room with the technical setup and a chair. The participants had to conduct the study seated, because this is the common position in a car and the chair matched the position of the virtual car seat in VR. First, the participants had to give their consent for the user test to be recorded and evaluated, and they had to complete the demographic questionnaire. Then, they were introduced to Virtual Reality and to some technical constraints regarding the Leap Motion hand-tracking device. It was important to understand that there is only a limited tracking area in front of the HMD and that the back of the hand should never cover the fingers while interactions take place. After the technical introduction, the participants learned the gesture to open and close the hand menu and the basic interaction concept. In VR, they had enough time to try the gestures themselves and to get familiar with the virtual environment before the researcher set the first task.

The user tasks are listed below:

1. *Please call the car.*
2. *You are hungry. Tell the car to drive to the restaurant and reserve a table at the restaurant.*
3. *It is too hot in the car; adjust the climate settings according to your preferences.*
4. *You want to listen to good music. Explore the media player.*
5. *You want a relaxed atmosphere in the car. Choose an ambient according to your mood.*

The tasks were neutral and offered a broad freedom for the participant. It was almost not possible to fail at a task and they encouraged the participants to explore the user interface and the virtual environment. The observation of the participants' explorations revealed usability issues with the user interface and the design of sliders, buttons and other UI elements.

Immediately after finishing the VR experience, the participants had to complete the User Experience Questionnaire (UEQ) to avoid distortion of the results through talking about usability issues beforehand. Additionally, in US2 the presence of the participants was assessed with the Igroup Presence Questionnaire (IPQ) directly after completing the UEQ. The usability issues were discussed in both studies during the retrospective think-aloud which followed the questionnaires. The participant and the researcher watched the recorded screen capture of the VR experience together and the participant had to think aloud and explain his behaviour. At some points, the researcher paused the video and asked questions to get more in-depth information from the participants.

8. Results

In this chapter, the results of the initial user study (US1) and the follow-up user study (US2) are presented. The results of user study 1 provided a baseline to learn from and to further improve the prototype during this research project. User study 2 evaluated the second version of the prototype. The studies' results enabled the researcher to draw a comparison between the initial version and the second version of the prototype in the next chapter (see 9. Discussion).

The results of both studies are categorised according to their related usability topic (see 6.3.2 Creating the Codebook). Each category starts with US1 followed by US2. The first category is about reachability and placement of UI elements in virtual space.

8.1 Reachability and Placement

User Study 1

During the evaluation of US1, four issues were found directly related to the placement of an UI element in space surrounding the user. Almost every user had problems to interact with some buttons and sliders because they were out of arm's reach. The most common UI element that caused difficulties was the yellow climate slider. The yellow climate slider activates and handles the amount of air coming through the vents. The Climate UI appears as a 3D object in front of the windshield, above the dashboard. The yellow slider is placed as a semicircle around the 3D object. The low ranges of the slider are at the bottom, to reach the high ranges users have to drag the slider upwards. Especially in the high ranges, participants had difficulties to push the slider furthermore to the top to the highest value of eight.[1]

Two participants mentioned that UI elements on the table to the right of the passenger were uncomfortable to access. One mentioned this in relation to the position of the navigation map, the other participant regarding the song covers in the Media Player UI.[2] In case of Media, participant 7 also stated that a horizontal list is much harder to use than a vertical list. The spawn position of the navigation map was indicated by an animated glowing sphere. However, participants easily overlooked the short and subtle animation. Another participant disliked the position because usually the navigation is placed in the field of view when looking through the windshield.

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[1] Code: reachability-buttons, button-position

[2] Code: position-map

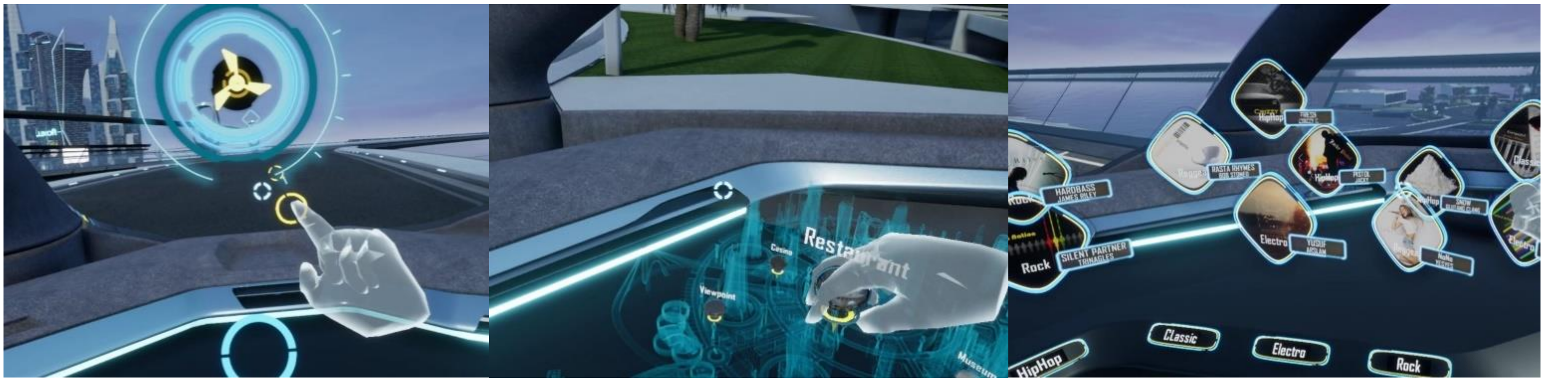

Figure 8.1: Climate UI, Navigation map, and Media Player in P1 (left to right).

The Media Player UI includes buttons for different music genres. Those buttons are located at the bevel of the dashboard. Four participants missed them during the User Study and therefore they could not use the sorting by genre feature.[3] However, a participant stated in the retrospective think-aloud, that they were easily recognizable as buttons.

