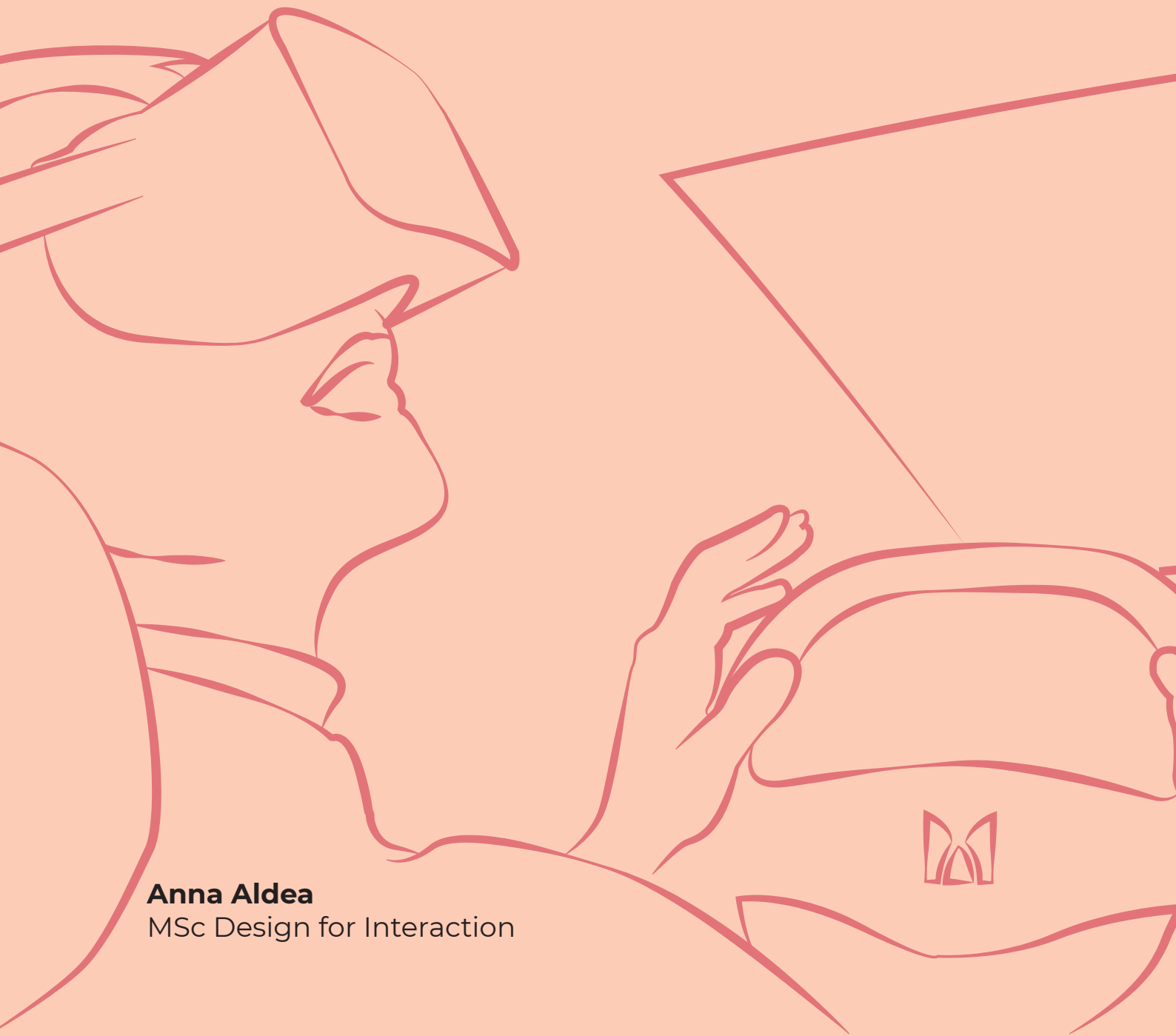# Virtual Reality for the Evaluation of Human-Machine-Interface in Autonomous Vehicles

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MSc Design for Interaction

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Abstract

This master's thesis reports on the development of a tool intended to support the evaluation of a Human-Machine-Interface (HMI) through the use of Virtual Reality Technology.

The project was initiated and supervised by **SWOV**, the Dutch Institute for Road Safety Research, as part of the **MEDIATOR Project**, which tackles the challenge of developing a mediating system between human drivers and intelligent driving systems. The design of a well-thought-out HMI is imperative to such a system. Multiple experiments, designed to evaluate the users' interaction with the HMI and to validate its effectiveness in guaranteeing a safe and comfortable driving experience, will be conducted. Due to its unique qualities, which allow us to simulate highly detailed and interactive environments, Virtual Reality is considered useful as a tool to support product evaluation and aid in the design process. This is particularly true in the earlier design phases when the development of high fidelity prototypes is out of reach.

In the first half of the graduation project, a number of research activities were conducted to gain insight into the best practices for the development of VR applications and into the requirement for a tool dedicated to facilitating the Mediator HMI design and evaluation process. The outcomes of the research result in a list of design requirements that were used as the blueprint for the conceptualisation of the final design. An iterative prototyping and evaluation process of three Minimum Viable Products (MVP) served to test initial design concepts and further inform the development of the tool. The second half of the report presents the design concept and implementation of the Mediator VR Evaluation Tool as well as the User Manual, which was created to facilitate the use of the VR tool be the Mediator design and research teams. Finally, the evaluation of the two products is described and the results of the two studies are discussed.
The outcomes of this graduation project suggest that VR is effective in supporting the evaluation of the Mediator HMI.

Contents

1

Introduction

This chapter provides a general overview of the graduation project from the problem definition and the solution space, the connection with the stakeholders and the design approach.

1.1 Problem Definition

In past years we have seen rapid developments in the field of automated transportation. However, there are several steps before full vehicle automation. In the process of moving toward full vehicle automation, there will be a period in which the driving task and responsibility will be shared between the driver and the autonomous vehicle. This comes with new challenges such as mode confusion (Sarter & Woods, 1995), reduced situational awareness (Endsley, 1995), over-reliance, and misuse (Lee & See, 2004), which can decrease the driver's performance ability and lead to an unsafe driving experience.

The MEDIATOR project is a 4-year project led by SWOV, started on May 1, 2019, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 814735 (https://mediatorproject.eu/). This project aims to tackle these issues through the development of an intelligent system that mediates the transition of control between the human driver and the autonomous vehicle. The mediating system will assess whether the human driver or autonomous vehicle is more fit to drive in the current situation, based on the driving context, the driver's state and the vehicle automation status.

The Human-Machine Interface (HMI) represents a crucial part of the Mediator system. The interface should ensure a safe collaboration between the human driver and the autonomous vehicle, as it is the means through which information travels to and from the driver. The system is faced with several important challenges, including that of maintaining at all times the situational awareness of the driver and preventing mode confusion as the driving task is passed from the human to the automated vehicle and vice versa. **A key requirement for the HMI is to keep the driver informed, while trying to prevent information overload or underload, and to create trust in the system while preventing the overreliance of the driver on the automation.** Furthermore, the HMI is also tasked with facilitating both conventional driving-related tasks as well as secondary tasks, such as climate and media control. To account for the complexity of such an interface, a holistic approach has been taken to the design of the Mediator HMI.

For the development of the HMI, it is important to evaluate how its design features impact the user's driving experience as well as their understanding of the information which is being communicated. Within the Mediator project, several experiments are foreseen. These experiments are meant to assess multiple HMI design concepts and converge towards a final list of design requirements. **In this context arises a need for a tool that can facilitate the evaluation process of the different HMI components and of the holistic HMI design.**

Virtual Reality (VR) provides an opportunity in the area of design evaluation. Virtual Reality is generally defined as a digital simulation, in which users can interact with a three-dimensional environment. Developing Virtual Prototypes of the design concepts is an effective solution to test different features of autonomous vehicles technology, including human factors, and it allows for the experimentation of different situations or driving conditions by implementing multiple virtual environments. (Rastogi et al. 2019) Furthermore, this technology allows the creation of detailed Virtual Prototypes, with elements that would be otherwise difficult or expensive to acquire or create. Evaluating human-centred HMI designs in a realistic use context is highly desirable. **Unlike other digital media, VR provides a more immersive experience for the users.** Through the use of VR, the test participants can be fully immersed in a simulated scenario and experience the interaction with the HMI in a realistic context, therefore, expressing more genuine responses to the design.

This master's project will explore the needs for the evaluation of the Mediator HMI designs and look into the benefits of using VR for testing interactive designs. **The goal is to develop a VR evaluation tool that will facilitate researchers and designers working on the Mediator project in their evaluation process.**

Virtual HMI prototypes

Virtual vehicle model
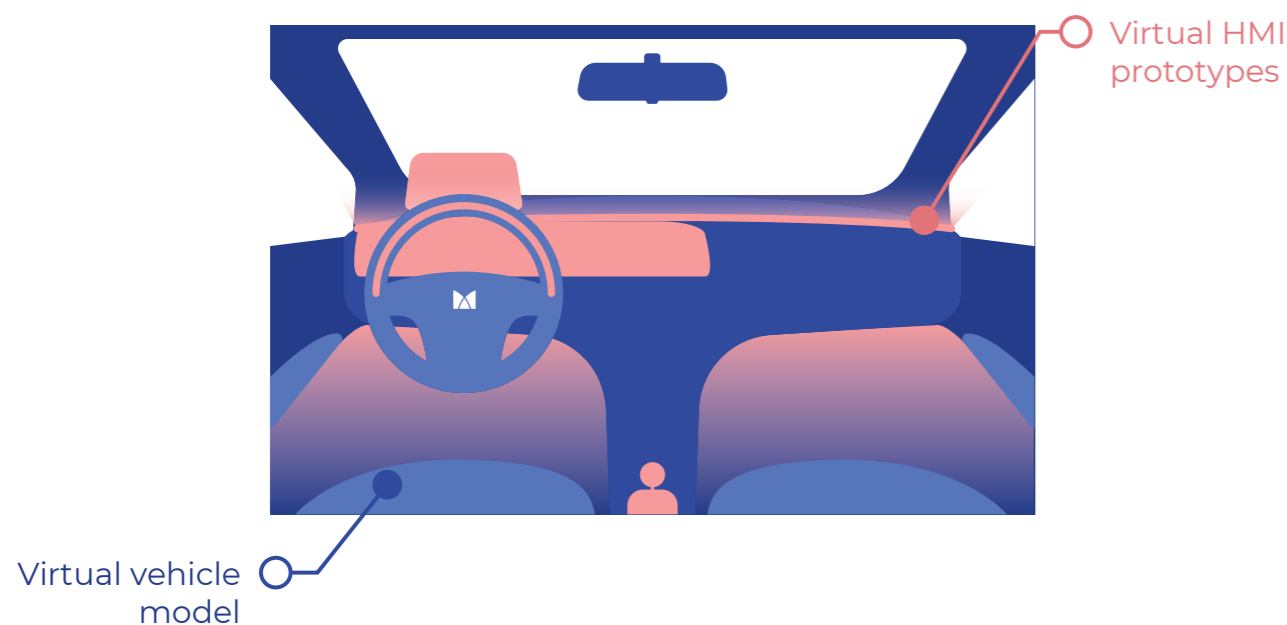
Figure 1: Envisioned Solution Space

1.2 Stakeholders

This Master's thesis is part of the **MEDIATOR project** (https://mediator-project.eu/) and is conducted in collaboration with **SWOV, the Dutch Institute of Road Safety Research**, and lead of the MEDIATOR project.
The outcomes of the graduation thesis are intended to facilitate further design activities carried out by SWOV and other partners of the Mediator consortium, including TU Delft.

Figure 2, details all interested parties, their influence on the project, and the potential benefit this project can bring to them. In the middle of the circle, the direct collaborators of the project are indicated, who directly influence the outcomes of this project. **Two key stakeholders are SWOV and TUDelft employees**, who will directly benefit from the use of the VR evaluation tool that will be developed. Their needs and interest in the project, as

users of the tool, are detailed in chapter 5.2. In the outer part of the ring, other partners of the Mediator consortium are displayed. They have contributed to this graduation project by providing insights and feedback, and who will indirectly benefit from the knowledge generated as a result of the outcomes of this project.

Mediator Consortium:
- Contributing resources, insights and feedback
- Indirectly beneﬁciaries

Direct Collaborators:
- Directly inﬂuencing the outcome of the project
- Direct beneﬁcieries (users) of the outcomes of the project

Figure 2: Stakeholders of the graduation project.

1.3 Project Approach

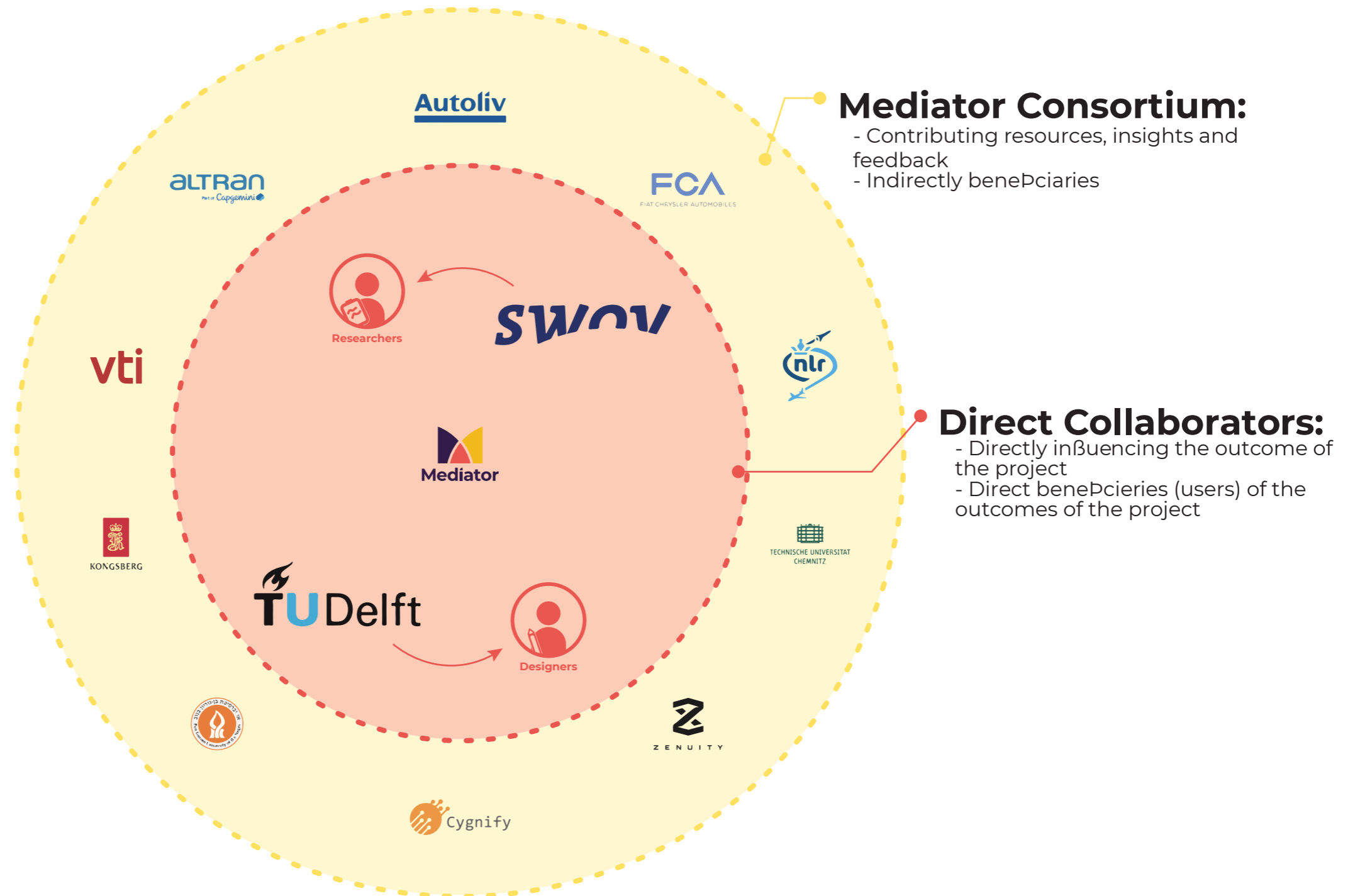The structure of this graduation project follows the **Double Diamond approach** (Design Council, 2007), a design process model developed by the British Design Council. Traditionally, the Double Diamond model is divided into four sections:

1. **Discovery**, finding insights into the problem
2. **Definition**, choosing a scope and focus for the design
3. **Development**, designing solutions to the problem
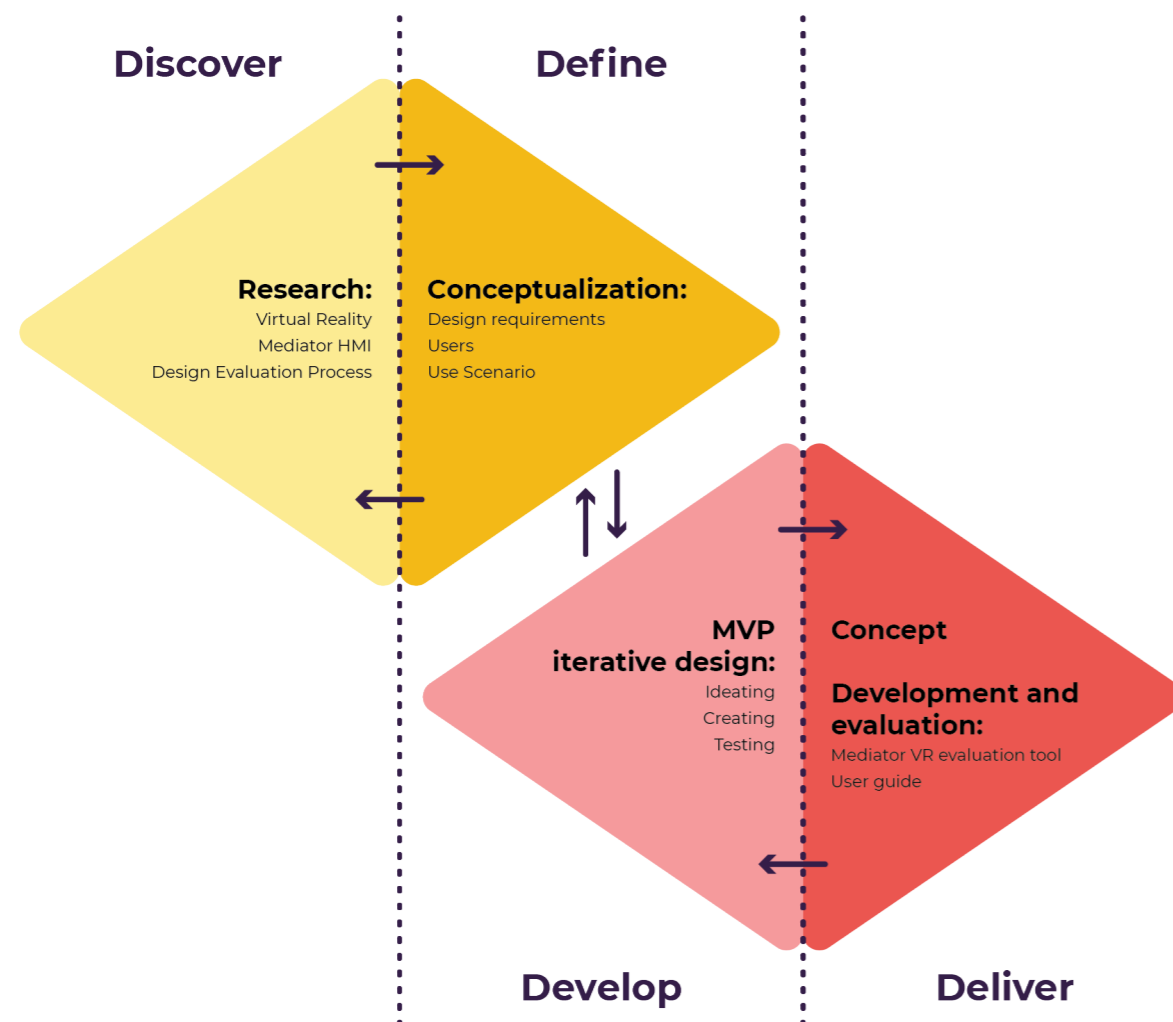4. **Delivery**, refining and testing the final solution

Discover

Define

Research:
Virtual Reality
Mediator HMI
Design Evaluation Process

Conceptualization:
Design requirements
Users
Use Scenario

MVP iterative design:
Ideating
Creating
Testing

Concept

Development and evaluation:
Mediator VR evaluation tool
User guide

Develop

Deliver

Figure 3: Project Approach, based on Double Diamond model

In the first phase of the project, **the Discovery phase is defined by a series of research activities focused on understanding the context of the assignment.** I looked into the characteristics of Virtual Reality to identify opportunities and limitations for its use in the area of design evaluation.
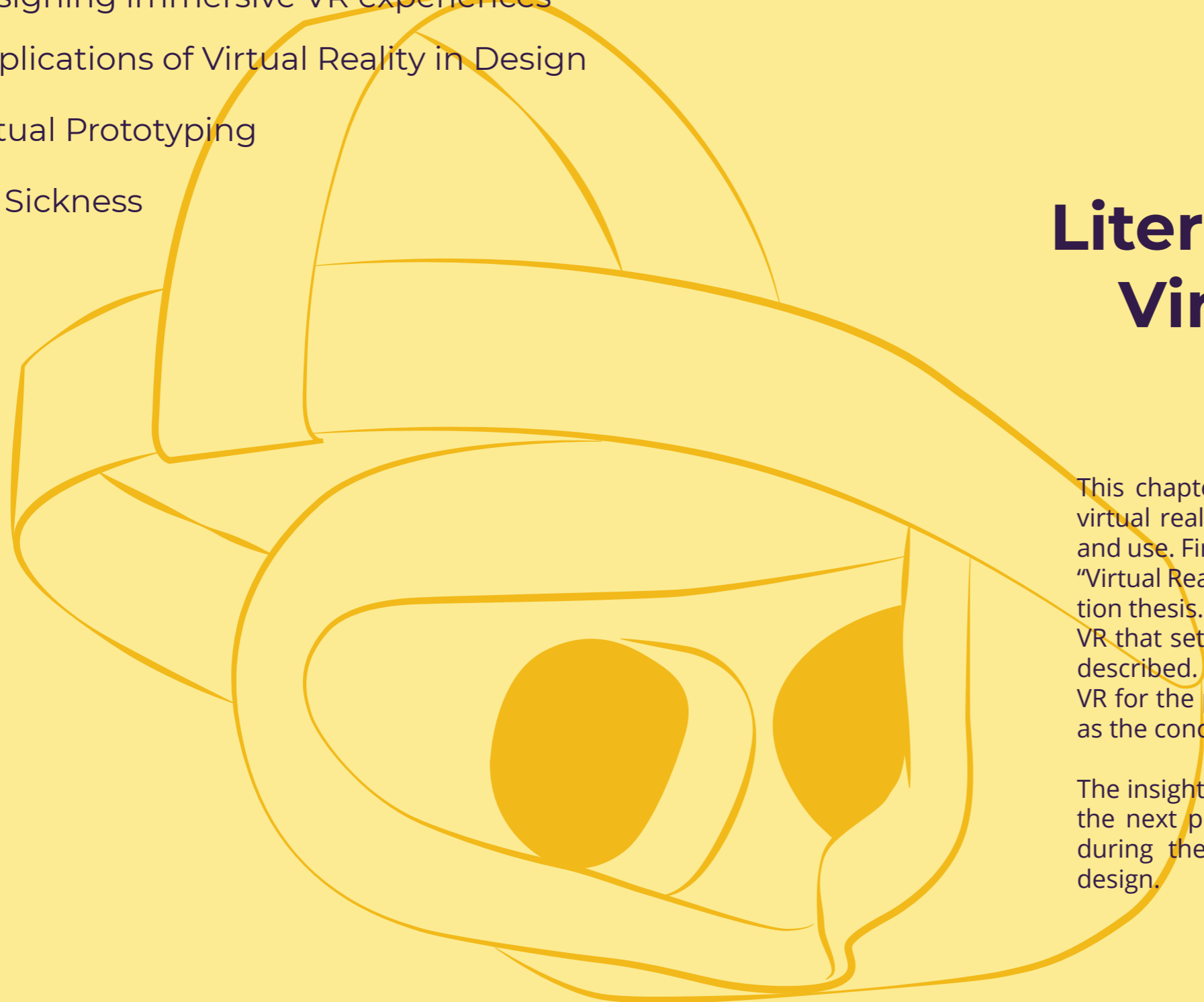
While the Double Diamond model presents itself as a linear model, it is common for designers to move back and forth between the various stages, as they discover more insights in an iterative process of development and testing.
In this project, as illustrated in figure XX, the Definition and Development stages were fully overlapping. **Following the initial research phase, an iterative process of development and testing of a series of MVP (Minimum Viable Products) was started early on.** The design of each MVP was based on requirements identified from research and insights gathered from the evaluation of previous iterations. This approach was valuable for two reasons. Firstly, it was an opportunity to experiment in a hands-on approach with the development of VR applications, which pose unique challenges compared to other types of interactive media, and contributed to the quality of the final design. Secondly, the initial design iterations, developed with the guidance and feedback of the main designer of the Mediator HMI, helped define the focus of the project. They allowed me to experience first-hand which elements of the design were needed and appreciated by the main user group, but also to better understand how the design could be used in practice.

In the Delivery stage of the project, the efforts were mainly focused on refining the final design concept and creating and evaluating the final product. To support the future use of the prototype within the Mediator project, a User Manual was also developed.

2
Literature Review: Virtual Reality

This chapter consists of a literature review on virtual reality technologies, their characteristics and use. Firstly, it is necessary to define the term "Virtual Reality", as it is being used in this graduation thesis. Secondly, the three characteristics of VR that set it apart from other technologies are described. Further, we look at the applications of VR for the purpose of design evaluation, as well as the concept of Virtual Prototyping.

The insights derived from this chapter informed the next phases of the project and were used during the ideation and development of the design.

2.1 Definition of Virtual Reality

Virtual Reality (VR) is typically associated with a digital simulation in which people can experience and interact with a three-dimensional environment. Today's Virtual Reality technology uses specific devices, such as Head-Mounted Displays (HMDs), body-tracking sensors and input devices, which allow users to be immersed in the artificial environment and experience it as realistic.

VR is a broad area with several definitions within literature. While there are various types of VR systems, including non-immersive VR and semi-immersive VR, otherwise known as augmented reality, the term is most often used to refer to an immersive VR system (Badmodu & Ye, 2013).

For the purpose of this Master's Project, the term Virtual Reality (VR) will be used to refer specifically to immersive VR systems. Immersive VR systems are computer-generated experiences that enable users to immerse themselves in a virtual environment, which contains a variety of synthetic stimuli and leads them to perceive the environment as real (Duarte et al., 2010).

Next to the VR software used to render and manage the simulated scenario, current **VR systems are generally supported by a collection of hardware components** (figure 4), which are classified by Badmodu & Ye (2013) as below.

A **VR Engine or computer engine** is responsible for processing and generating the virtual environment, rendering all the graphical data in real time, and managing the interactions with the users.

Output devices, which transmit audio, visual and haptic information to the users. These often include a stereoscopic Head-Mounted Display (HMD), which gives a three-dimensional view of the virtual environment through two separate displays, one for each eye. Commercial VR headsets also come with built-in speakers, which support 3D spatial audio. However, they provide limited haptic feedback, which is generally transmitted through the device's controllers.

Input devices, which allow users to navigate and interact with the virtual environment. Tracking systems capture the movement of the user's hands, head and body, and include a variety of sensors, controllers and data gloves. The controllers that accompany most commercially available VR headsets also enable users to input information through a point-input system.

In recent years, Virtual Reality technology has become easily accessible, with many companies such as Oculus, HTC and Google developing different types of inexpensive VR headsets for the consumer market. Furthermore, the rapid advancements in technology have allowed for the creation of more capable devices, and an improvement in user experiences and interactions in virtual environments.

Output device (HMD)

VR Engine

Input devices
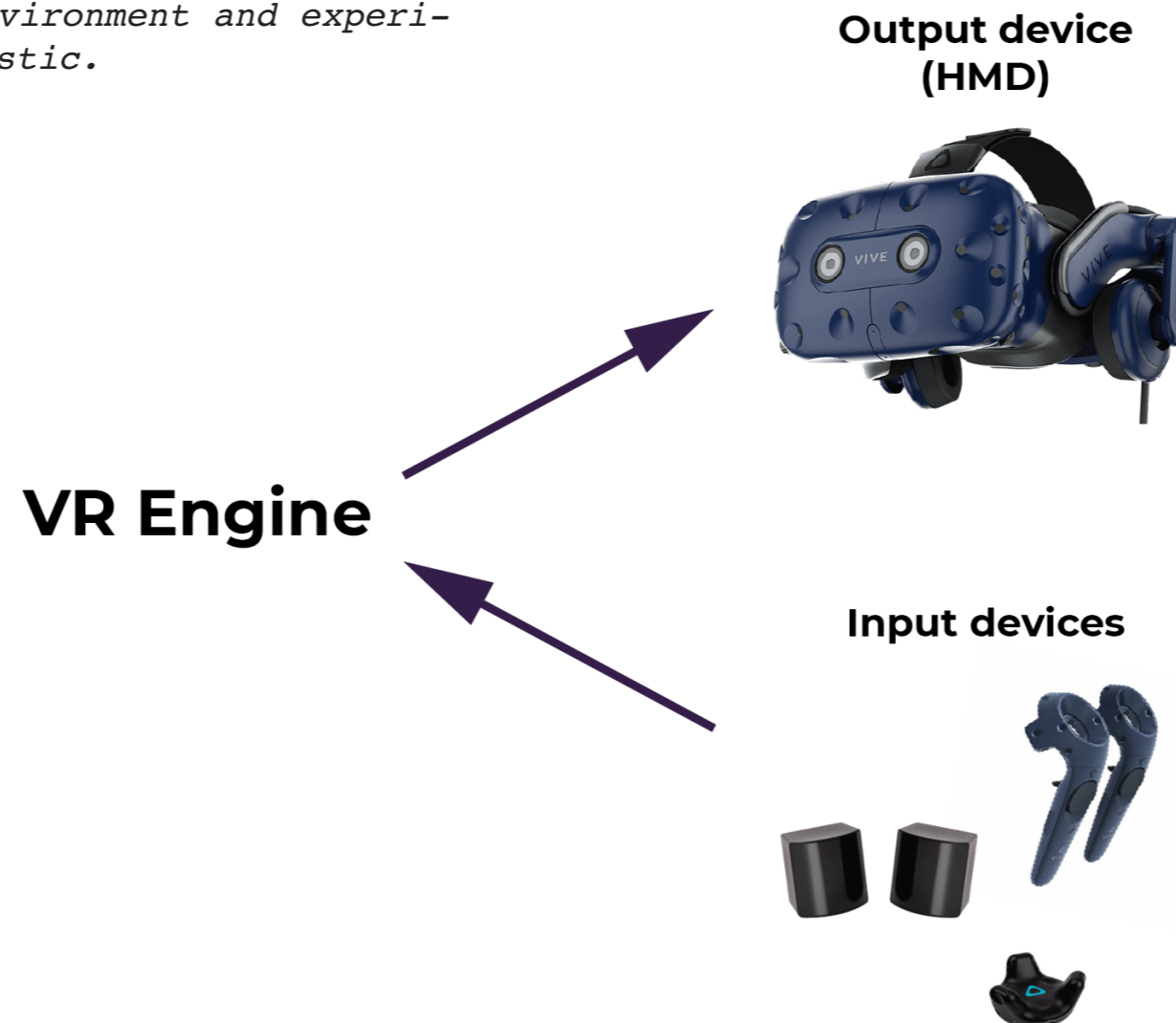
Figure 4: VR system architecture. Example of HTC Vive devices.

2.2 Characteristics of immersive VR

Virtual Reality provides different affordances compared to other forms of digital media, allowing the users to experience a much greater degree of realism in the virtual space. **The three main characteristics of VR that set it apart from other technologies are immersion, interactivity, and presence** (Witmer & Singer, 1998).
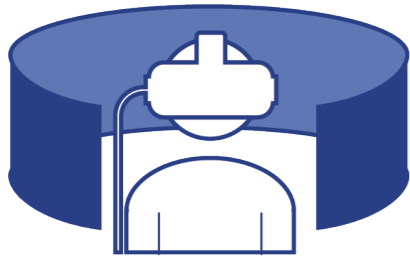
Immersion can be defined as **the extent to which a subjects feels as if they are part of the virtual environment and removed from the real world.** Witmer & Singer (1998) describe immersion as a psychological phenomenon caused by the interaction with a virtual environment that provides a continuous stream of stimuli. As such, the feeling of immersion can be increased when users can interact naturally with and control the environment, and are able to perceive self-movement. Another factor that can affect this feeling is the degree of isolation from the real environment. When users are deprived of outside stimuli, the feeling of immersion into the virtual environment will intensify. The subjective experience of immersion has also been linked to the concept of flow, which is defined as *"a state of optimal experience where one is completely absorbed and immersed in an activity"* (Nah et al., 2014). Based on this relation between immersion and flow, Mütterlein (2018) describes immersion as being related to feelings of involvement and absorption by the content, and differentiates it further from telepresence (or presence), which is related more to the perception of being in a place, as described below.

Interactivity **is related to the extent to which subjects have the possibility of affecting the form and content of the virtual environment in real-time** (Witmer & Singer, 1998). The degree to which users are able to interact with the environment will influence their feelings of immersion and presence in the space. When users are able to naturally affect, and be affected by, the stimuli present in the virtual environment they will become more immersed into the environment. Mütterlein (2018) describes interactivity as a psychological state of mind, focusing on the user's perceived interactivity with the environment, which he regards as subjective.

Presence, also referred to as spatial presence, is defined as **the subjective feeling of being part of, or physically present in the simulated environment, rather than in the real location the person is in real life.** As mentioned previously, the feeling of presence is greatly influenced by immersion and interactivity with the virtual environment, but also by the extent to which a user is involved with the content present in the virtual environment. Conversely, when users focus their attention on the virtual environment, they become more involved, thus increasing the feeling of presence (Witmer & Singer, 1998; Mütterlein, 2018).
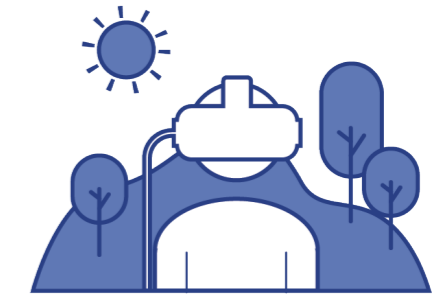
Therefore, **when a user experiences a well-designed Virtual Reality environment, they can feel as if they are present in the simulated space, and interact with objects within the virtual environemnt as they would in reality.** This characteristic provides a unique opportunity for the use of VR in various disciplines, and particularly when there is a need to recreate a realistic experience with products that are not yet materialized or in an otherwise inaccessible context or situation.

2.3 Designing immersive VR experiences

A high-fidelity virtual environment can closely replicate a real-world experience, making the most of VR technology. **To design successful VR experiences, considerable attention must be paid to the factors that influence a user's sense of immersion and presence in the space.** These factors were examined and summarized as follows.