In general, most participants did not like objects or UI elements restricting their view through the windshield. Even though the researcher pointed out, that they were in a self-driving car and there is no reason to be worried about safety. A participant implied that it still felt like sitting in the driver's seat and that the feeling would be different sitting in the rear of the car.[4]

Related Codes

reachability-buttons (7*)
restricted-view (5*)
genres-position (4*)
button-position (1*)
position-map (3*)

Explanation: code (*indicates how many users experienced this issue)

User Study 2

The follow-up study showed two issues related to the placement of objects. Reachability was not an issue anymore. In the ambient settings, some participants did not notice the campfire after activating it. This was caused by its spawn position most likely outside the field of view of the participant. Additionally, sound effects were missing to draw the attention of the passenger to the

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[3] Code: genres-position
[4] Code: restricted-view

right side of the dashboard.[5] This issue is related to the placement of the navigation map in the first prototype.

A participant stated that he does not like objects restricting his view through the windshield for safety reasons. This statement was made regarding the palm tree in the jungle ambient setting, which covers the left part of the windshield.[6] As described above, some participants also made this statement during US1.

Related Codes:

campfire-position (3)

restricted-view (1)

8.2 Interaction Techniques and Menus

User Study 1

The initial user study showed that the selection and interaction with remote objects caused some confusion. The selection was achieved by hovering with the gaze cursor above the interactive object. This selection technique was not explained to the participants beforehand. Almost all participants struggled to understand this method. They ignored the cursor and tried to select objects by pointing at them. In the end nobody failed at the task of reserving a table with the gaze cursor technique, but many participants accomplished it by accident.[7] Only two participants understood how to use the cursor. After discovering the gaze cursor technique in the restaurant, a participant thought that he could use the gaze cursor to control the climate slider. Another participant asked, if it is possible to use the cursor to select the restaurant on the navigation map, which also does not work.[8] However, the selection of UI elements within the participants' arm's reach did not cause any problems. Every participant felt comfortable to interact with UI elements by touching them directly.

In the first version of the prototype, participants were confused by an inconsistent number of vertical levels in the ambient hand menu. For the Navigation, Climate, and Media application, the HM implemented a toggle button in level 0 that indicated the state (visible/invisible) of the

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[5] Code: campfire-position
[6] Code: restricted-view
[7] Code: gaze-interaction, direct-selection
[8] Code: inconsistent-selection

application by a yellow outline. The only application with two additional HM depth layers was Ambient (see Figure 5.6). Many participants opened Ambient in the HM and switched between the different ambient scenes by pushing the Jungle, Zen, Campfire, and Fireworks toggle button. At some point of the process, they also used the Colour button that opened the third level of the HM. Participants tried the colour slider in the HM and used the back button to get back to the other ambient scenes. After this action, participants also tried to close the other ambient scenes with the back button. This inconsistency brought them back to level 0 of the HM and they had to reopen the Ambient UI for more explorations.[9]

Related Codes:

gaze-interaction (6)
direct-selection (7)
inconsistent-selection (3)
inconsistent-return (5)
direct-interaction (5)

User Study 2

Despite the usability issues with the gaze cursor in US1, the second version of the prototype also implements it as a selection technique for remote objects. At the beginning of the VR experience, four participants had issues to understand how to use it. The first challenge was to enter the autonomous car by looking with the gaze cursor at the waypoint above the car seat. Some participants entered the car by accident. New to the virtual restaurant environment, many participants tried to reserve a table by pointing. Some also tried to touch the table directly. However, during the learning process in the restaurant, all participants understood how to use the gaze cursor to select a table or move around. After gaining this insight, all participants easily interacted with remote objects via gaze cursor.[10]

During the reservation of a table in the restaurant, participants stated that it is impractical to interact via gaze cursor and then, after the selection of a table, to submit the action via submit button in the HM. Some participants even forgot about the HM in the restaurant at all. In the retrospective think-aloud, an affected participant stated that it felt like a breach in the interaction to switch from the interaction with 3D objects back to the menu to submit the last action via button. Another participant stated that she expected HM interaction only in the car. A similar statement

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[9] Code: inconsistent-return
[10] Code: gaze-interaction, direct-selection

by another participant was that he felt present in a spatial, 3-dimensional restaurant, and that he expected to submit the reserved table in the same spatial context.[11]

The follow-up study also showed that many participants did not like the shift between the application UI above the dashboard and the HM to access further beneficial or necessary functionalities. A participant stated that he was deeply involved interacting with the Media UI above the dashboard, so that he forgot about the HM. Only when the music was too loud and he struggled to find the volume settings in the Media UI, he reminded himself about the hand menu. In the hand menu, he discovered the volume slider. However, he also expected to have a volume slider in the Media UI above the dashboard. Another participant would have liked to set and close the airflow strength in the Climate UI. He asked the question, why he could not find everything in one user interface. Overall, five participants made statements about this issue.[12]

Some participants did not recognize the UI above the dashboard right away, after activating an application via HM. The hand menu restricted the view on the dashboard, or the participants were concentrated on the hand menu and did not expect the application UI to be displayed above the dashboard in the car.[13]

Related Codes:

gaze-interaction (4)

direct-selection (4)

switch-interaction-methods* (7)

switch-menus* (5)

Hidden-by-menu (4)

** New usability issue: Focus shifting*

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[11] Code: switch-interaction-methods
[12] Code: switch-menus
[13] Code: hidden-by-menu

8.3 Misleading Affordances and Design

User Study 1

The Navigation app contained a holographic map of the city with some interactive point-of-interest (POI) elements, including the restaurant. In US1, many participants had difficulties selecting the restaurant on the navigation map because of the misleading design. The participants had to select the restaurant POI to reserve a table and to set the restaurant as destination for the following journey. The POIs floating above the map were 3D spheres. The material of the spheres was not translucent, which made them look like solid objects with collision. When the users' hands approached a POI, an animation scaled the spheres up. The design of the spheres encouraged many users to pick them up like physical objects, which was not the intended selection method. The users had to touch and hold the index finger into the spheres to select them. A loading ring appeared and after a few seconds, the restaurant app was loaded. In conclusion, the design of the POI elements implied a false affordance.[14]

The participants' behaviour towards 3D objects in the scene was natural and direct. During the initial user study, many participants tried to touch the miniature trees, the stones or the little waterfall in the Zen and Jungle ambient setting. Participants wanted to interact with them likewise real physical objects. The vent visualization in the Climate UI implied the same affordance to the users like other 3D objects. Some participants tried to use the vent like a rotary knob to activate the airflow, which was not possible. The airflow strength was controlled by a slider.

Figure 8.2: Map POI elements, Climate vent visualisation, travel waypoint (all P1, left to right).

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[14] Code: map-poi-affordance

Some participants had problems to recognize the slider in the Climate app as sliders. The blue, horizontal slider was often misinterpreted as a button. A participant had the same problem with the yellow climate slider. By touching the sliders, all participants recognized that they could move them around to adjust the climate settings. However, three participants did not understand the functionality of controlling the airflow direction with the blue slider. They used the slider to move the Climate UI to the side to have a clear view through the windshield while being driven by the autonomous car.[15]

In the virtual representation of the Restaurant, the waypoints for travelling were indicated by a yellow circle on the floor with a translucent glowing sphere above it. At the beginning, many participants did not understand how to navigate through the restaurant. They moved around by accident. This was not only caused by the design of the waypoints, the fact that many participants did not understand the functionality of the gaze cursor might have also been a reason for this usability issue.[16]

Related Codes:

map-poi-affordance (5)

slider-recognition (4)

airflow-direction (3)

waypoint-design (4)

inactive-ambient-buttons (7)

User Study 2

The POI elements in the navigation map still caused some irritations in the second version of the prototype, even though a redesign was applied to them, the interaction technique was not changed. Participants tried to push the top of the POI element like a button. This worked out better than with the 3D spheres in the previous prototype, because the loading bar appeared in much bigger sizes and many participants realized how to use the POI element correctly after the first try. Still it is a usability issue, which can be further improved by removing the misleading affordance of the design.[17] Additionally, some participants performed an uncomfortable hand gesture to select the restaurant POI on the map. Because of the holographic, 3-dimensional design of the map, they tried not to collide with the buildings. Their finger was held carefully onto

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[15] Code: slider-recognition, airflow-direction, restricted-view
[16] Code: waypoint-design
[17] Code: map-poi-affordance

the POI from above.

The design of the waypoints in the restaurant caused misinterpretations. The design follows the form of a pin with a thin shaft and a sphere on top. Entering the restaurant, some participants thought that they could use the waypoints to select and reserve a table, until they realized that there is reserve table button in the hand menu that activates reservation mode.[18]

The new status bar in the car shows the current artist and song, the airflow strength of the climate and the battery status of the electric car. A vent symbol, a play icon and a battery symbol helps to understand the information. However, the symbols and icons motivated some participants to interact with them directly by touch, but this action does not open the Climate or Media application UI as they expected.[19]

The strength of the airflow in the Climate UI is controlled by dragging a button across the curved plane. When the user drags the button upwards, the airflow increases and when the user drags it to the left or right side of the plane, the visualized airflow follows the movement (see Figure 5.12) and the airflow direction is changed. The drag and drop button looks like a normal button surrounded by arrows. Some participants did not understand that they had to push and drag the button across the plane. They pushed the arrows and the button jumped in the respective arrow direction. Another participant tried to use the button likewise a rotary knob. He stated that the white, rotating outline of the button indicated the rotary functionality for him.[20]

Related Codes:

map-poi-affordance (4)
waypoint-design (4)
statusbar-affordance (5)
drag-drop-affordance (4)
airflow-direction (6)

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[18] Code: waypoint-design
[19] Code: statusbar-affordance
[20] Code: drag-drop-affordance, airflow-direction

8.4 Interpretation in Context

Usability issues in this category were only found in US1, in the initial version of the prototype. In many cases, the triangle symbol pointing to the right on a button is interpreted as a play button in the context of a Media Player. In the self-driving car, two participants interpreted the button with the play symbol as an engine-start or start-driving button. The play button was placed on the dashboard next to the location of the steering wheel in non-autonomous cars. This might also mislead the interpretation of the play button functionality.[21]

Sometimes the exit button in the HM caused ambiguity. For example, participants expected the exit button to stop the functionality of the vents in the Climate UI. Instead, it was only intended to close the UI itself. In the restaurant, another participant assumed that the exit button cancels the reservation of the table, but it just closed the restaurant app. A similar issue occurred related to the return button in the HM. The different menu depth in the ambient settings caused unexpected behaviour when using the return button. This was also a matter of consistency between the different ambient options in the HM as mentioned above.[22]

Related Codes:

play-interpretation (3)

exit-interpretation (3)

8.5 Cover Flow Design Pattern

The new Media UI in the second version of the prototype implements a cover flow. It is possible to swipe through the available songs and sort them by genres.