Figure 5: A man using an immersive VR system at the "10.000 moving citie" Telepresence-Based Installation by Marc Lee.
(http://marclee.io/en/10-000-moving-cities-same-but-different-vr/)

SCENE REALISM

This refers to the degree of visual realism of the virtual scene (resolution, dimensionality, texture of materials and lighting, etc.) (Witmer & Singer, 1998). **It has been shown that higher degrees of visual realism in VR positively influence the feeling of presence in the scene and the overall experience with the virtual environment.** In an experiment which measured the degree of presence in two virtual environments that used different visual rendering techniques (the main difference being the presence of shadows and reflections, also for the participant's avatar, in one of the scenes), Slater et al. (2009) found that participants reported a higher level of presence in the more realistic scene. Furthermore, participants also exhibited higher levels of anxiety, related to the height of the pit they were standing close to in the virtual environment, when experiencing the scene with the detail of shadows. This suggests that **scene realism can elicit in users a more genuine emotional response to a VR experience.** In a similar study, Debattista et al. (2018) investigates the effects of visual quality of the virtual environment in a driving simulator on the participant's perceived experience, comparing three degrees of graphic quality. While the results showed a significant difference in the way participants experience the low quality scene, which made use of basic illumination, compared to the medium and high quality scenes, both of which had more depth given by the use of shadows and reflections, there was only a negligible difference between the latter. The authors therefore conclude that **once a certain threshold for graphic quality is met, further improvements will not significantly impact the experience.** Other factors can also define visual realism. One study compared two experiences with a different degree of realism, defined by the polygon count of the geometry of objects in the scene and the texture resolution, and showed that participants expressed a higher degree of presence in the more realistic-looking scene (Hvass et al., 2017).

MULTISENSORY INFORMATION

Although commercial VR is often focused on providing accurate visual feedback, multiple studies have investigated the effect of different sensory feedback modalities, as well as multimodal feedback on user experience. **Multimodal transmission of information has been observed to positively affect VR experiences, boosting realism and immersion** (Martin et al., 2021). Adding sensory stimuli that are realistic and coherent with the environment has been shown to improve the perceived realism of the experience, also by enhancing the plausibility of the scene. **Users perceive a VR experience as they would a real life scenario. Therefore, there is an expectation that the events that are experienced in the virtual environment create a reaction that would be experienced in real life** (e.g. an object that falls should create a sound, when we touch something we feel the texture, shape and temperature). Therefore, **when users are able to physically touch an object they are simultaneously interacting with in VR, their experience is perceived as being significantly more realistic** (Martin et al., 2021; Hoffman, 1998).

INTERACTIVITY

A greater degree of control over the virtual environment influences the feeling of immersion in the space. In his research, Mütterlein (2018) has found a direct relationship between interactivity, presence and immersion. The results of this study demonstrate that interactivity represents an important foundation, influencing both the feeling of presence and immersion given by a VR experience. **Not only the degree of interactivity, but also the way in which a user interacts with the virtual environment can have a great influence on a VR experience.** This can be linked to the "control factors" identified by Witmer & Singer (1998), through which they explain how the experience of the users can be influenced by how much control they have over the experience, by how immediate the reaction to their actions is translated in the VR simulation, by their ability to anticipate and predict what will happen next and whether they have control over it, by the way in which they can interact with the environment and whether it reflect naturalistic or familiar interaction, and finally by their ability to modify or interact with objects in the virtual environment. In order for a user to feel fully immersed and present in a VR world, interactions with elements of the virtual environment should reflect our expectations, which are influenced by real life.

AVATAR AND MOVEMENT

The term avatar refers to the digital representation of the user. **In VR, an avatar represents the user's body (or parts of it) and is viewed from a first-person perspective. The appearance of the avatar can have an effect on** the subjective feeling of presence, and give the illusion of body ownership in VR. While there are many ways in which the avatar has been shown to influence user perception, it is not necessary for it to have a realistic human appearance in order to induce a sense of body ownership. In fact, a higher human resemblance can sometimes decrease acceptance by users, which can be linked to the uncanny valley effect (Lugrin et al., 2015). A study conducted by Schwind et al. (2017) found three levels of deviation from one's real body (in the case of the study, limited to the hands) which affect the feeling of presence: Deviations from common human appearance, their own gender, or their own body. The study concludes that if the use of human-like hand models is desired, it is best to provide participants with a hand avatar that matches one's gender, as mismatched hands can negatively affect the experience. However, a safe trade-off is to make use of a gender-neutral representation if the same model is used by both men and women. While the use of a stylized anthropomorphic hand was not found to reduce the sense of embodiment, an abstract non-anthropomorphic hand has been found to significantly reduce the sense of ownership, agency, and location in space (Ogawa et al., 2019). In their study, Ogawa et al. (2019) also proved **the size of the realistic hand avatar affected the user's perception of the size of other objects in the virtual space**: users perceived handled objects to be smaller when the avatar was enlarged. This condition was not true when an abstract hand was used. Furthermore, as Joy et al. (2021) have proven, **the representation of the body in VR can affect one's perceived affordances when interacting with an object.** Therefore, **it is preferable to** provide VR users with fully able hand models (that have full finger tracking) when attempting to recreate a realistic interaction within the virtual environment.** The representation of the user's body in the virtual environment can affect their sense of immersion as well as their perception of affordances. The perception of one's own movement in the space adds to the feeling of presence. Lee et al. (2020), observed how **presence and body ownership increased when the avatar's leg motion was synchronized to the user**, compared to the use of a fixed body (no motion) and a pre-recorded animation that did not match the real movement of the test participants. Therefore, in order for the user to feel immersed in the experience and have an increased feeling of presence, the representation of the avatar does not need to be visually realistic. However, it must be consistent with the user's expectation and match the actions of the real body.

EXTERNAL INFLUENCES VS. ISOLATION

As the unique experience of VR is associated with the feeling of being in another space, it is implied that the users must have a certain degree of separation with the real environment they are in. In a study of user acceptance of VR technology, Mütterlein & Hess (2017) discuss the effect of environmental attributes on the users' experience. Individuals experiencing VR can be distracted by other people who are in the same room or by the objects (i.e. furniture) present in the real environment. **Receiving stimuli that are inconsistent with the VR can be distracting and negatively influence the feeling of immersion and presence.**

PARTICIPANT BIAS

The degree of experience with VR can influence a user's perception. **Individuals who had not used VR in the past have been observed to experience a novelty effect, which creates a positive bias in their rating of the perceived degree of immersion.** Mütterlein & Hess (2017) have observed this effect, indicating that users in a more advanced stage of the adoption process of VR technology were less likely to be impressed or surprised by the experience. Other studies have also highlighted a difference in attitudes and response to VR experiences between gamers, or people with previous experience in video games, and non-gamers (Geslin et al., 2011).

2.4 Applications of Virtual Reality in Design

While Virtual Reality has been popularized mainly within the video-game industry, VR technology has been adopted in many industries, where the uniquely immersive experience has been used to train new users or employees, facilitate remote communication or collaboration, or to allow customers to view a product before it is built. **In the fields of design and engineering, the use of VR has also been explored in several parts of the research and design process.**

Berni & Borgianni (2020) provide us with a comprehensive review of the applications of Virtual Reality technology in the design process. Following a review of 86 sources, the authors categorize the applications of VR in the design process. The categories were determined according to various criteria, including the **design functions supported by VR technologies** (figure 6), **the VR devices/technologies used** (figure 7) and **the presence of supporting tools or complementary technologies** (figure 8). The latter two are of interest in this project. On the one side, **the use of specific VR technologies, which provide different degrees of immersiveness, underlines how this aspect can affect the benefits that VR can bring to a design function.** The authors explain, *"More specifically, since VR technologies are very heterogeneous, their usability and the degree of the sense of immersion and presence could affect the user during the virtual experience. Therefore, it is likely that these factors could play a fundamental role in the effective application of this technology in the design process."* On the other side, the authors observed how VR visualization devices were integrated with interaction hardware to allow the user the opportunity to interact with the virtual world. *"As aforementioned, these integrated devices are actually deemed crucial for VR's effectiveness in design."*

The supporting tools were used to stimulate different senses, such as the tactile sense, and enhance the interactivity provided by the VR system.

In the sources reviewed by Berni & Borgianni where VR was used for the purpose of evaluation (Riegler et al., 2019; Rentzos et al., 2014; Bordegoni & Ferrise, 2013; Van Der Voort & Tideman, 2008), we notice the use of VR technologies that offer a high degree of immersion (Head-Mounted-Displays) and supporting devices, particularly haptic devices, motion tracking devices and controllers, which enhance interactivity with the virtual environment.

Macro-categories	Sub-categories and design activities included
1. *Early phases*	Creative design phases (mainly supported through virtual sketching), individual brainstorming, concept development
2. *Co-design*	Group brainstorming, collaboration in the simulations, assessment and re-design of a project, sharing models and data
3. *3D modelling*	Virtual clay modeling, detailed/concept immersive sketching/geometric manipulation and visualization
4. *Virtual* assembly and *prototyping*, mechanical simulation, finite element method (FEM)	Control operations and simulations to verify whether the design and the assembly/disassembly of the parts work, finite element analysis, 3D human model simulations and ergonomic evaluations
5. Product *Evaluation*	Evaluation of the virtual prototype, gathering of users' feedback (reactions and experience/preferences of product variants)
6. *Education*al purposes	Supporting the learning process of students dealing with design issues

Figure 6: Categories of the functions supported by VR technologies. (Berni & Borgianni, 2020)

Technology used for visualization	Devices
Head-mounted displays (*HMD*)	Oculus Rift, HTC Vive (Headset + controllers) or similar, TiciPrep/TiciView (Headset), Microsoft™ Hololens™
CAVE or similar	CAVE system and other technologies which involve a large field of view and 3D glasses for visualization, Cyviz (rear-projected wall display)
Desktop VR with stereo glasses	Desktop VR with stereoscopic glasses for a three-dimensional view
Unspecified VR system	Unknown/ unspecified VR system and adopted devices for mixed reality mock-ups
Other	OpenRT (Open Ray-Trace) techniques, AutoEval interface, two stereo, VirDe, stereoscopic screen with collocated motion parallax which renders the visual experience logical and realistic, V.R.A.D.U., WorldViz VR devices, Photographed VRs, Ramsis system, SATIN system

Figure 7: Categories of VR technologies involved. (Berni & Borgianni, 2020)

Supporting tools for interaction	Devices
Hands controller	HTC Vive hands controllers, FlyStick (a 3D pen), Virtual pencil, Wii remote, pliers tool, two-handed Bezier tool, stylus, wand
Interaction *gloves*	CyberGlove, Pinch gloves, Mattel PowerGlove TM, Immersion CyberTouch
Sound inputs and/or outputs	Voice recognition, audio output, stereo speakers
Haptic systems (*haptics*)	Phantom haptic force devices, free force haptic systems, tactile feedback, haptic feedbacks in general, 3D mouse, spaceball mouse, real objects (e.g., chairs or steering wheels, pedals, vibrating elements in driver's seat), VirtuoseTM6D35-45 haptic device
Motion tracking devices	Head motion tracker/hand motion tracker, head-repositioning device, leap motion
Traditional control devices	Keyboard, mouse, joysticks, gamepads, touch screens
Biometric instruments	Eye Tracking, Galvanic Skin Response, OptiTrack optical tracking system
None/unspecified	No supporter device was used
Other	Projector, spherical mirrors, spherical screen, digital tablet, and drawing support

Figure 8: Categories of VR supporting tools for interaction in the virtual environment. (Berni & Borgianni, 2020)

2.5 Virtual Prototyping

Even before the use of VR in the design evaluation process was popularized, computer simulations were used to evaluate products at various stages of the design and development process, in order to cut back on the time and cost involved. **The computer simulations of physical products are referred to as Virtual Prototypes.**

Wang (2002) gives a clear definition: *"Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analyzed, and tested from concerned product lifecycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP)."*
This definition encompasses all forms of digital simulations that allow for a 3D presentation of the product model, such as CAD models, and for the testing of various aspects of the design, and does not require
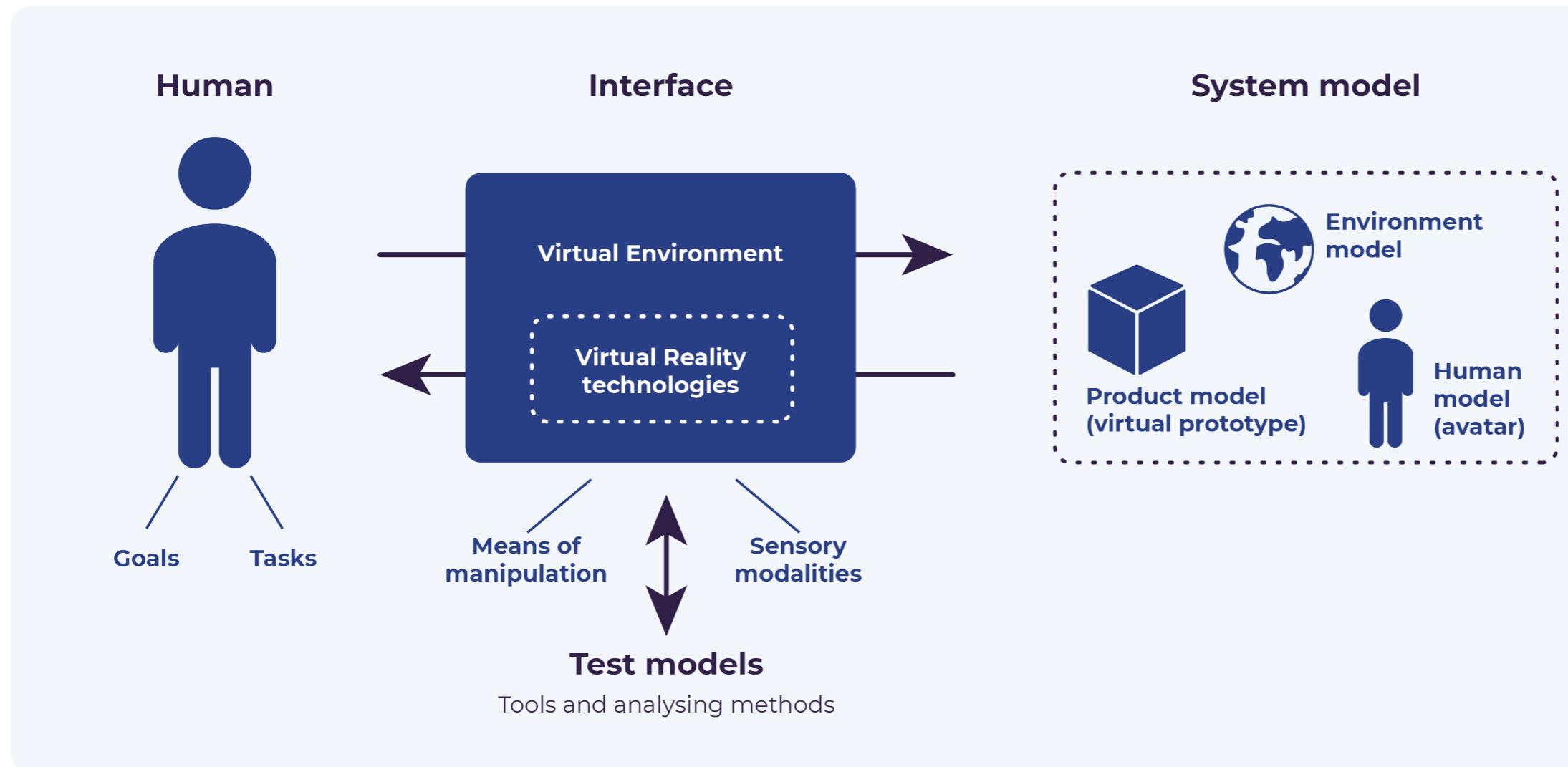
the use of VR technologies. The possibility of interaction with the digital prototype, more precisely, the physical interaction, which allows the user to touch or move an object which is part of the virtual environment, is not a strict requirement for Virtual Prototyping. However, **a human-product interaction model is desirable, especially when considering designs that must be evaluated in terms of the user experience and interaction** (Wang, 2002). **In this area, using VR technologies can greatly enhance the benefits of Virtual Prototyping.** Due to the immersive qualities of VR, designers

and users alike can get a good feeling of the product from the initial stages of the development. They are able to better assess its aesthetic and ergonomic features by transporting themselves in the virtual space with the product, as well as being able to interact with it in real time.

Considering Wang's definition, **we can consider part of the proposed design solution that is being developed as part of this graduation thesis to be a Virtual Prototype of the Mediator HMI.** Therefore, it was considered relevant to look into the literature at the process of creation and implementation of Virtual Prototypes.

Preparing a design evaluation using any sort of Virtual Prototyping requires the extra step: the development of the interface. In order to guarantee that the Virtual Prototype which is created serves its intended purpose, Aromaa et al. (2014) suggest starting the process by defining the goals of the evaluation and identifying the required characteristics for the interface that is being built.

In their study, Aromaa et al. (2014) provide a framework to aid designers and developers to systematically construct virtual prototypes. **The framework** (figure 9), **which is based on theories and human-centered design concepts, distinguishes three elements that define the interaction within the virtual prototype: the subject is the human or the user, the tools through which the interaction is mediated are the interface (the Virtual Reality) and the object, which is defined as the system model.** When using Virtual Prototyping, designers should allow the human to achieve their **goals and tasks** in the interaction with

Human

Goals   Tasks

Interface

Virtual Environment

Virtual Reality technologies

Means of manipulation   Sensory modalities

Test models
Tools and analysing methods

System model

Environment model

Product model (virtual prototype)   Human model (avatar)

Figure 9: A framework for virtual prototyping in human-machine interaction (Aromaa et al., 2014)

the **system model, which includes the digital prototype**, but also other digital content (e.g. the environment or context of use, the digital avatar of the user or other users in the scene, etc), as they would when interacting with a physical prototype. **In Virtual Prototyping, the interaction is mediated by the tools included in the interface**, which should provide appropriate means of manipulation of the virtual environment and give sensory feedback to the user.

A fourth element, **the test models**, is added to the framework to account for the needs that arise from the use of Virtual Prototyping for design evaluation. The test models are characterized by the tools that are needed to record data (e.g. measuring time, distance, biometric data, etc) and support the analysis of the product's performance.

This framework was used as a reference for the formulation of a set of questions posed to the designer of the Mediator HMI to identify specific requirements for the design of the first two prototype iterations, or Minimum Viable Products (see chapter 5.4). Further, it helped define the various elements of the final design concept, described in chapter 6.

2.6 VR Sickness

There is one downside to VR systems: a phenomenon that has been called **cybersickness or VR sickness** (McCauley & Sharkey, 1992). **Users who suffer from VR sickness experience symptoms similar to motion sickness including nausea, disorientation, as well as eye fatigue.** These render the experience uncomfortable for users and can even prevent them from using VR altogether.

Chang et al. (2020) reviewed several sources to identify the causes of VR sickness and classified them into three factors: **hardware factors, content factors and human factors.**

Hardware factors refer to the hardware components of the VR device. These play a major role in determining the quality of the VR, particularly of the quality of the display. Several studies have shown that **the use of HMD devices** led to more VR sickness compared to other types of display, such as large screens. Chang et al. (2020) explain: *"These results can be associated with the degree of discrepancy between expected and perceived sensory information."* Other hardware factors which can influence cybersickness include a wider **field-of-view (FOV)**, **flickering of the display** and higher **latency**, or the delay between actions that the user expects to see and what they actually see in the virtual environment.

Content factors refer to what the user can see in the virtual environment including changes of variations in the VR scene. Chang et al. (2020)
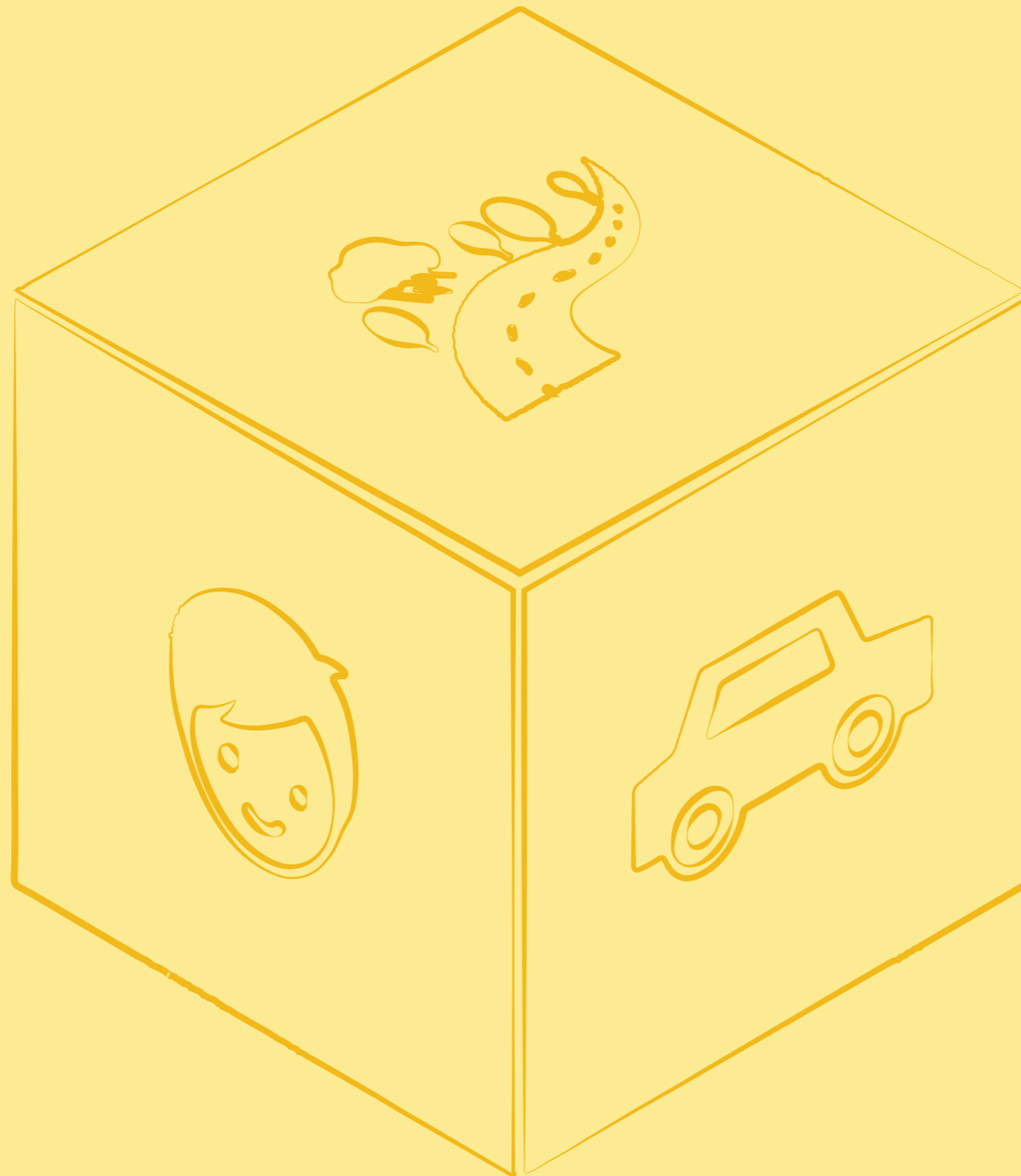
identified several factors related to the content of a VR scene have been found to cause VR sickness. **Optical flow** is produced by the movement of virtual objects which can cause a user to experience a strong feeling of vection, or the illusion of self-movement, and consequentially VR sickness. Higher speed of moving objects has been associated with heightened VR sickness. Interestingly, a higher degree of **graphic realism** of the scene was observed to correlate with more negative effects. The authors speculate this could be caused by the discrepancies between visual and vestibular stimuli. *"In other words, as the visual stimulus becomes more similar to reality, the user is more immersed in the VR and expects vestibular inputs corresponding to the visual stimulation. However, users cannot acquire such vestibular information, so the degree of conflicts as well as VR sickness increases."* The addition of **fixed or static objects** in the virtual scene, which serve as a point of reference for users, has been found to reduce VR sickness symptoms.

Human factors can also have an effect on the negative symptoms each individual can experience when using a VR device. Several factors have been investigated in literature such as **age, gender, and motion sickness susceptibility.** The latter has been show to affect VR sickness in particular. Chang et al. (2020) conclude that *"Based on these experimental results, the same quality of the VR system can provide different user experiences depending on various human factors."*

Chapter 2
Key Takeaways

- Virtual Reality is a technology that **allows users to experience and interact with a simulated three-dimensional environment.**

- Three characteristics distinguish VR media: **immersion, interactivity and presence.** In a well-designed Virtual Reality environment, users can feel as if they are physically present in the simulated space, and interact with objects within the virtual environment as they would in reality.

- To increase the sense of immersion and presence in a virtual space, several factors must be considered when designing a VR application. These include **the degree of realism of the content, the ability to convey information in a multisensorial way, the degree of interactivity with the virtual environment, the appearance and movement capabilities of the user's avatar, the reduction of external stimuli during the VR experience, and mitigating the effects of user bias.**

- VR technology **has been applied to several parts of the design process**, from the early conceptualization phases to product evaluation.

- **Supporting tools** sometimes are necessary to stimulate different senses, particularly the tactile sense, during a VR experience.

- A virtual simulation of a physical product is defined as a virtual prototype. In Virtual Prototyping, it is important to consider all elements of the system (**human, interface, system model and test models**) that define the interaction with the virtual prototype.

- Using a VR device can cause negative side effects, such as **nausea, disorientation and eye strain**. They are referred to as **VR sickness** and are influenced by several factors related to the hardware, the content displayed and the users.

3

Context Research | Mediator HMI

In order to develop the concept for a VR tool that could be used to support the evaluation process in the context of the Mediator project, it was necessary to first look into the already established requirements for the HMI and foreseen implementations.

In this chapter, we take a closer look at the context of this project, and in particular at the characteristics of the Mediator system's Human-Machine-Interface (HMI). The main functions and features of the HMI are described, as well as the ways in which information is exchanged between the driver and autonomous vehicle. Finally, the use cases that have been defined for the development of the Mediator system will be explained.

3.1 Functional Requirements of the Mediator HMI

As mentioned above, **the MEDIATOR system's HMI plays a crucial role in creating a pleasant and safe driving experience for its users**, as it is responsible for mediating the interaction between the driver and the automated vehicle.

Project partners have defined a comprehensive set of general functional requirements to guide the design process of the HMI:

- The HMI module must perform all HMI functions of the original vehicle HMI.
- The HMI should keep the driver aware of the current automation level and the driver's sense of responsibility, through the use of primary and secondary sensory cues.
- The interaction with the driver, during preventive and corrective actions and control transfers, should be fulfilled through a recognizable and predictable ritual.
- The HMI should negotiate with the driver in cases where they indicate a different automation preference. A seductive negotiation strategy will be used for low necessity levels, while for higher levels a persuasive negotiation of forced take-over (no negotiation) is used.

In addition to these general functional requirements, more have been defined, which are applicable to specific use cases (see chapter 3.3), and further specify the type of behavior the HMI must exhibit, what information it must relate to the driver, and what actions it must take in various situations. While the functional requirements generally describe the functions of the HMI in different moments, further exploration is needed to define the most appropriate ways in which this will be fulfilled and translate them into design requirements.
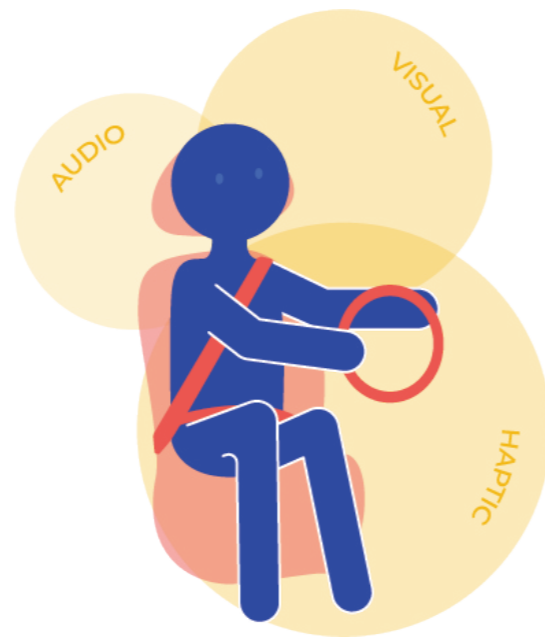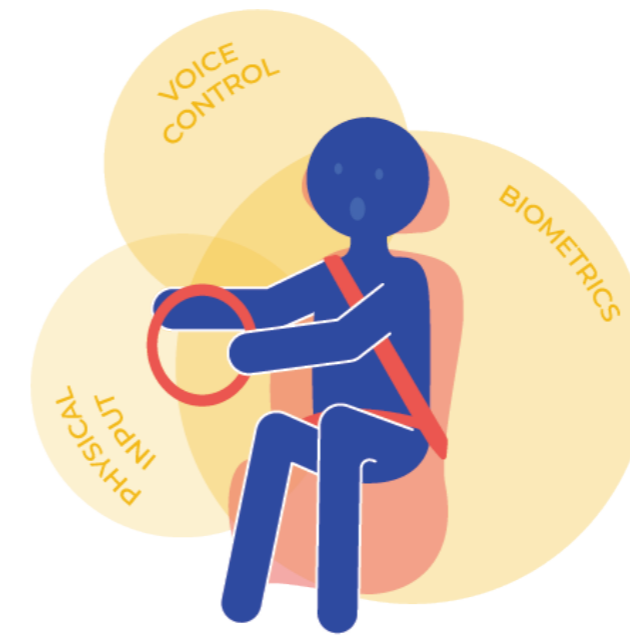

Figure 10.1: Information output modalities of the Mediator HMI.

3.2 Interaction Between Driver and HMI

The interaction between the human driver and the Mediator HMI makes use of various communication modalities. Information is exchanged through multiple types of input and output controls (figures 10.1 and 10.2).

Through input controls, the system receives information from the users. To indicate their preference for switching to a different driving mode, for example, the driver can communicate their intention through a mechanical interaction with one of the proposed HMI components (e.g. by pushing the gear lever into the desired position). Other types of commands may be given to voice controls or gesture

controls. Furthermore, the Mediator system will respond to biometric data (iris identification) that it records from the user, identify their driving fitness and give the appropriate response, including proposing a takeover of control or performing a corrective action.

The HMI communicates back to the driver and other passengers through multiple output controls. In order to deliver information in the clearest and appropriate way throughout a variety of use cases, information is related through the use of various stimuli. Most of the information available to the driver is given visually via the displays (instrument cluster screen and Head Up Display) present in the vehicle. In order to enhance the effectiveness of the visual communication and improve the situation awareness of the driver, the Mediator HMI makes use of LED lighting strips and ambient lighting to keep the driver informed of the current driving mode and time budget, or the time which remains before the system will initiate a takeover request. Auditory and haptic feedback is also used to attract the user's attention and give additional information.

The Mediator HMI communicates with the human driver in a multimodal/multisensory way, by using different stimuli simultaneously. Therefore, the different HMI elements must be synchronized to transmit the relevant information to the driver at any given time. This style of communication is proven to be highly effective, especially in moments when the driver is engaged in non-driving related tasks that stimulate their visual or auditory senses.

Figure 10.2: Information input modalities of the Mediator HMI.

3.3 Mediator Use Cases

The Society of Automotive Engineers (SAE) has defined six automation levels, from "no automation" (level 0), where the driver has full control and responsibility of the driving task, to "full automation" (level 5), where the driver does not need to be involved at any moment. **Within the MEDIATOR project, a more human-centered perspective on the different automation levels has been taken.** To aid in the development and evaluation of the system, the following three semi-automated driving modes were distinguished: **"Continuous Mediation" (CM)** refers to the lowest levels of automation (SAE level 1-2), during which the driver is assisted in the driving task, but must be alert and keep their hand on the wheel at all times. **"Driver in Stand By" (SB)** is consistent with automation levels (SAE level 3) during which the automation can reliably take-over control for short periods of time. In these moments, the driver can perform secondary tasks, but must be ready to take over the driving task on short notice. Finally, **"Time to Sleep" (TtS)** is a higher automation level (SAE level 4), which allows the driver to dedicate longer periods of time to other activities, as they will not be required to take over the driving task. Together with **Manual driving**, these represent the four 'high level' use cases in which the Mediator system is used.

The HMI is required to keep the user informed about the above mentioned driving modes at any given moment. However, in order to improve the clarity of the feedback to the user, a different approach was used for the communication towards the driver, distinguishing three driving modes: **Manual driving, Assisted driving (CM) and Piloted driving, which includes both SB and TtS driving modes.**

To address specific challenges related to the transfer of control, ten narrower use cases were constructed (figure 11). These are detailed in the Mediator project deliverable D1.5, HMI Functional Requirements (Gondelle et al., 2020).

The ten narrow use cases are used by designers of the Mediator HMI as a base for the exploration of the richness of information that must be transmitted to the users, as well as the modalities through which it is communicated. Each of these cases describes a set of actions the HMI must perform to safely mediate the transfer of control between the human driver and vehicle, or to correct human behavior and prevent degraded driving performance. A crucial part of the HMI design is to ensure that the information being communicated during each moment is efficient and facilitates a safe and seamless interaction with the system. As shown in figure XX, a combination of these cases can be used to construct an evaluation scenario, to test the performance of the HMI during several moments of the driving experience.

As this graduation project aims to facilitate the evaluation of the holistic HMI, **it is important to consider the interactions that happen in all use cases, as well as the "during phases", which are characterized by the four driving modes mentioned above.** The "during phases" are driving moments in which the vehicle is not approaching a situation in which a particular action must be taken, as described by the ten use cases, but simply cruising in one of the specified driving modes. In these moments, the information delivered by the system to the driver is mainly related to the current driving mode. During the evaluation, it should be possible to explore different information exchange modalities and measure the driver's responses and behavior in various scenarios.
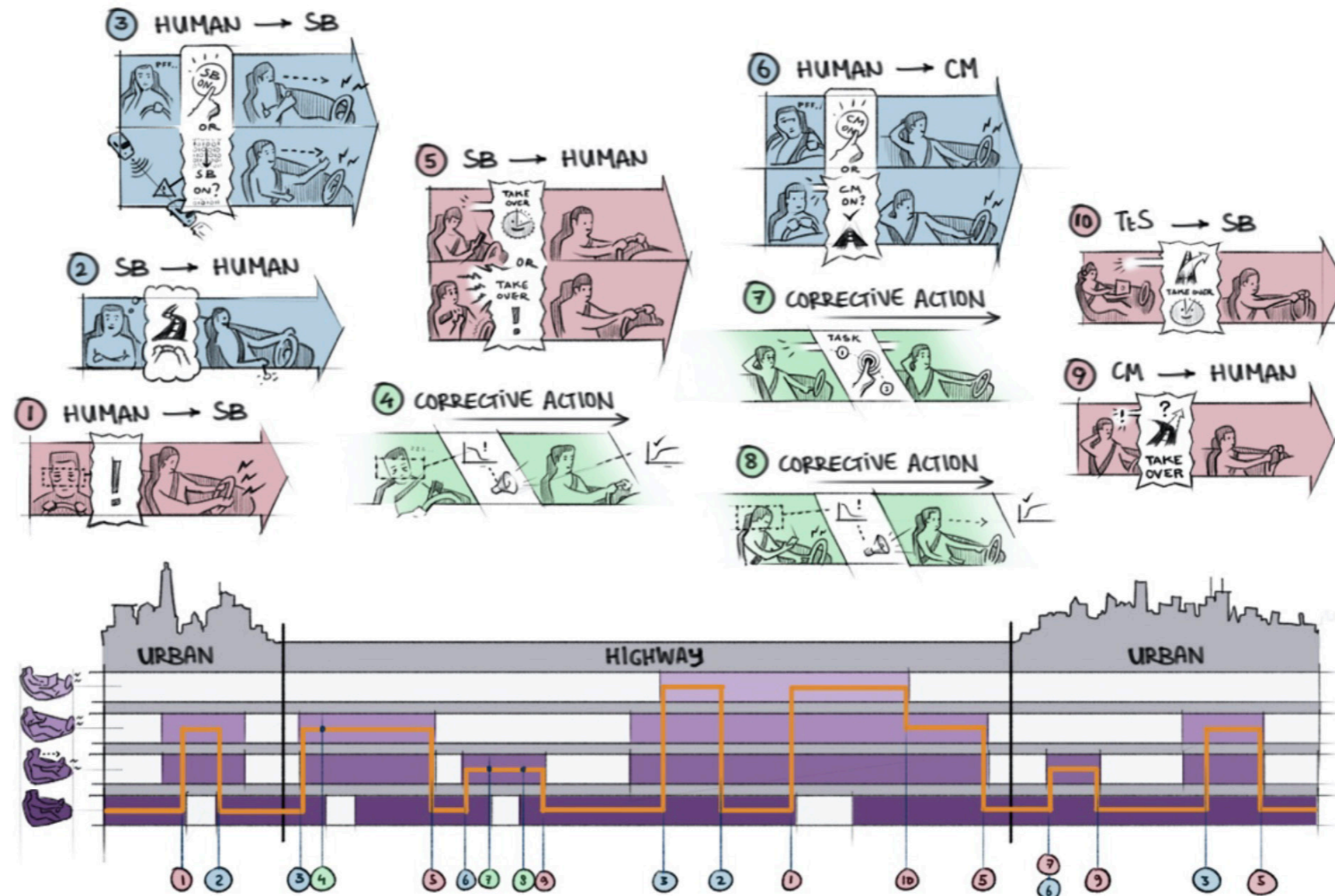
Figure 11: On the top, the ten 'narrow' Mediator use cases, divided into three categories: safety related control transfers (red), comfort related control transfers (blue) and corrective actions (green). On the bottom, a visualization of an imagined scenario and the moment in which various use cases come into play. (Gondelle et al., 2020)

Chapter 3
Key Takeaways

- The HMI has a **holistic design concept** and is meant to deal with multiple challenges simultaneously.