In US2 most participants were familiar with the cover flow design pattern. Only two participants did not try to swipe through the vertical list of song covers. One skipped through the list with the next or previous song button in the hand menu, while she was watching the covers move vertically in the cover flow. The other one started to swipe through the covers after a hint by the researcher. She said she did not expect to be able to swipe through the covers. Both used the skip buttons in the HM to navigate through the covers. They were able to access all songs without swiping with

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[21] Code: play-interpretation
[22] Code: exit-interpretation

this technique. Therefore, there is no restriction due to not recognizing the swiping functionality.[23]

In order to indicate the swipe functionality of the cover flow, two additional covers are displayed on each side of the active cover. Those covers are smaller, and they are inactive. It is not possible to select or interact with them. They only indicate the ongoing list. Some participants tried to interact with the inactive covers. A participant tried to grab the cover like a physical object. Another participant stated that he thought the inactive covers were buttons that offer additional information or functionality. He suggested adding the feature that by pushing one of the inactive covers, the cover flow slides automatically to the cover's position.[24]

Another interesting observation could be made. Two participants used a different gesture to swipe through the covers than all other participants. They swiped with the flat hand through the cover flow, which does not always work reliable. It is intended to use the index finger to swipe between the covers, as it is well known from the interaction on a touch screen.[25]

Related Codes:

swipe-affordance (2)

interact-following-covers (4)

swipe-gesture (2)

8.6 Functionality

User Study 1

In the first version of the Media Player, participants used the genre buttons to sort the covers by a specific genre. Afterwards, some participants tried to get back into the unsorted cover view. The Media UI had no functionality to get back to the unsorted cover view, so it was not possible for the participants to achieve this. Another participant regretted that the music playback stopped when opening an ambient scene, but the ambient scenes had their own individual music and sound effects.[26]

Many participants did not figure out how to influence the shooting direction of the rockets in the fireworks ambient. In the first prototype, a vector pointing out of the palm set the shooting direction of the rockets. Even though a how-to text was shown above the dashboard, many participants

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[23] Code: swipe-affordance
[24] Code: interact-following-covers
[25] Code: swipe-gesture
[26] Code: startview-music, ambient-stops-music

tried to point with the index finger to the sky in order to set the shooting direction and fire rockets. Only a hint of the researcher let them successfully experience the fireworks.[27]

Related Codes:

startview-music (3)	ambient-stops-music (1)	fireworks-direction (4)

User Study 2

The functionality of the skip song buttons in the hand menu were questioned in the second user study. A participant said that he expected the next and the previous button to skip to the respective song and to play it directly. He was confused that the buttons only switched the cover flow in the background to the respective song, but the active song continued to play. He also said that in his understanding the hand menu should be a short cut. It should not copy the interactions that are already possible in the cover flow. Another participant affirmed this statement.[28]

Two participants were confused, that when they closed the Ambient UI the selected ambient scene disappeared. A suggestion was to keep the selected ambient scene active, until another application UI, which needs the space above the dashboard, is opened. One of both stated that she missed the functionality to confirm the chosen ambient scene, like it was the case in the Climate UI with the SET button. She said that the whole process of choosing an ambient scene and setting it to enjoy the mood in the car, did not feel completed. The ambient scenes felt like a preview.[29]

Another issue, which also occurred in US1, was the fireworks shooting direction. At first, many participants did not see the rockets because they exploded behind or directly above the car. It took some time, until they realized that the pointing direction of the index finger is the shooting direction. Setting the shooting direction with the index finger was not completely reliable.[30]

Related Codes:

skip-song-function (4)	set-current-ambient (2)	fireworks-direction (5)

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[27] Code: fireworks-direction
[28] Code: skip-song-function
[29] Code: set-current-ambient
[30] Code: fireworks-direction

8.7 Evaluation of the User Experience Questionnaire (UEQ)

During the evaluation process, the answers of each participant were added to the data analysis tool. The tool transformed the input data for each semantic differential, or questionnaire item, to the range -3 to +3, whereas +3 represents the most positive and -3 the most negative value. Values between -0,8 and +0,8 represent a relatively neutral evaluation. As a result, the overall user experience is described in six scales. Attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. Each scale is made up of four items except for attractiveness, which consists six items. The mean (μ), variance, standard deviation, and confidence for each scale and item was calculated.

User Study 1

The first version of the prototype (n = 8) performed well. The figures below show the mean of each scale and quality, and the error bars indicate the confidence (p = 0,05). Figure 8.4 shows that Novelty (μ = 2,28) has the highest mean followed by attractiveness (μ = 2,17) and stimulation (μ = 2,06). Novelty and stimulation are hedonic qualities. The scales perspicuity (μ = 1,69), efficiency (μ = 1,44), and dependability (μ = 1,22), which indicate the pragmatic quality, give insights about the overall usability. Their mean scored lower compared to attractiveness and both hedonic quality scales.

When looking at the mean of the individual items, there are three items lower or equal than 1,0. Those are the semantic differentials impractical-practical (μ = 1,0) in efficiency, does not meet expectation-meets expectations (μ = 0,9) in dependability, and unpredictable-predictable (μ = 0,5) also in dependability. Only the last one is in the range of -0,8 and +0,8 which represents the range for a relatively neutral result.

According to Schrepp (2019) it is very unlikely to observe mean values above +2,0 or below -2,0. The evaluation of the first prototype resulted in an unlikely high score of 12 items above +2,0. This includes five items belonging to attractiveness, six items belonging to hedonic quality and only one item belonging to the pragmatic quality. This item is the semantic differential difficult to learn-easy to learn (μ = 2,3) belonging to the scale perspicuity.

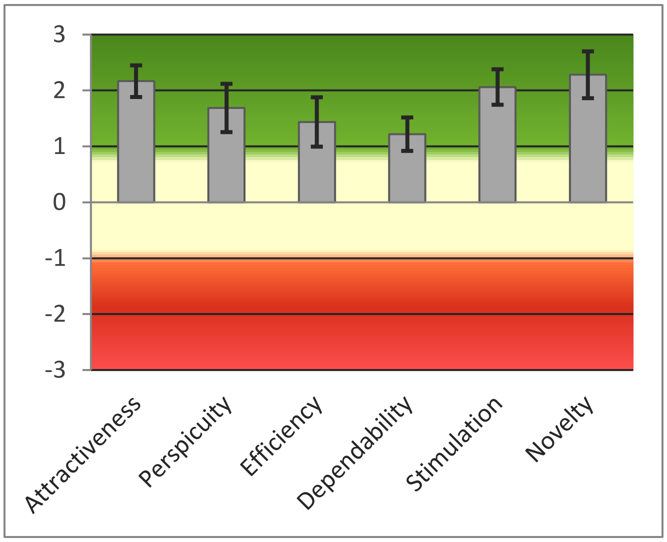

Figure 8.4: Mean and confidence of each scale.