- The Mediator HMI design is made up of **multiple components** that serve different roles in the mediation between driver and vehicle.

- The HMI uses a **multimodal communication style**, transmitting information to the driver through various channels that engage multiple senses simultaneously.

- The types of information that is being exchanged and the ways in which it is communicated are defined based on a set of **predefined use cases and four driving modes**, which capture the whole experience of the system's use.

4

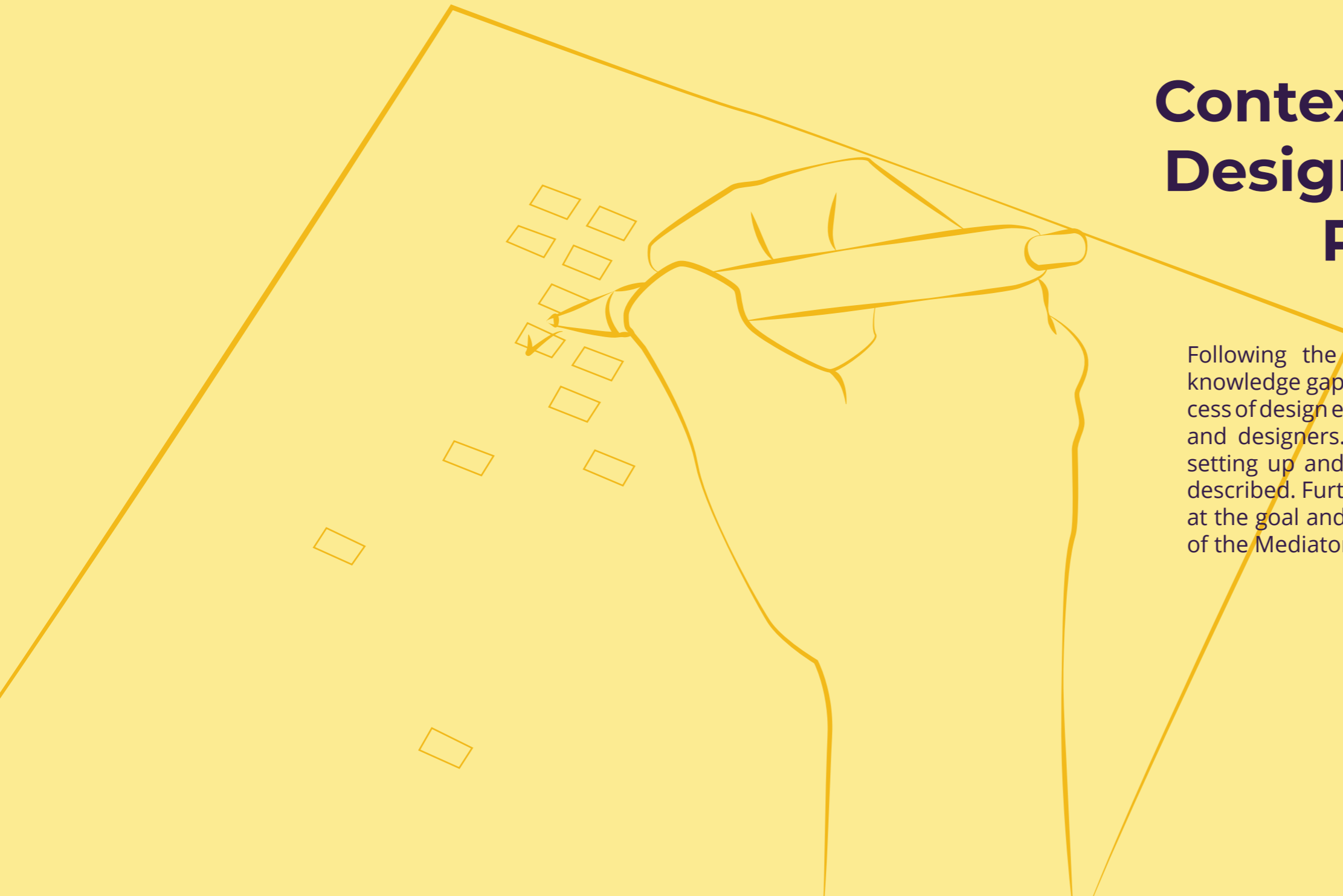# Context Research | Design Evaluation Process

Following the previous research activities, a knowledge gap was identified regarding the process of design evaluation of Mediator researchers and designers. In this chapter, the process of setting up and conducting experiments will be described. Further, we take a more detailed look at the goal and requirements for the evaluation of the Mediator HMI.

4.1 Evaluation Process

To identify how the use of a VR evaluation tool would facilitate researchers and designers in evaluating the Mediator HMI, **it was first necessary to dissect the evaluation process, looking into each step and the different activities that are done while constructing and conducting an experiment.**

After an interview with one of the researchers involved in the Mediator project, the evaluation process was analyzed and synthesized as follows:

1. EVALUATION SETUP

Research Question Definition

The process of setting up an evaluation starts by choosing an area of focus for the research. After analyzing existing literature on the topic and deriving the existing knowledge, researchers are able to narrow down the focus and define specific research questions that will be explored through the experiment.

Constructing the experiment

Once the research questions are defined, researchers must construct the experiment, choosing the conditions and manipulation that have to be researched. For certain experiments, defining a scenario that the participants will follow during the experiment is also necessary. In the scenario, the context and situation of use of the design, which can affect the experience with the product, are defined. The scenario itself can also be more or less defined, depending on the goals of the study. While a highly controlled use case, in which participants experience the same predefined events (e.g. a route with specific obstacles or traffic conditions), can help researchers validate their findings, in the evaluation of the overarching interaction with a product or system, a more natural, uncontrolled setting can give better results as the participants perceive the experience as realistic.

Finally, the data collection methods must be chosen, looking at what information is necessary to answer the research question and the most appropriate methods for recording the data.

2. PILOT EVALUATION

After constructing the experiment, performing a pilot evaluation is advised. This moment can help identify and rectify issues related to the experiment.

3. EVALUATION MOMENT

Introduction

The evaluation starts by introducing the experiment to the participant, explaining the context of the research, and ensuring that the participants understand what they will be experiencing and reacting to. Once the participants understand the terms of the evaluation and, if applicable, the associated risks, they will be asked to sign an informed consent form. Next, the participants are instructed on the actions they need to perform during the evaluation. If relevant to the experiment, a preliminary questionnaire/interview will be conducted.

Experiment

During the experiment, participants are asked to perform the required actions, including interacting with the prototype. Depending on the structure of the performed experiment, researchers might ask a set of predefined questions about what the participants are experiencing, while in other cases the interaction with the participants is kept to a minimum, so that they do not influence the results of the study. In this time, researchers will observe the actions of the participant and record data through various methods. (e.g. video/audio recording, biometric data, etc.).

Follow-up

Once the experiment is concluded, participants are asked to relate their subjective experience. This is done by responding to interviews or questionnaires.

4. ANALYSIS

The final step of the evaluation process is the analysis of the collected data, through which the research questions can be answered.

4.2 Evaluating the Mediator HMI

From the interviews conducted, more information was derived about the type of information researchers are expecting to gather from future experiments. Two main research questions were asked:

1. **What topics will the evaluation of the Mediator HMI focus on and what sort of experiments can be conducted to answer the research questions?**
2. **What sort of data must be collected during the evaluation moment to reliably answer the research questions?**

While it is not possible to predict all of the requirements for the evaluation of the HMI at this stage of its design process, considering the known features and functional requirements of the HMI that have already been defined, we can attempt to answer the above-mentioned questions.

4.2.1 Evaluation Focus

As previously discussed, the Mediator HMI serves several functions that range from managing conventional driving tasks to non-driving-related activities, and supporting the exchange of control between the driver and the automated vehicle (see chapter 3.1). As such, the interaction with the HMI, which happens during all moments of the driving experience and all automated and non-automated driving modes (see chapter 3.3), plays a significant role in the overall experience with the Mediator system. Furthermore, the way in which information pertaining to the active driving mode, imminent mode changes and time-budget is related to the driver is highly important in guaranteeing safety during control transfers and improving the driver's situational awareness.

These main functions of the HMI will represent the focus of future experiments, which will analyze the experience with the various HMI components and identify whether the HMI meets the predefined functional requirements.

The different driving modes that have been defined (Manual, CM, SB and TtS) and the ten use cases, which define the interaction with the HMI in different situations where a control transfer is initiated, as well as corrective actions taken to improve driver fitness, will all be explored during the evaluation of the system. **It is important for researchers to assess the drivers' behavior and experience in all of these scenarios, in order to evaluate the HMI at a holistic level.**

Depending on the specific research questions that will be formulated, different types of experiments will be conducted.

For the purpose of this graduation project, two different types of experiments were defined:

- **Small scale**, or focused, **experiments** are ones that are meant to look into a specific element or function of the design concept. An example of a research question that could be investigated in such an experiment is: *Does the driver understand the time budget that is being communicated by the LED strip on the dashboard of the car while driving in assisted (SB) driving mode?* **These experiments are meant to support the design process of the HMI, informing future decisions and helping to identify points of improvement on the current design concepts.** Because of the focused nature of these experiments, a large amount of control over the experience is desirable, allowing the researchers to manipulate only one variable and, therefore, to extract reliable data by ensuring that other factors do not influence the participants' responses.

- **Holistic experience evaluation** refers to an experiment that looks more broadly at the driver's experience and interaction with the HMI. **Researchers will look into the performance of the HMI in different scenarios and explore how participants interact with the design.** For such experiments, recreating a more natural, realistic experience is desirable, as the participants' reactions will be more genuine when they are fully immersed in the usage scenario.

4.2.2 Data collection

In order to authentically answer their research questions, researchers must be able to collect a variety of reliable data from each experiment.
Three dimensions should be considered in describing what is happening during the interaction with the HMI: *What is the HMI communicating to the user? What is happening in the environment at the moment? What is the participant experiencing?* Recording data related to each of these factors helps paint a full picture of the participant's experience and understand how their reaction is influenced not only by the design, but also by the context of use.

For each of these dimensions, the following data should be collected:

- **HMI feedback:** recording data on the information being conveyed as well as the time in which it is being given.
- **Context:** recording data about what is happening in the environment and the time in which events take place.
- **Experience:** collecting subjective and objective data about the participant's experience and behavior in different moments during the evaluation.

Several data recording methods can be used for each experiment to gain insights into the test participants experience with the prototype: video and audio recordings, interviews, questionnaires, think aloud method (i.e. asking the participant to describe what they are thinking during the evaluation), biometric data (e.g. eye-tracking, heart rate data, etc.), and others. These will be chosen based on what is needed to answer the specific research questions.

An important consideration to be made is related to the recording of a time measure for each data point. It is essential that all measures taken can be synchronized with the events that take place at the time through the use of timestamps. This ensures that results can accurately be connected to each other. For example, if a specific quote recorded from the participant during the evaluation can be linked to a specific time in a recording of an experienced virtual scene, researchers will be able to make more accurate assumptions about what triggered the participant's reaction.
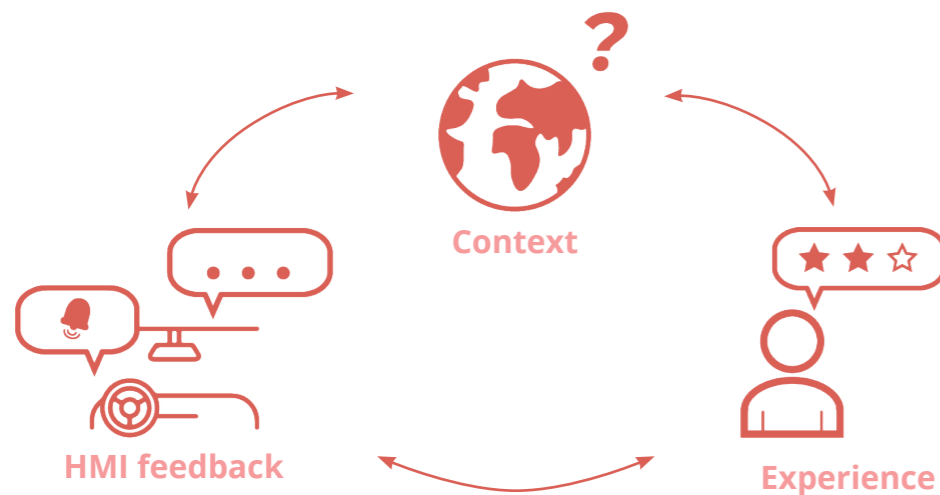

Figure 12: Type of data collected during an experiment.

Chapter 4
Key Takeaways

- The evaluation process contains several steps: **the evaluation set-up, the pilot evaluation, the evaluation moment and the analysis.**

- During the evaluation set-up moment, researchers design an experiment, choosing the right manipulation that will enable them to answer their research questions.

- For the evaluation of the Mediator HMI, different types of experiments can be conducted. **Small scale experiments** focused on answering specific research questions or **holistic experience evaluations**, intended to observe test participants' natural interaction with the HMI.

- Researchers must collect **several forms of data** during the evaluation moment. To get a full picture of the test participants; experience, data **related to the feedback given by the HMI, what is happening in the exterior context, and the user's subjective experience** can be collected.

5

From Research to Design

In the following chapter, the insights gathered from previous research activities and their implications for the design of the Mediator VR evaluation tool will be presented. A list of requirements is created to guide the design, and details regarding the specific design goals for each of the two user groups, and usage scenarios are laid out.

5.1 Design Requirements

Based on the results of the previous research activities, a list of requirements for the VR evaluation tool was formulated, divided into four categories: **VR requirements related to the direct interaction with the HMI, VR requirements related to other experiential factors within the virtual environment, technological requirements and evaluation requirements.**

Technological Requirements:

- It should be possible to use the VR tool on multiple VR systems (Oculus Quest 2 and HTC Vive headsets will both be used in this project).
- Supporting tools (e.g. physical prototypes, haptic devices, etc.) should be used in conjunction with the VR device.

Evaluation Requirements:

- The VR tool should allow researchers/designers the possibility to customize or adapt the content of the virtual environment for each experiment, such as the HMI elements.
- The VR tool should allow researchers/designers to define a scenario for each evaluation.
- The VR tool should allow the collection of data during the evaluation moment (e.g. recordings, timestamps, etc.).
- The VR tool should be used in a physical environment that matches, as much as possible, the content of the virtual environment.

VR Requirements - Interaction with HMI:

- The VR tool should include a realistic vehicle interior model, as well as separate models of the HMI elements.
- The VR tool should realistically simulate the behavior of the various HMI components in various use cases.
- The VR experience should elicit genuine emotional responses to the interaction with the HMI.
- Test participants should interact realistically with all HMI components. A higher degree of interactivity (ability to manipulate the content of the virtual environment) will increase the feeling of immersion.
- During the VR experience, test participants should feel in control of and engaged in the experience.