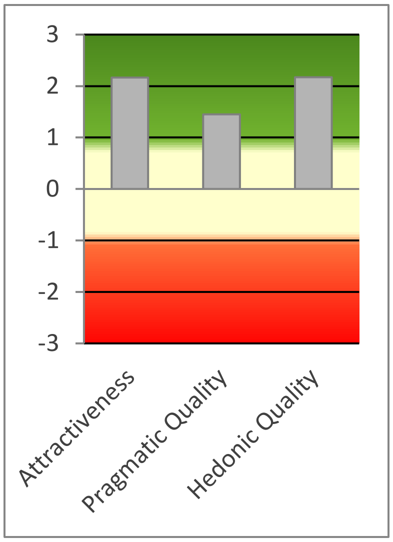

Figure 8.3: Mean value of each quality.

User Study 2 and Comparison

The participants of US2 rated the second version of the prototype with high scores in almost all scales. As in US1, the measured mean of attractiveness (μ = 2,09) and the hedonic quality (μ = 2,00) showed an unlikely high score above 2,0, which is excellent. The hedonic quality is calculated from the mean values of the scales stimulation (μ = 1,97) and novelty (μ = 2,03).

Regarding the pragmatic quality (μ = 1,44), which is an indicator for the usability of the second prototype, the results are above average, considering the UEQ benchmark. The highest rated scale in this quality is efficiency (μ = 1,67), which can be labelled as good. Perspicuity (μ = 1,61) scored above average and dependability (μ = 1,06) below average. Dependability includes the item with the lowest result of all. It is the semantic differential does not meet expectations-meets expectations (μ = 0,2). This is the only item which scored in the range of a relatively neutral evaluation (μ > -0,8 and μ < +0,8) in US2.

A comparison of each scale of the initial user study (N = 8) with the respective scale of the follow-up study (N = 9) showed, that the user experience in US1 was rated higher than in US2, with the exception of the scale efficiency (US1: μ = 1,44; US2: μ = 1,67). A simple T-Test was used to compare the mean values of each scale. The T-Test assumed unequal variances and used an Alpha-Level of 0,05 to verify if there is a significant difference between both studies. The T-Test showed no significant difference on the 5% level in all scales (see Figure 8.5).

SCALE	MEAN (US2)	VARIANCE (US2)	MEAN (US1)	VARIANCE (US1)
Attractiveness	2.093	0.22	2.167	0.17
Perspicuity	1.611	0.08	1.688	0.39
Efficiency	1.667	0.27	1.438	0.41
Dependability	1.056	0.26	1.219	0.19
Stimulation	1.972	0.59	2.063	0.21
Novelty	2.028	0.30	2.281	0.36

Table 8.1: UEQ scales (Mean and Variance) of both studies.

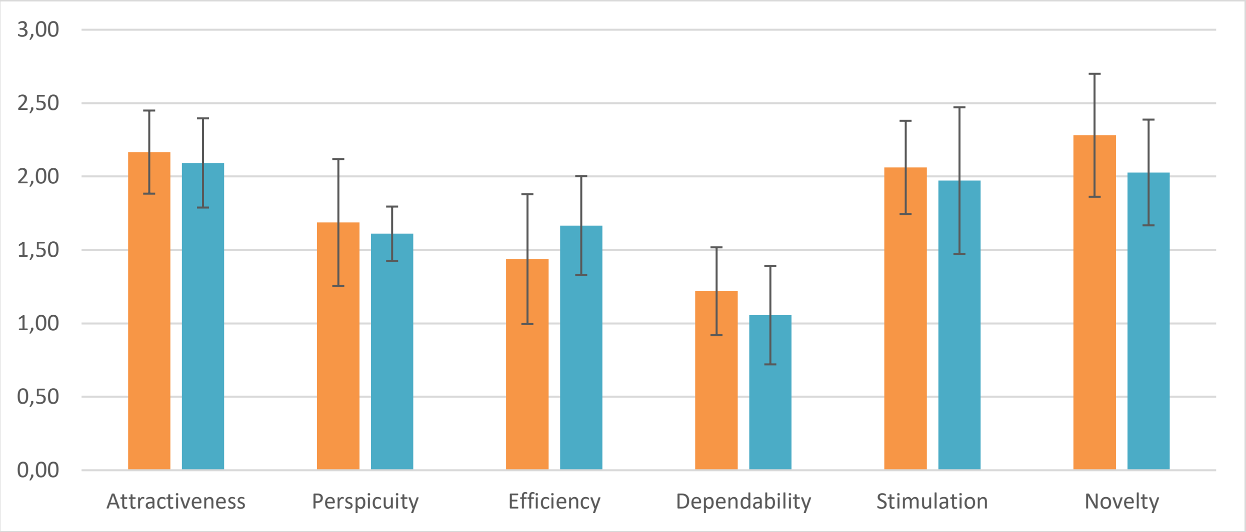

Figure 8.5: UEQ Mean values of each scale (US1 orange, US2 blue).

The figure below shows the mean value of each item and gives an idea about the surveyed semantic differentials of UEQ. The striped bars are the results of US2, and the colours indicate the scale of the respective item.