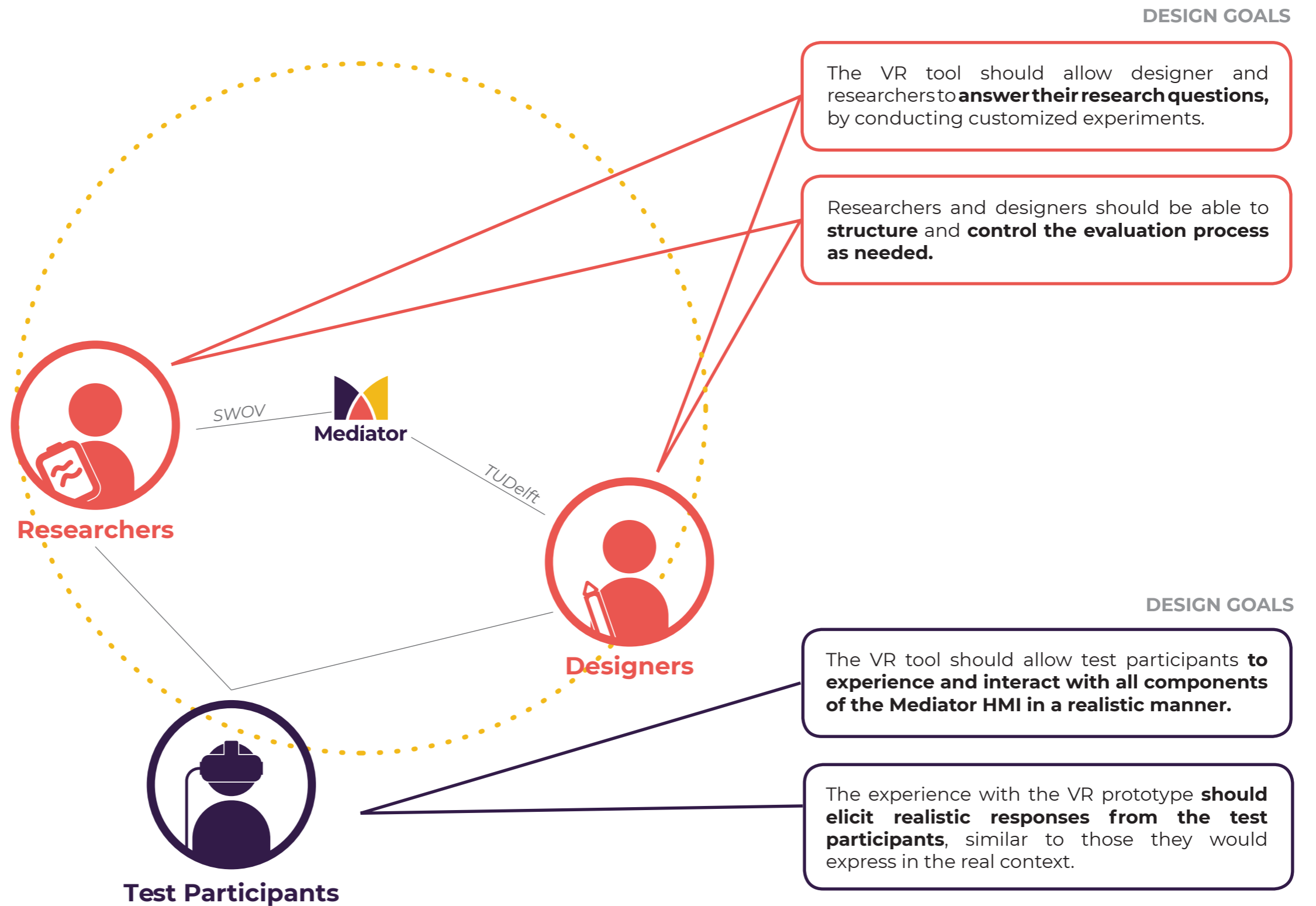## VR Requirements - Other Experiential Factors:

- The VR tool should include an external context of use (road scenario).
- The VR experience should include a realistic use context/driving scenario.

The aforementioned requirements were defined, first of all, with consideration to the interests of SWOV and other Mediator partners in the VR tool. It is important to remember that the focus for this graduation project within the Mediator context is testing the HMI design concepts. The interest in the use of VR technology comes from its ability to convey information, particularly visual information, in a very realistic way. As such, the requirements pertaining to the realism of the HMI components and the immediate context (the interior of the vehicle) are considered most important.

5.2 Users and Design Goals

There are three distinct users of the VR tool: **the test participant, who will experience the VR simulation and interact with the HMI during the evaluation moment, as well as researchers and designers working on the Mediator project, who will be using the tool to conduct the evaluation of the HMI.** Figure 13 shows the users and **details the goals of the design, formulated for each user type with condiseration to their use of the product.**

While researchers and designers have similar goals and needs relating to the use of the VR tool, a difference was identified in their specific needs for the evaluation of the HMI and the way in which the VR tool could benefit them. Specifically, designers can benefit from using the tool in earlier design phases: by conducting small evaluations of design concepts or simply examining them in an immersive 3D environment, they can detect issues early on and improve the quality of the design without the need to build a physical prototype.
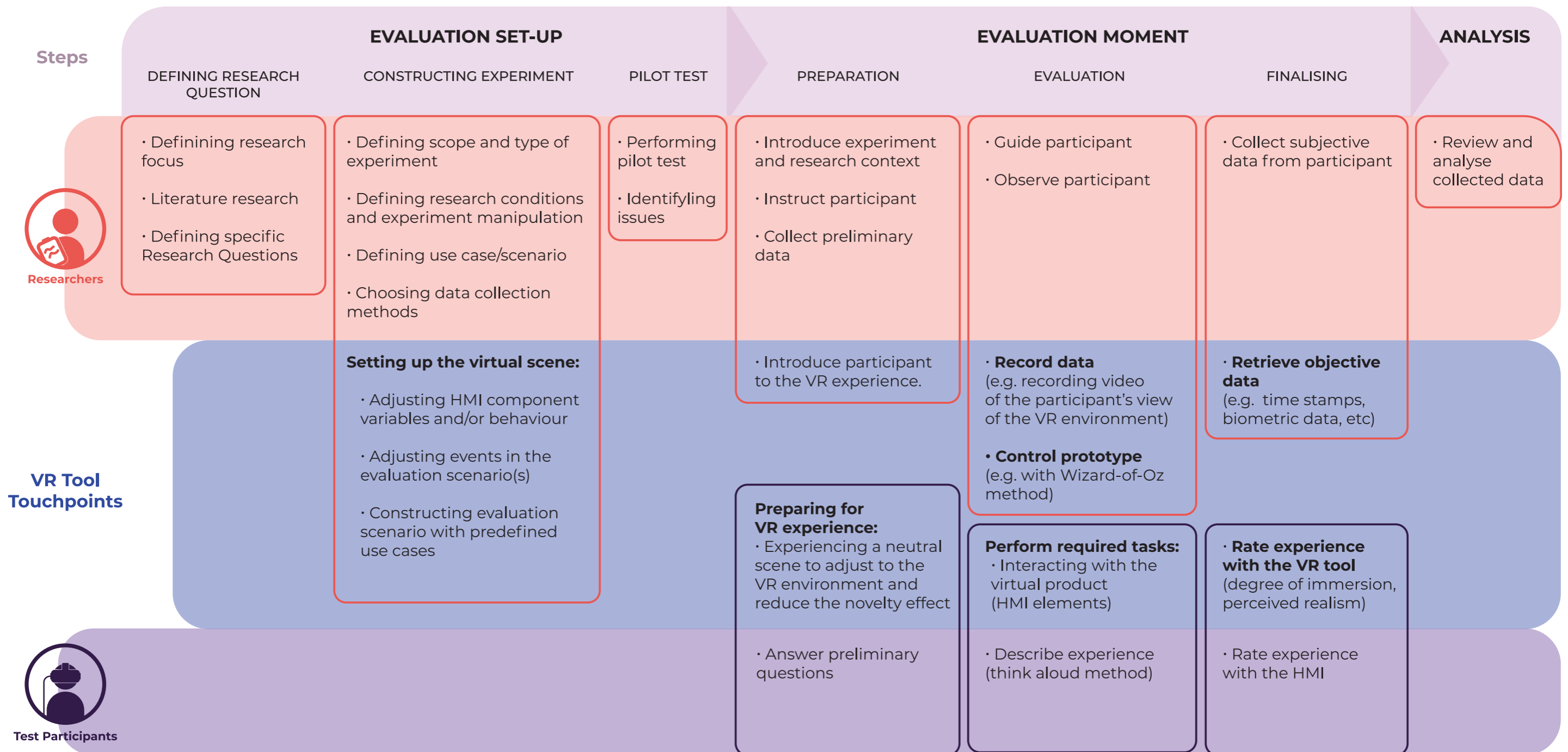
DESIGN GOALS

The VR tool should allow designer and researchers to **answer their research questions,** by conducting customized experiments.

Researchers and designers should be able to **structure** and **control the evaluation process as needed.**

DESIGN GOALS

The VR tool should allow test participants **to experience and interact with all components of the Mediator HMI in a realistic manner.**

The experience with the VR prototype **should elicit realistic responses from the test participants**, similar to those they would express in the real context.

Researchers

SWOV

Mediator

TUDelft

Designers

Test Participants

Figure 13: User types of the Mediator VR Evaluation tool and design goals formulated for each user.

5.3 Use Scenario

Using insights derived from previous research activities, a scenario of the evaluation moment was created. **By mapping out each step in the evaluation journey, from set-up to data analysis, it was possible to identify the moments during** **which the VR tool would be used, and the types of interactions with the tool performed by both the researchers/ designers and the participants that would be taking part in the evaluation**, as shown in figure 14.

Figure 14: Journey map: Evaluation process using the VR tool.

Steps	EVALUATION SET-UP			EVALUATION MOMENT			ANALYSIS
	DEFINING RESEARCH QUESTION	CONSTRUCTING EXPERIMENT	PILOT TEST	PREPARATION	EVALUATION	FINALISING	
Researchers	· Definining research focus · Literature research · Defining specific Research Questions	· Defining scope and type of experiment · Defining research conditions and experiment manipulation · Defining use case/scenario · Choosing data collection methods	· Performing pilot test · Identifyling issues	· Introduce experiment and research context · Instruct participant · Collect preliminary data	· Guide participant · Observe participant	· Collect subjective data from participant	· Review and analyse collected data
VR Tool Touchpoints		**Setting up the virtual scene:** · Adjusting HMI component variables and/or behaviour · Adjusting events in the evaluation scenario(s) · Constructing evaluation scenario with predefined use cases		· Introduce participant to the VR experience. **Preparing for VR experience:** · Experiencing a neutral scene to adjust to the VR environment and reduce the novelty effect · Answer preliminary questions	· **Record data** (e.g. recording video of the participant's view of the VR environment) · **Control prototype** (e.g. with Wizard-of-Oz method) **Perform required tasks:** · Interacting with the virtual product (HMI elements) · Describe experience (think aloud method)	· **Retrieve objective data** (e.g. time stamps, biometric data, etc) · **Rate experience with the VR tool** (degree of immersion, perceived realism) · Rate experience with the HMI	
Test Participants							

5.3.1 Use of the VR tool by the researchers/ designers

One requirement of the VR evaluation tool is to support various evaluation activities in the Mediator project. T**his implies that the tool should provide both researchers and designers working on the Mediator HMI the opportunity to construct a customized experiment within the virtual environment.**

After defining the research questions, researchers must construct an experiment through which they can be faithfully answered. **Based on the need to define the condition and manipulation of the experiment it was derived that the following elements of the virtual environment should be customizable:**

- **HMI elements:** HMI components included in the virtual environment should be fully customizable through various adjustable variables (e.g. color, animations, position, etc). Furthermore, it should be possible to easily add or remove them from a scene.

- **Constructing scenarios:** The Mediator project uses a set of predefined use cases and driving modes (see chapter 2.c) to describe the interaction with the HMI in different scenarios. Using these smaller events, researchers should be able to construct larger, custom scenarios that will play out during the experiment.

- **Environment and use context:** The route of the vehicle should be customized to march the rest of the scene, allowing the researchers to align the events happening on the road to the behavior of the HMI. As they have an influence on the participant's experience, several variables in the outdoor scene (e.g. weather condition, traffic, etc.) should also be customizable.

The customization of the virtual environment's content and scenarios will take place during the evaluation set-up process. **A challenge for the design of the VR tool will be to provide the users with an intuitive and effortless way of applying these changes and supporting them in the activity.**

In the development of the final design, it should be taken into account that the end users of the tool do not have prior experience of VR development or content creation.

5.3.2 Use of the VR tool by the test participants

As already established, the main requirement for the HMI is to allow test participants to realistically experience the Mediator HMI. In order for this to be met, two considerations need to be made related to the use of the VR tool by the test participant:

1. How can a participant's experience with VR technology during the evaluation moment be improved?

In order to prove the validity of their finding, researchers must ensure that test participants experience the VR environment with a certain degree of immersion

and realism. The subjective experience of the realism of a VR environment can vary from person to person. As discussed in chapter 2.3, it has been observed that subjects who experience VR for the first time can be positively biased when evaluating the degree of immersion, which is due to a novelty effect. To counteract this effect, a moment of preparation of the participant to the VR should be reserved before the actual evaluation. At this moment, participants should be exposed to a neutral VR scene, one which does not contain any of the HMI elements, so as not to influence the results of the study. Given some time to experience and adapt to the virtual environment, the novelty effect can be reduced, and also allows participants to experiment and get more comfortable. Another factor which can influence the participant's experience, which is unrelated to the design of the VR interface, is the influence of external stimuli perceived while they are immersed in the VR world. Therefore, it is important to consider the physical environment in which the evaluation will take place. Because the feeling of immersion and presence in the virtual environment is further enhanced when the environment surrounding the user is consistent with the environment viewed in VR, it is advised that the participant is seated in a car seat or a full vehicle prototype during the experiment.

2. What sort of interactions with the HMI should the VR tool afford users?

It is important to remember that to fully evaluate the interaction with the HMI, participants must be immersed in several different driving scenarios that simulate driving in the four distinct driving modes (Manual, CM, SB and TtS), which were described in chapter 3.3. Each of these modes represents a completely different

experience, in which users can engage in different activities and behaviors. The activities that the test participants must perform during the evaluation include interacting with the HMI by engaging in both driving-related and non-drive-related (e.g. media control, consuming entertainment, etc.) tasks. When high-automation driving modes are simulated, it is essential that test participants perceive the affordance of engaging in a non-driving-related or secondary activity, as they would in the real situation. Failing to provide them with this possibility could greatly influence the results of the evaluation. While performing driving related activities, feeling in control of the vehicle, as well as being able to influence HMI behavior, for example, by expressing preference to switch to a different driving mode through an interaction with the HMI, can have a significant influence on the behavior that participants will exhibit during the evaluation and their experience with the design. Therefore, the VR tool should afford test participants a high degree of interactivity with the HMI, as well as other elements of the virtual environment, allowing them to behave as naturally as possible in the given scenarios.
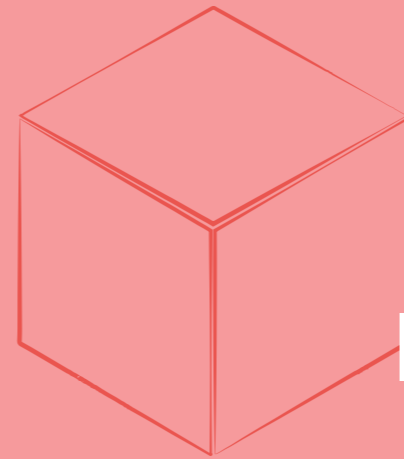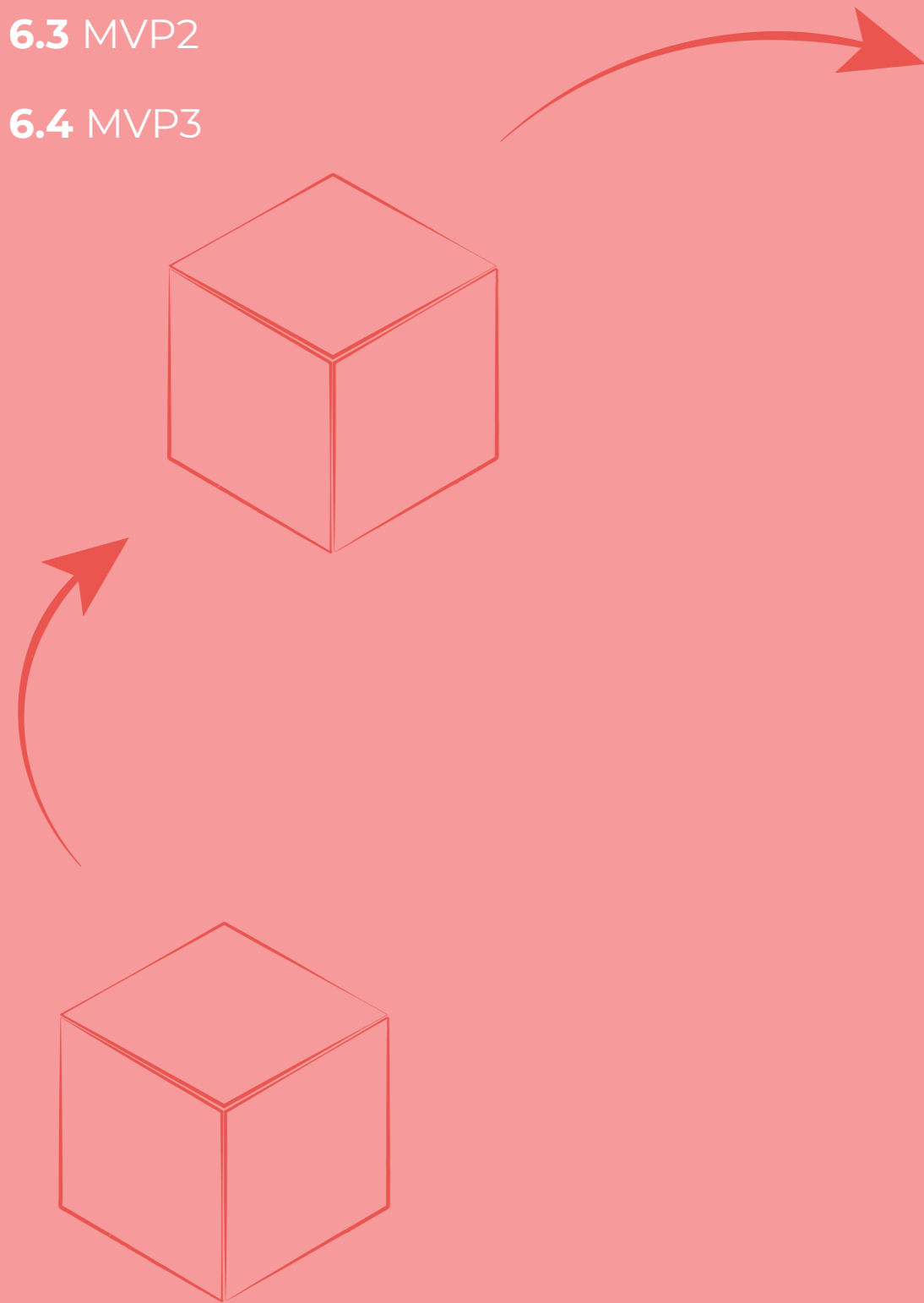
6

Iterative Design Process | Creating MVPs

In this chapter, I describe the process of design, implementation and testing of three MVPs (Minimum Viable Products). The insights gathered from these explorative design activities lead to the definition of the final concept.