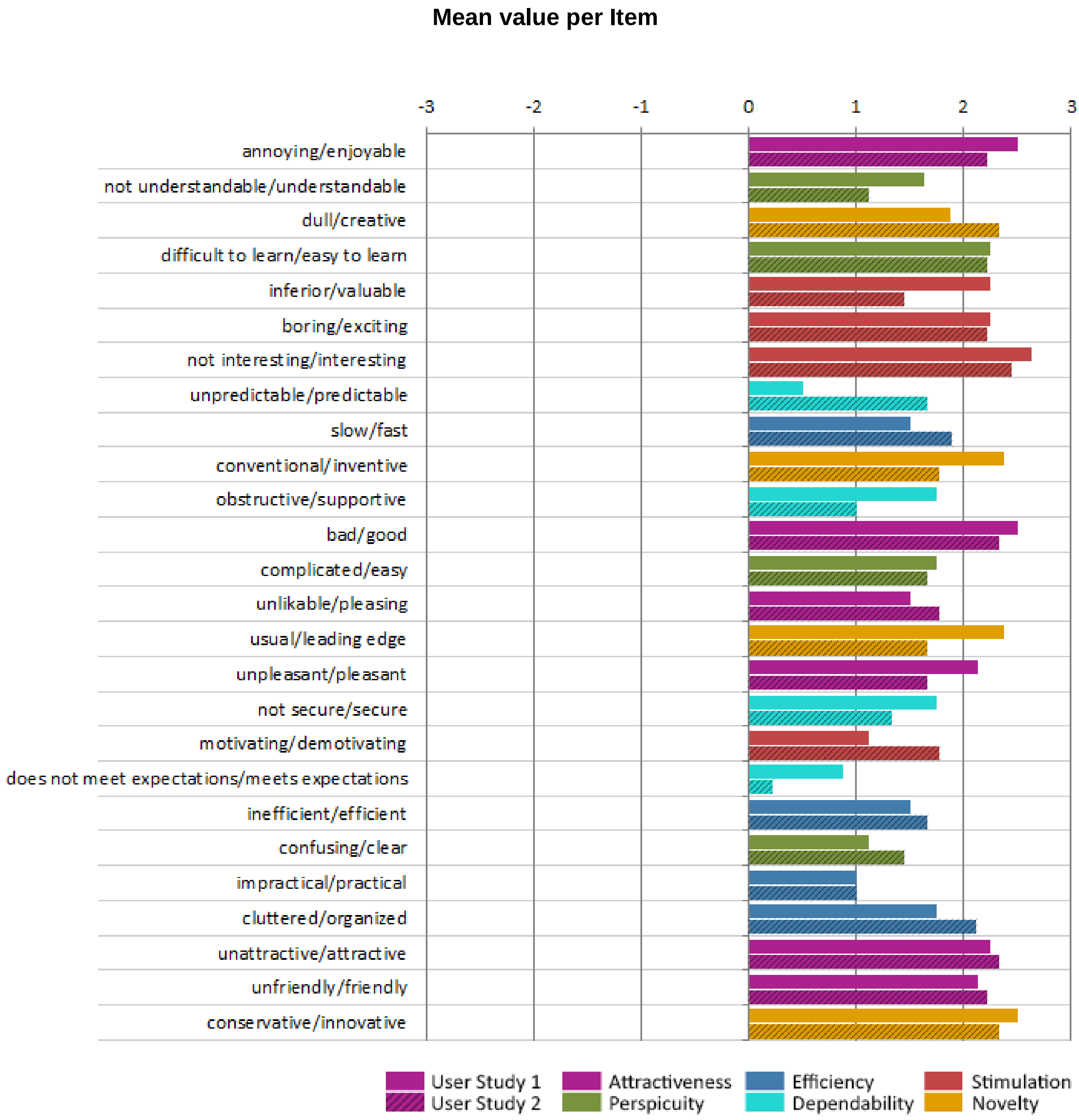

Figure 8.6: Mean value per UEQ item of US1 (top bar) and US2 (striped, bottom bar).

8.8 Evaluation of the Igroup Presence Questionnaire (IPQ)

In the follow-up study, nine participants answered the IPQ after the VR experience. The IPQ was not applied in the initial user study (US1) and for that reason a comparison between both prototypes cannot be drawn. The participants evaluated the items on a scale from -3 (no feeling of presence) to +3 (feeling of presence).

The results of the questionnaire were mediocre: The second version of the prototype achieved in the general item (G), which assesses "the sense of being there", and therefore represents a combination of all three scales (SP, INV, and REAL), a mean value of 1,0 (G: μ = 1,0; SD = 1,32). Only spatial presence (SP), which is the sense of being physically inside the virtual environment, scored higher than the general item (SP: μ = 1,13; SD = 2,14). The scale involvement (INV) evaluates the attention devoted to the virtual environment, and it also scored in the positive range (INV: μ = 0,86; SD = 1,88). However, the participants did not perceive the virtual environment as real. The scale realness, which evaluates the sense of reality attributed to the virtual environment, is located in the negative range (REAL: μ -0,61; SD 1,68). Figure 8.7 shows the mean value of each scale and the error bar illustrates the 95% confidence interval. Overall, the large confidence interval and high standard deviation (SD) of each scale requires a discussion of the significance of the results.

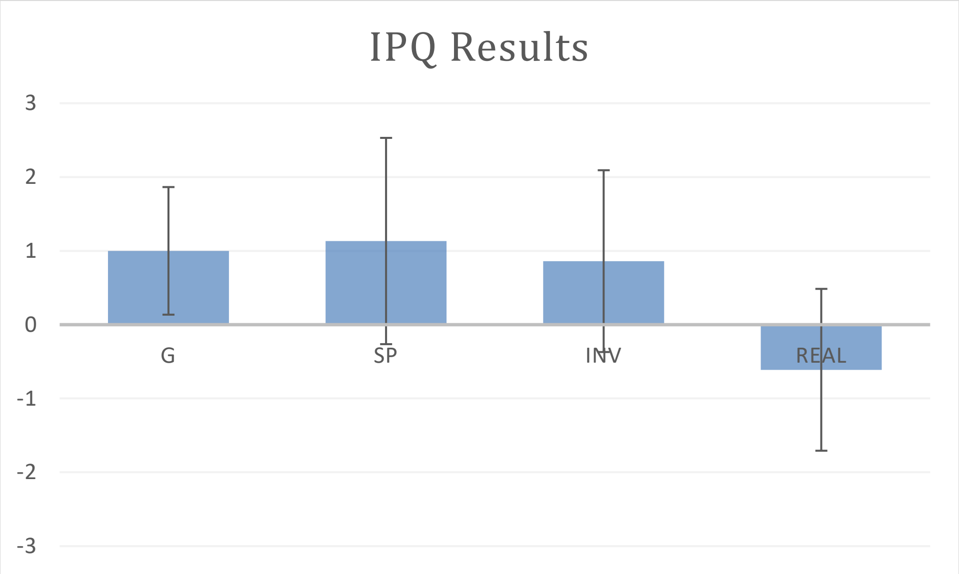

Figure 8.7: IPQ mean and confidence for each scale.

9. Discussion

Basis for discussion are the questions raised in the chapter study objectives. In the following, the results of both studies are compared and interpreted. The adjustments made to the prototype during the redesign (see 5.3 Design Process) are brought into relation to the study results and their influence on the usability is discussed.

User Experience

Following questions provide the basis for discussion in this section. (see 7.1 Study Objectives)

1. *Do participants master the 3D user interface of the autonomous car intuitively without guidance?*
2. *How does P1 perform in terms of overall user experience (UEQ)?*
3. *How does P2 perform in terms of overall user experience and is there a significant difference compared to the user experience of P1?*

The evaluation of the user experience showed excellent ratings in the scales Attractiveness, Stimulation, and Novelty in both studies. The participants really liked both versions of the prototype, the interaction was exciting and motivating, and they valued the creativity.

The scales related to the pragmatic quality and usability were rated with lower values, but still “good” and “above average” according to the UEQ benchmark. Dependability, which describes the user’s feeling in control of the interaction, scored lowest. The feeling of control might have been negatively influenced by the limitations of the hand-tracking device. Tracking errors sometimes led to false inputs and unpredictable behaviour of the interface. According to the rating “good” in the scale Perspicuity, both versions of the prototype were easy and intuitive to learn. The only improvement was measured in the scale Efficiency. Efficiency climbed from the rating “above average” to “good” in the second version of the prototype, but the increase is not significant.

The main purpose of measuring UX with the User Experience Questionnaire (UEQ) was to verify an improvement in usability of P2 with measurable data and to strengthen the results of the qualitative observations and think-aloud. However, the conduct of a T-Test showed no significant difference regarding the UEQ ratings of P1 and P2. Surprisingly P2 scored slightly lower in all scales, except for the above-mentioned scale Efficiency. Although both studies followed the same procedure to be comparable, there was a slight change in demographics. Only two participants of US2 (N = 9) had no prior experience with VR, compared to five participants in US1 (N = 8). These participants were most likely impressed by the experience of immersion and the novelty of head-mounted VR. As a consequence, their UEQ ratings might have been positively influenced solely by the novelty of the technology. Whereas participants that were already familiar with VR tended to rate the prototype itself. Their ratings might be unaffected by the novelty of VR technology, which caused a decrease of the average ratings in US2.

Another aspect is that the User Experience Questionnaire (UEQ) was originally created for the evaluation of interactive products like business and productivity software (e.g. statistics software package, cell phone address books, online-collaboration software) (Schrepp, 2019). In contrast, the virtual prototype of a 3D UI is experience driven and addresses the users' feelings to a higher degree. Hence, the ratings related to the hedonic quality, which are influenced by the feeling of immersion, presence, and involvement, are unlikely high. The UEQ might not be the perfect choice to evaluate the UX of virtual reality applications. The development of a UX questionnaire especially for games and other immersive (VR-) applications and experiences might be necessary.

Qualitative Data

Following questions provide the basis for discussion in this section. (see 7.1 Study Objectives)

1. *Is there a decrease of usability issues regarding the identified categories "reachability and placement", "interaction techniques and menus", "misleading affordances and design", and "interpretation in context"?*
2. *What usability issues can be identified that did not occur in US1, and do they have to be addressed in future work?*

Evaluating the UX did not indicate whether there is an improvement in user experience and usability of P2. However, the qualitative evaluation of US2 showed that many identified usability topics were solved. Especially the design rework and improvements of P2 regarding the category reachability and placement were very effective.

In the development process, ergonomic guidelines were followed to improve the reachability of UI elements. In P2 the interactive UI elements are consequently placed in the range of 60 degrees in front of the user so that the field of view always covers the whole UI when looking through the windshield. The Media Player UI implements different layers of depth to achieve an improved reachability of the genre buttons and to separate the genre buttons from the swiping area/plane (see Figure 5.13). Textures like grids and lines are used to indicate depth. The redesign of the Climate UI was used to explore the perfect distance between the user and the area for direct interaction. In the Climate UI, the interactive area is a curved plane that is approx. 0,5 m away from the user. A button can be dragged over the surface for airflow adjustments. Participant 6 really enjoyed the interaction with the draggable button and said that the distance felt totally right and convenient. As a result of these adjustments, all usability issues regarding the reachability and placement of UI elements were solved in the second version of the prototype by following basic ergonomic guidelines and the iterative evaluation of adjustments and design ideas.

Another identified usability topic is interaction techniques and menus. Although the gaze cursor is a selection technique suggested by literature (see 4.2.2 Selection Techniques), the participants of US1 did not understand this technique without explanation. P2 successfully solved this issue with the help of animations that draw the attention to the gaze cursor when hovering above an interactive object. However, selecting remote objects via pointing was suggested by many participants in both studies. Therefore, the pointing technique seems to be very natural and intuitive and should be considered by the time the hand-tracking technology evolves.

The second version of the prototype addressed ambiguity caused by inconsistent levels of depth in the hand menu by restructuring it to a consistent and flat structure. The ambiguity did not occur anymore, however the added application specific menu levels in the hand menu caused focus switching. Focus switching occurs when users have to shift their attention from one interaction area to another. This was the case in P2 regarding the hand menu and application UI above the dashboard, and in the restaurant due to the shift between the interaction with remote objects (e.g. tables) and the HM. The concept of using the HM as an always accessible remote controller for several applications did not work in the setup of a self-driving car. There is no need for a remote control-like menu that is attached to the user, when the position and movement of the user is constrained by the seat, and the reachable area for direct interaction always stays the same.