6.1 MVP Design Process

An iterative design and prototyping approach was used for the development of the VR evaluation tool. The prototyping activities started early in the project, with the development of three MVPs (minimum viable products). An MVP can be defined as a prototype which includes a minimum set of features, which can be used to collect the maximum amount of insights about a product (Lenarduzzi & Taibi, 2016). **This approach was used to gather early insights into the use of VR technology in the process of design evaluation, by observing interactions with the virtual environment and collecting data about experiences with the prototype.** The MVPs were created based on the Mediator HMI design concepts, as they were at the time the MVP was developed. The goals and requirements for the evaluation of the implemented HMI elements were defined together with the designer. The process of ideation and evaluation of the MVP also provided further insights into the needs specific to the evaluation of the Mediator HMI.
The three MVPs were each evaluated with a small sample of participants (2-3).

With each iteration, the prototype was improved adding new HMI components and functionality, based on the insights resulting from the previous evaluation as well as the continuous collaboration with the mediator design team.
The process that was followed for the creation of each MVP is illustrated in figure 15.

Prototyping

Developing the VR prototype (MVP)

Ideation

Identifying needs and requirements for the evaluation of the Mediator HMI

Testing

Gathering insights for the improvement of the VR tool concept and prototype

Optimizing VR prototype
- Fixing identified issues
- Implementing impovements
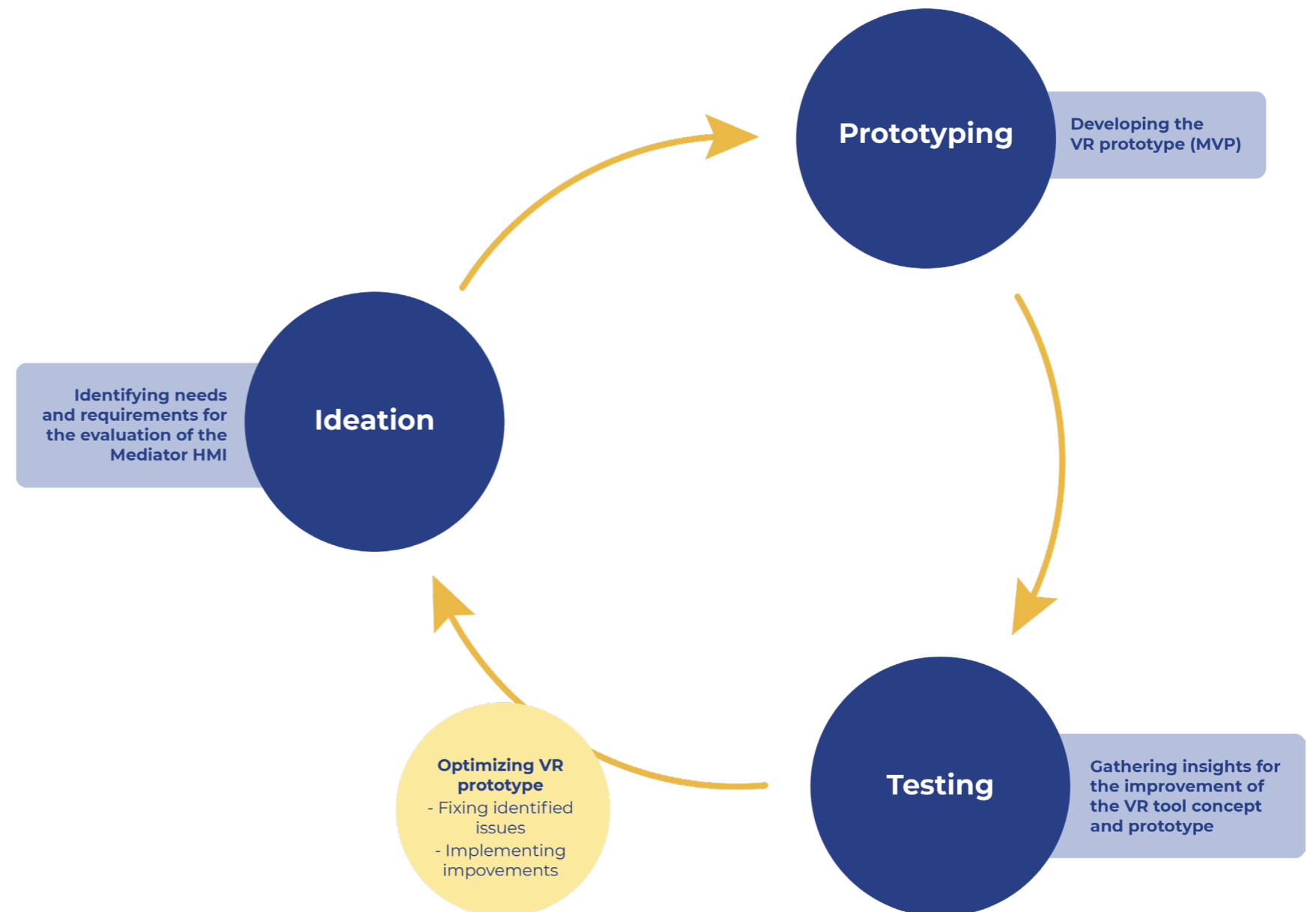
Figure 15: Design process of the three MVPs.

6.2 MVP 1

6.2.1 Ideation

Before creating the first iteration of the VR Evaluation Tool, it was necessary to understand how it could support the evaluation of the HMI concept, and with this understanding, develop a concept that would detail the necessary components of the prototype. To do this, **an interview was set up with the designer of the Mediator HMI to discuss which part of the design could be implemented and how the VR prototype could support the evaluation of the chosen design concept.**

Taking inspiration from the framework proposed by Aromaa et al., 2014 (see chapter 2.5), during the interview, I inquired about the characteristics of the evaluated product, the context in which it would be inserted, the tasks that the user would have to perform during the evaluation, but also about the goal of the evaluation experiment, the research questions it could answer, and the data that should be collected to answer them. These insights were structured and recorded using a form designed to be used as a reference in the design of the MVP, which can be seen in Appendix 2.

Following the discussion, the next points (pages 65 - 67) were defined and used as a basis for the development of the first MVP.

HMI Concept: LED Lighting

Together with the designer, it was decided that the first HMI element to implement into the VR Evaluation Tool would be the Mediator LED lighting, described below:

The LED strip placed on the dashboard (or a-pillars) of the car communicates time budget through its length. The lighting is animated, decreasing towards the driver and remaining in their 30° cone vision.

The lighting strips placed on the steering wheel, lever and foot compartment flicker to alert the driver to a driving mode change when they are looking down.

Driving mode is communicated by the color of the lighting: white for manual driving, amber for assisted driving and purple/turquoise for automated driving.
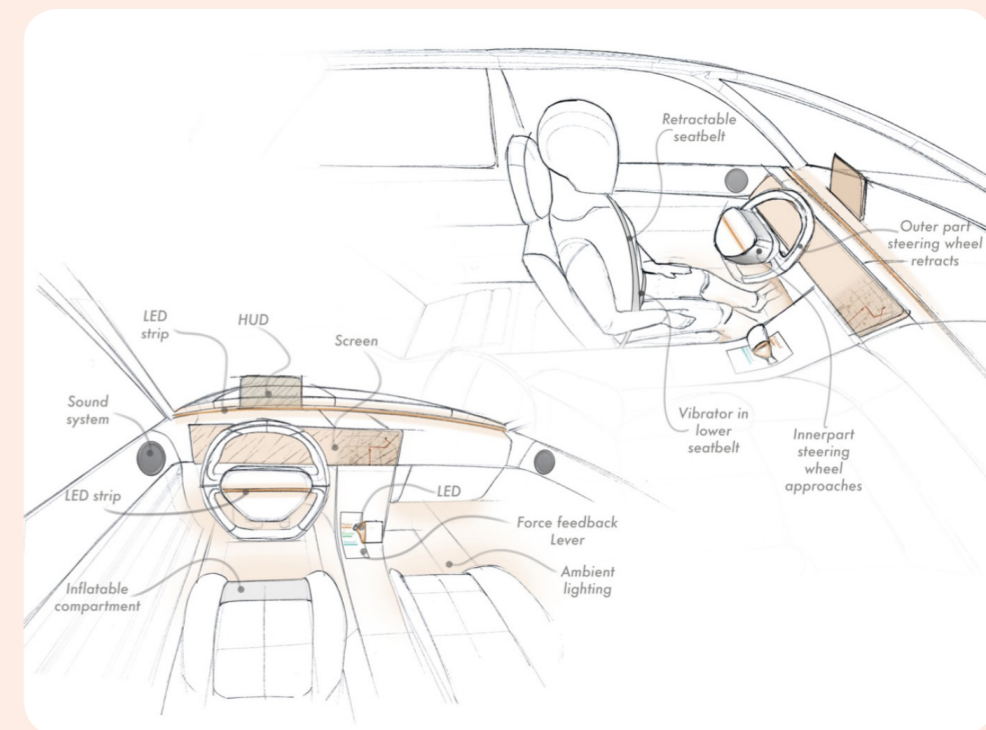
Figure 16: Concept sketch, created by Mediator designer.

Goals of the Evaluation of the HMI concept:

- Comparing the visibility in different locations of the LED strip in the upper parts: a-pillar vs dashboard.
- Understanding if the ambient lighting at the lower level is visible, and if it enhances the understanding of the driving mode, even when the driver is occupied in secondary tasks.
- Understanding if the color and animations of the lighting convey the required information relating to time budget, driving mode, and driving mode changes.

Research questions:

- Is the upper LED lighting more visible when placed on the a-pillars or the dashboard?
- Is it clear if the length of the LED strips communicates time budget and/or urgency? When using only half of the LED strip is it clear the driver must still monitor the situation?
- Does the color and animation (flickering) of the lights in the lower section convey information regarding the driving mode and imminent changes?

Task performed by test participants during the evaluation:

Upper (dashboard or a-pillars) lighting: participants must monitor changes.
Lower lighting: participants should observe changes, even while performing secondary tasks (e.g. looking at a phone, watching a video...).

Context:

The context of use of the Mediator system is the interior of a vehicle, but it extends to the exterior environment, which will vary in terms of the location of the vehicle, time of day and weather conditions. For the evaluation of the lighting design, several contextual factors could influence the user experience.

Outside lighting conditions (e.g. sunlight) might impact the visibility of the LEDs (especially on the dashboard/a-pillars). This offers an opportunity to test in different lighting conditions.

Lighting intensity and color might influence visibility.

The position of the driver (e.g. leaned back on seat) might affect the visibility of the dashboard LED strips.

Data to be collected during the experiment:

During the evaluation, the data should be collected through a questionnaire and observation of the participants, as well as recording their view in the VR environment and their movements during the evaluation.

An example of what could be observed during the experiments is: *Do the participants look up when a driving mode change is signaled? Do participants look away when they see a small time-budget left?*

Not all the above mentioned requirements could be fully satisfied in the timeframe which was dedicated to the development of the MVP, particularly recreating a realistic exterior environment and allowing test participants to engage in secondary activities to evaluate the effectiveness of the ambient lighting when users are distracted by something else. Therefore, the concept for the first iteration was to develop a prototype in which participants could observe the behavior of the Mediator lighting inside a simulated vehicle and rate its effectiveness and visibility, comparing two positions for the upper strips (dashboard and a-pillars).

6.2.2 Prototyping

From a prototyping perspective, **the goal of the first iteration was to create a foundation from which the following prototypes could expand on.** One of the main requirements for the VR tool was to contextualize the HMI design, allowing test participants to experience them in a three-dimensional vehicle.

A realistic vehicle asset[1], shown in figure 16, was used for this purpose. Head and hand tracking functionality was also implemented, allowing the user to freely turn and move inside the vehicle. To give the users a sense of the movement of their hands, they were also given 3D hand models (see figure 18), which were already animated, in anticipation of future interactive functionalities, such as grabbing and turning the wheel. Besides improving the immersion of the experience, hand animations can also suggest affordances available to the users in the virtual environment. At this stage, the animations of the hands included a grabbing motion (showing the hand closing into a fist) and a pinching motion, which are often used in VR applications to indicate the affordance of picking up various objects in the virtual environment. In this particular context, the grabbing gesture induced participants to intuitively grab the wheel, as they would in a real vehicle.

In this iteration, only one element of the Mediator HMI design concept was included, the lighting. As shown in figure 17, this included a number of "LED strips", placed on the wheel, shifter and foot compartments of the vehicle, to create ambient lighting, as well as an "LED strip" following the length of the entire dashboard that, by decreasing from right to left, could indicate to the driver the time budget, or time left in the current driving state. Together, the lights would flash to alert the driver of an upcoming transfer of control, and would change color to symbolize a shift in the driving mode: blue/turquoise for piloted driving, yellow/amber for assisted driving, and white for manual driving.

To represent the behavior of the lights in the VR prototype, a number of animation clips were created for each part: ambient lighting and dashboard LED strip, which also needed to show a decreasing/increasing motion. A solution was needed to easily manage multiple animations, synchronizing them with those of other objects in the scene, and arranging them on a time axis to recreate the entire routine they would display in various use cases.

Figure 17: Virtual environment of MVP1. In the image, the version containing the dashboard and ambient lighting LED strips (in blue) is shown. The virtual prototypes are placed inside of a vehicle asset[1].

To simplify this task, it was chosen to use the Timeline tool included within the Unity Game Engine. This tool allows developers to create complex animated sequences, by combining animation clips and audio clips on a timeline, similar to other video editing software. The use of this tool was beneficial to the project overall. As, in later stages of the development of the prototype, it allowed me to add new HMI elements into existing animation sequences, cutting down on the time required for prototyping. More details about the Timeline tool and how it was used are included in chapter XX..

Figure 18: Hand avatars in MVP1.

1: Vehicle asset was downloaded form the Unity asset store: https://assetstore.unity.com/packages/3d/vehicles/land/realistic-car-hd-01-135301

6.2.3 Testing

After completing the first MVP, a small number of user tests were conducted with the intention to gather insights that could guide the next iteration of the design.

GOAL
In conducting the user tests, the intention was to observe whether participants were able to evaluate the HMI components with the use of a VR simulation, and whether any aspect of the virtual scene prohibited them from doing so.

PROCEDURE
The evaluation of the first MVP was conducted with three naive participants, who had little to no knowledge of the Mediator system and no prior experience with VR use. The evaluations were conducted in a home environment, as shown in figure 19. In the absence of a more suitable set-up, the participants were seated in a rotating office chair throughout the experiment. A short introduction to the Mediator system and the function of the lighting design was given to each participant, after which they were instructed on the use of the VR equipment.

During the experiment, they were exposed to three scenes (see figure 20), showing different behavior of the lighting strips, and asked to describe their experience with the think aloud method. They were asked to imagine themselves in the given context and mimic the behavior that would be expected of them in a driving situation (e.g. holding the wheel when in the manual driving mode). The participants' interaction with the VR environment was observed, noting how the prototype affected their behavior. After the experience, participants were asked to answer two questionnaires. The first contained questions about their understanding of the HMI lighting concept. The purpose of this questionnaire, in the context of this graduation project, was to determine whether participants had enough information from the VR prototype to give detailed answers to the defined research questions. The second questionnaire contained a number of questions related solely to the participants' experience with the VR application, with the purpose of gathering qualitative data related to the perceived realism and immersiveness of the virtual environment and the users' comfort (the full questionnaires can be viewed in the appendix 3).

Figure 19: A participant during the evaluation of MVP1.

Figure 20: Frames taken from the three scenes used in the evaluation of MVP1.

6.2.4 Main Takeaways

The first user tests demonstrated the potential of VR in supporting the evaluation of automotive HMI designs. Despite the simplicity of the design, the richness of the answers given by the three participants regarding the HMI lighting concept indicates that there might be an added value to using this type of technology for conducting design evaluations. In particular, participants were able to express themselves on the positioning of the LED strips and their visibility. *"The LED strip on the right a-pillar was not visible when looking at the road. It might be more useful if I turn right, and I am looking that way."* These types of observations would have been more difficult to make if other materials (e.g. an animation shown on a flat screen) were used for the evaluation.

Overall, the users were positive about the experience with the VR application. All three indicated feeling immersed and perceived the experience as being realistic, especially due to the detail of the vehicle asset which was used.

None of the participants experienced discomfort or other side effects from the use of the technology, which could be attributed to a lack of movement in the experience (Chang et al., 2020).

Multiple opportunities for the improvement of the prototype were also identified during this experiment.

1. **The size of the virtual vehicle:** The car model that was used for the prototypes was bigger compared to real vehicles. This caused participants to feel as though they were not correctly positioned, and certain parts of the car, such as the pedals, would be out of reach. It also affected the visibility of the HMI, as the right side of the vehicle was not within their field of view.

2. **Insufficient interactivity:** Despite being told that the prototype did not include the possibility of interacting with the elements of the virtual environment, upon seeing the hands' grabbing animations, users always attempted to turn the wheel. This indicates that the animated hand avatars were effective in suggesting the affordance of grabbing the wheel; this phenomenon is consistent with that observed by Joy et al. (2021). However, by not being able to interact with the environment as expected they were left disappointed.