Misleading affordances were addressed by the redesign of UI elements. In the development process of P2, the navigation map POIs were changed from solid 3D spheres into a flat design. The affordance to grab and hold completely disappeared and users started to tap them with the index finger. The draggable button replaced the sliders in the Climate UI, but there is still room for improvement regarding the affordance to drag and drop the button. The waypoints in the restaurant were redesigned and a larger trigger box to activate the action was added. The interaction improved but the design still does not explain the travel functionality to the users. Generally, a flat design indicates tap and push interactions like known from touchscreens. Solid 3D objects indicate a physicality. Users often interact with these objects by grabbing and holding them.

Usability issues regarding the interpretation of UI elements in their context were solved completely in the second version of the prototype. During the process of prototyping, it was taken care to prevent from misinterpretation of UI elements in their context. The volume slider and play button in P2 is placed directly in the context of the Media Player UI and thereby the problem of misinterpretations was solved.

The qualitative data gathered by the think-aloud method and observations show an improvement of the prototype in the second version. The main usability topic reachability and placement was solved completely as well as the topic interpretation in context. Interaction techniques and menus improved vastly even though the usability issue of focus switching was raised in P2. This issue should be addressed in future versions of the prototype. Two main issues regarding misleading affordances were solved, however there are still some minor problems. Although it was not possible to verify the improvement of P2 over P1 with the results of the UEQ, the qualitative data showed an improvement of the prototype. Many participants gave positive feedback regarding the look and feel of the Media Player UI. They liked swiping through the songs and found the UI clearly structured. Considerably less usability issues were found in US2 and the participants enjoyed using the automotive 3D UI.

Presence

The assessment of presence in this study design is arguable. During the study, the awareness of the real world outside of VR was obviously given. The researcher talked to the participants to sequentially present the tasks and the participants were encouraged to talk about their experience, which must result in a high reduction of presence.

However, spatial presence (SP) was rated highest. The value of spatial presence gives insights about the feeling of being present in the virtual environment. The positive score indicates that the feeling of being in an autonomous car was achieved. This feeling is reflected in some user statements. For example, a participant said that he enjoyed sitting in the car and that the first impression matched with his imagination of an autonomous car. The scale involvement (INV) measures the attention devoted to the VE and the experienced involvement and was rated lower, but still positive. Realism (REAL) was rated with a negative score and the reasons are obvious. The scenery of a futuristic city without traffic on the streets cannot be perceived as realistic, autonomous cars at level 5 are a future scenario as well, and the computer graphics do not attain photo-realism. Additionally, only the visual and auditory human senses were addressed in the prototype. There was no haptic feedback, no real car seat, and no vibrations while driving. All these aspects raise the degree of immersion and possibly the feeling of presence.

In summary, the spatial presence might indicate that the virtual prototype is capable of simulating the interaction with a real autonomous car. However, the general assessment of presence in this study design is arguable and the results are distorted.

10. Conclusion and Future Work

The changes that come with the new experience of being a passenger in an autonomous electric vehicle will expand the possibilities for the integration of 3D user interfaces based on AR/VR technology for in-car infotainment. The thesis explored the usability and user experience of a 3D UI prototype for an autonomous car within a virtual test environment. During the iterative design process based on Lean UX, a redesigned version of the prototype was created, and the conduction of a user study showed an improvement of the prototype in several usability topics.

The design process discovered guidelines and best practices that improved the usability of the prototype. The issues regarding the reachability and placement of UI elements were completely solved by applying basic ergonomic guidelines. It was shown that animation can draw the user’s attention to interaction techniques that were not intuitively understandable like it was the case with the gaze cursor. A higher consistency in the redesigned prototype enabled users to transfer learned behaviour to similar tasks. The study also showed that the interpretation and affordance of UI elements strongly depends on their surrounding context. The creation of the new Media Player confirmed that the common 2D cover flow/carousel design pattern is also applicable in 3D UIs. Many users intuitively swiped through the vertical list of songs and enjoyed the redesign.

The enhancement of the hand menu with additional functionality raised the issue of focus shifting. Many users did not like to shift their attention from the static dashboard UI elements placed in the virtual-world reference frame to the hand menu placed in the hand-reference frame and vice versa. The idea of a “remote control”-like hand menu did not work in the seated automotive context. For some participants, the slightly bigger size of the hand menu led to the occlusion of dashboard UI elements. The topic of focus shifting from system controls within the body reference frame to interactive elements placed in the virtual-world reference frame must be explored further. It is an often-suggested technique that did not work in the automotive context.

The evaluation of the user experience with the UEQ did not show any significant differences between both versions of the prototype, even though major changes were made during the redesign of the prototype and the evaluation showed a decrease of usability issues. For further UX evaluations of immersive applications like games or VR experiences, the design and development of new methods to assess UX in this use case is necessary.

Regarding the virtual test environment of LUI AR, it would be interesting to evaluate the feeling of presence in an additional study. The evaluation might show its capability for user interface and

UX evaluation in general. A comparative study design comparing the VTE to an ADS, or a real car setup might also be an option. Positive results would argue for the creation of a new product that provides an advanced virtual test environment for UX and UI design evaluation. This product could evolve from LUI AR.

Digital Addendum

Master Thesis (PDF)

Data for each User Study including:

  Transcripts
  Usability Categories
  Codebook
  Consent for Study Participation
  UEQ Evaluation Sheet
  UEQ T-Test Comparison
  IPQ Evaluation Sheet (US2 only)
  Demographic Questionnaire Responses
  Video recordings of Participants (not all due to file size)

Design Visuals:

  Screenshots of Prototype 2
  Video of Prototype 1

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