3. **Road environment:** The current prototype saw the vehicle standing in an empty world with only a sky on the horizon. The test participants expressed a desire to see the prototype in a broader context. The addition of a road environment would allow them to be more immersed into the experience and imagine themselves in a realistic driving scenario.

4. **The evaluation environment:** An interesting observation to be made is related to the way in which the real world environment in which the evaluation took place affected the participants. The participants were seated in an office chair, which has clear differences compared to the seat of an automobile, the most evident being the height and its ability to rotate. The height of the chair further influenced the users' spatial perception, as the position of their feet was not aligned with the pedals of the virtual car. But, most importantly, the rotation of the chair caused all participants to exhibit unnatural behavior in the virtual environment, as they would rotate around to look at various parts of the vehicle's interior. These findings reinforce the need for certain aspects of the evaluation environment to match the content of the virtual environment, beyond improving the feeling of immersion, as is described by Mütterlein & Hess (2017) and discussed in chapter 2.3.

6.3 MVP 2

6.3.1 Ideation

The second MVP examined different use cases of the VR evaluation tools. Besides the improvement and further development of the VR application, **several considerations were made for the structuring of the prototype in a way which would allow designers/researchers of the Mediator project to use the tool with ease, both in the set-up phase of an experimental scenario and during the evaluation itself.** As part of this concept, together with a new version of the VR application, a simple user guide was developed, which can be found in Appendix 4.

For the development of the second MVP, it was decided, together with the Mediator HMI designer, to include the concept of the **instrument panel screen and the head-up-display (HUD) together with the existing LED strips.** As in the ideation of the first MVP, several details pertaining to the requirement of the prototype for the evaluation of the included HMI concepts were laid down with the help of their designer, as in the development of MVP1. These are described in the following pages (page 76 - 78).

Furthermore, **for this MVP, one of the Mediator narrow Use Cases** (see chapter 3.3) **was recreated using both the LED strip design and the newly developed HMI screen**. Following the scenario laid out in the design of the Mediator system, t**he two components were animated, and their animations were synchronized to display a holistic pattern.**

While thinking about the construction of the second MVP, I looked beyond how the information given by the HMI components could be recreated, and more towards the user's interaction with the virtual environment. In previous tests, participants expressed the desire to touch the wheel, to feel more connected to the act of driving. Therefore, the ability to grab and move objects in space was needed.
In the constructed use case, the users should be able to confirm the request for a transfer of control by switching the position of the gear lever. **To recreate the scenario, it was necessary to consider not only the users' ability to move the gear, but also how this could influence the events shown in the scene.** This issue was related to a second larger question posed during the ideation of this MVP: *How can designers/researchers manage the VR scenario during the evaluation?*

After a brief exploration into the possibilities for the management of the VR experience, namely switching from one scene to another, starting and/or pausing animation timelines, and defining which events to activate next based on the test participant's actions, **it was decided to develop a Wizard-of-Oz system, which would allow test leaders to perform all these actions remotely using a Bluetooth keyboard**. Figure 21 describe the way in which the Wizard -of-Oz system works.

Pre-evaluation Set-up

In the Unity editor, we define which keyboard keys can activate the timelines existing in the scene, using a custom script.

Remote controls

During the evaluation, the test leader uses the keyboard to activate timeline animations at the desired time.

VR Evaluation Participant

Test participants view the scene, with the changes applied by the test leader.

Figure 21: Wizard-of-Oz system concept.

HMI Concept: Instrument Panel Screen

The instrument panel of the Mediator HMI gives visual feedback to the user, adapted to the different driving modes. It informs the driver on the current driving mode and time budget, shows the route through a GPS and other driving-related, such as the speed. The screen's user interface changes at different moments, allowing the use of certain features (infotainment) only at appropriate times.
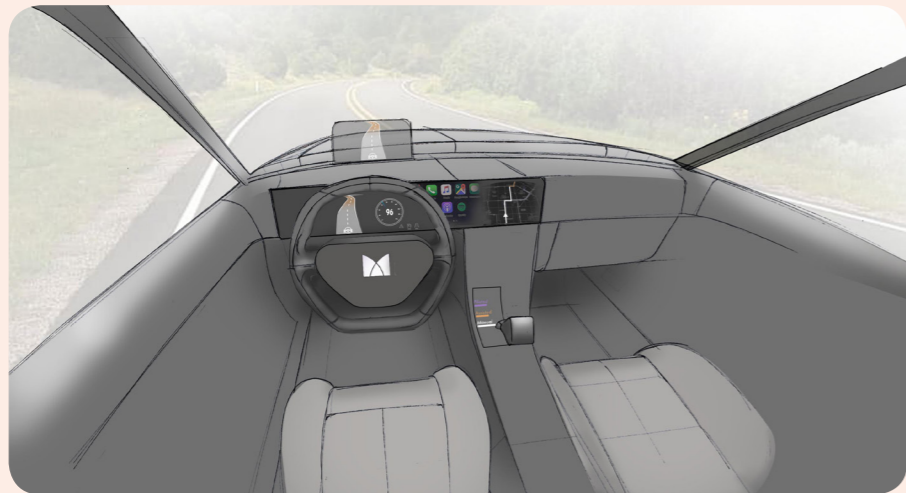

Figure 22.1 & 22.2: Concept sketches, created by Mediator designer.

Goals of the Evaluation of the HMI concept:

The goal of the experiment is to observe how users react to and understand the information displayed on the instrument panel screen, particularly information related to the current driving mode, transfer request and time-budget before the transfer of control is completed.

Research questions:

• Do participants understand the time-budget from the information they are given on the screen?
• Do they understand the urgency of taking over control?
• How does the driver react to the forced takeover initiated by the system?
• Is it clear that after the first alerts, the system does not directly switch to the other, but there is a countdown before the change happens?

Task performed by test participants during the evaluation:

During the evaluation, the user must monitor the information displayed on the screen, also while being engaged in a driving task.

Context:

Equal to the previous MVP, the context is defined by both the interior of the vehicle and the exterior. Contextual factors which might influence the evaluation of the instrument panel screen can include: Lighting conditions, which may reduce the visibility of the screen.
The position of the screen and other elements of the interior design of the vehicle, which may obstruct the view of the UI (e.g. the wheel, which is positioned in front of the screen and covers part of it).

Data to be collected during the experiment:

During the evaluation, the participant is asked to describe their experience and action using the "think aloud" method, as their observations are recorded by the researchers.
After the experience, they are presented with a questionnaire related to their experience and understanding of the information given by the HMI design.

6.3.2 Prototyping

Before implementing the new features defined during the ideation of the second MVP, the prototype was first modified to resolve some issues identified during the previous user tests, as well as to align the virtual environment with the design of the Mediator HMI. **The first step towards optimizing the virtual environment was to modify the asset of the vehicle that was used, as shown in figure 23.**

This asset, originally purchased from the Unity asset store, had a very detailed interior with several buttons, screens and an instrument panel that imitated those we find in contemporary vehicles. To implement the components of the Mediator interface, it was necessary to first strip the existing details of the interior, smooth out the curved dashboard, which was once raised to reveal the instrument panel, and then include new elements of the Mediator HMI design, such as the elongated screen, the head-up-display (HUD), the simplified wheel, with the Mediator logo and a new shifter model.

As the vehicle was perceived as too big during the previous tests, the size was adjusted to give a more realistic feel.

Figure 23: Modified vehicle asset. The large scree, head/up/display, LED lighting, wheel and shifter were changed or added to recreate the Mediator HMI design.

The Mediator use case scenario, which was presented during the evaluation, was created by combining several animations. **To display them in an organized scenario and synchronize the behavior of the different HMI components existing in the scene, the animation clips were again arranged using the Unity Timeline tool.** This tool was chosen for the development of the prototype, not only because it allows for complex scenarios to be created, but also because its use does not require any coding, meaning that modifications can be made by users who do not have knowledge of the C# scripting language. Furthermore, the Timeline Editor looks and functions similarly to other video editing software, making it intuitive to use for people with prior experience of such applications.

The intention behind the use of the Timeline, together with a small user manual, was to allow designers to make necessary changes to the scenarios, during the setup moment of an experiment.

As mentioned previously, for the management of the events displayed in the scene during the evaluation, a Wizard-of-Oz system was created. **By linking a Bluetooth keyboard to the VR headset used, an Oculus Quest 2, it was possible for the test leader to input commands to activate scenes and play or pause animations as desired, without the knowledge of the user participant.**
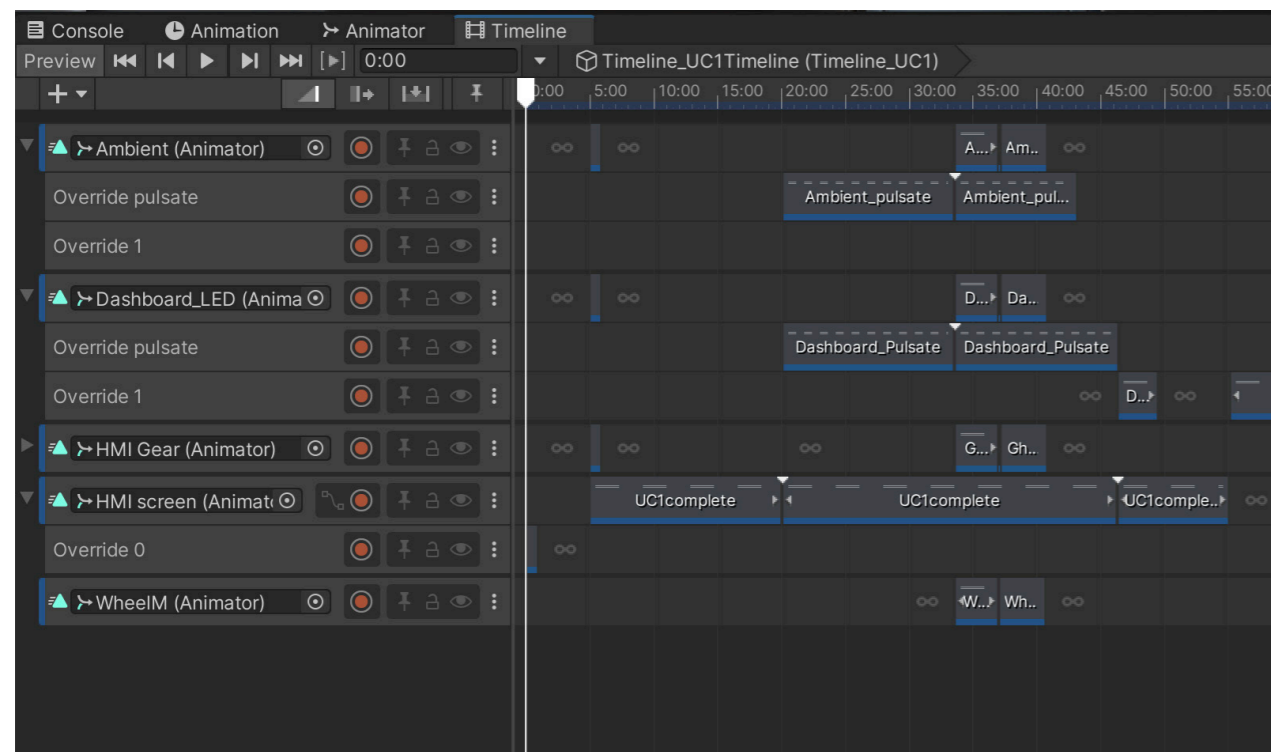
Figure 24: Scenario created using the Timeline tool in Unity.

6.3.3 Testing

The evaluation of the second MVP was divided in two. First, the usability of the Unity project, with the support of the user manual, was tested. Then the VR prototype was evaluated.

The first part of the experiment was conducted with one participant, who is part of the target user group as a designer of the Mediator HMI.

GOAL
The goal of this test was to observe whether a novice user would be able to apply changes to the VR tool in the Unity editor, as well as to gain insight into which type of information was needed to successfully create custom scenes.

PROCEDURE
The participant was asked to apply small changes to the scenario constructed in Unity 3D, following the step-by-step instructions given in the user guide (see Appendix 4). The participant was asked to speak aloud while completing the task, and following the experiment answered a number of open questions, which can be seen in Appendix 5.

The second part of the experiment was conducted with a second participant, who played the role of the "test participant" user type.

GOAL
As for the previous MVP, the goal of this evaluation was to observe the performance of the VR prototype for the evaluation of the Mediator HMI. Additionally, to determine whether the Wizard-of-Oz system was an adequate solution for the management of the events in the virtual environment.

PROCEDURE
The participant was exposed to the VR scene. Their interaction with the VR environment was observed, as they expressed their experience aloud.
During the evaluation, the participant was seated in a vehicle mock-up on a bench that resembles a car seat, as shown in figure 25. Following the evaluation, the participant was asked to fill in two questionnaires: one relating to their understanding of the HMI design, and another relating to their experience with the VR application (see Appendix 5).

Figure 25: The test participant during the evaluation of MVP2.

6.3.4 Main Takeaways

USER GUIDE: EXPERIEMNT SET-UP EVALUATION

Following the first part of the evaluation, related to the user manual, it was clear that users of the VR tool require greater support to be able to independently apply changes to the Unity project. Despite having prior experience with video editing applications, which helped the participant navigate some of the Unity interface, **the Game Engine was perceived as being too complex and overwhelming**. The participant was not able to complete all of the given tasks without support and further explanation of certain features. **These results indicate a need for more in-depth tutorials of the Timeline tool and other Unity features that can support users in applying small changes to the scene.** However, it is expected that more complex modifications, such as creating new animation clips, would still require the support of an expert.

VR PROTOTYPE USABILITY EVALUATION

Compared to the previous prototype, the second MVP saw a small improvement in the participant's experience in the virtual space. **Being seated in a low car bench inside a vehicle mock-up, which more closely resembles the position one has in the driver seat, seemed to improve the perception of being in a car.** However, the position of the participant in the virtual space was still not ideal. *"When looking down, I did not feel like I was sitting on the seat."*

The interaction with the gear lever was recreated using the Wizard-of-Oz technique: when the participant put their hand on the shifter, the test leader activated the switch by pressing a button on a keyboard. **While the participant understood that the shifter responded to their action, the delayed response of the animation had a negative effect on the experience.** It was observed that the participant expressed a sense of confusion when the interaction first occurred, and when being interviewed, this was indicated as one of the reasons the experience felt less similar to reality.

Another important observation that was made by the test participant was regarding the animation of the HMI instrument panel screen in VR. **As this was recreated using a small number of still frames, showing only the larger changes on the display, it affected the participant's interpretation of certain elements on the screen.** For example, the time budget indicator was not immediately understood, as the time was not shown counting down second by second. **This misalignment with the users' past experiences can cause a misinterpretation of the information that is displayed by the HMI and influence the immersion of the VR experience.** Therefore, it is preferable for these details to be taken into account in the final design.

6.4 MVP 3

6.4.1 Ideation

For the design of the final MVP iteration, I collaborated with a fellow TUDelft student, Yujie Shan, whose graduation project *"Human-Machine Interaction Design for Negotiation in Highly Automated Vehicles"* is also part of the Mediator Project and deals with the design of systems negotiation rituals (Shan, 2021).

This collaboration was deemed suitable, as the VR tool prototype was already developed to a point which allowed us to easily implement virtual prototypes of the HMI concept, as described in the following subsection. This enabled the student to evaluate her design in a more realistic virtual environment. **Furthermore, working with another designer of the Mediator HMI, provided an opportunity to observe how the VR tool could be used in practice and identify ways in which it could be improved.**

On pages 85 - 86, a description of the HMI design concept created by the student is given, and the goal for the evaluation of the concept is summarized.

HMI Concept

In this experiment, the VR tool was used to construct a total of six scenes, used to test different experimental conditions related to the student's **three design concepts**, which focused on different aspects of a negotiation ritual. The first concept focused on giving rewards after following recommendations. The second concept focused on using wordings for recommendations to support the driver's decision-making process. The third concept focused on using tones of voice messages that suit different negotiation purposes. For each concept, a scene was developed, which did not contain the correct negotiation mechanism. These were used as a control condition during the evaluation.

In each scene, a scenario played out during which participants were presented with a request to perform a transfer of control by the system. Depending on their preference, they could choose to accept the request or continue driving in the current mode, in which case the negotiation ritual would continue.

Figure 26.1: Concept 1 illustartion, created by Shan (2021).

"Piloted mode is
EXTRA safe & comfort"

Figure 26.2 & 26.3: Concept 2 and 3 illustartions, created by Shan (2021).

Goals of the Evaluation of the HMI concept:

The goal of the evaluation of the three concepts was to identify the strength and pitfalls of HMI design concepts. More specifically, experiments were aimed to figure out which design elements were or were not effective to make the driver follow recommendations and why.

6.4.2 Prototyping

A low fidelity prototype of the concepts was created, building upon the existing HMI elements which were included in the previous iteration of the VR tool, while other components (e.g. the dashboard LED strip and parts of the instrument panel screen's UI) were removed or not entirely used, to adapt the scene to the specific goal of the evaluation, and avoid attracting the test participant's attention towards detail that were not relevant to the concepts.

Each of the six required scenarios was built into a separate Unity scene and constructed using the Timeline tool. While some existing animations (e.g. light of the Mediator logo on the steering wheel changing color, gear lever movement/ interaction) were used, others had to be created. In addition, a number of video clips were imported and displayed on the virtual HMI screen. The video clips were played using a feature of the Timeline tool, the activation track, which can be used to define a timeframe during which a certain element in the scene is active and therefore visible. **Another addition to the prototype were audio clips, given verbal feedback from the Mediator HMI.** These were also inserted into the scenario by attaching them to the existing Timelines as part of an audio track. Using various types of Timeline tracks in the development of the third MVP showed the potential of this feature to adapt the existing VR tool to various types of use cases.

Before building the scenes specific to the evaluation of the design concepts, this version of the prototype was also improved to include some features that were lacking from the previous one. **The interaction with the wheel was improved, allowing users to grab the object with two hands and rotate it around. Grabbing and moving the gear lever in different positions was also made possible.**
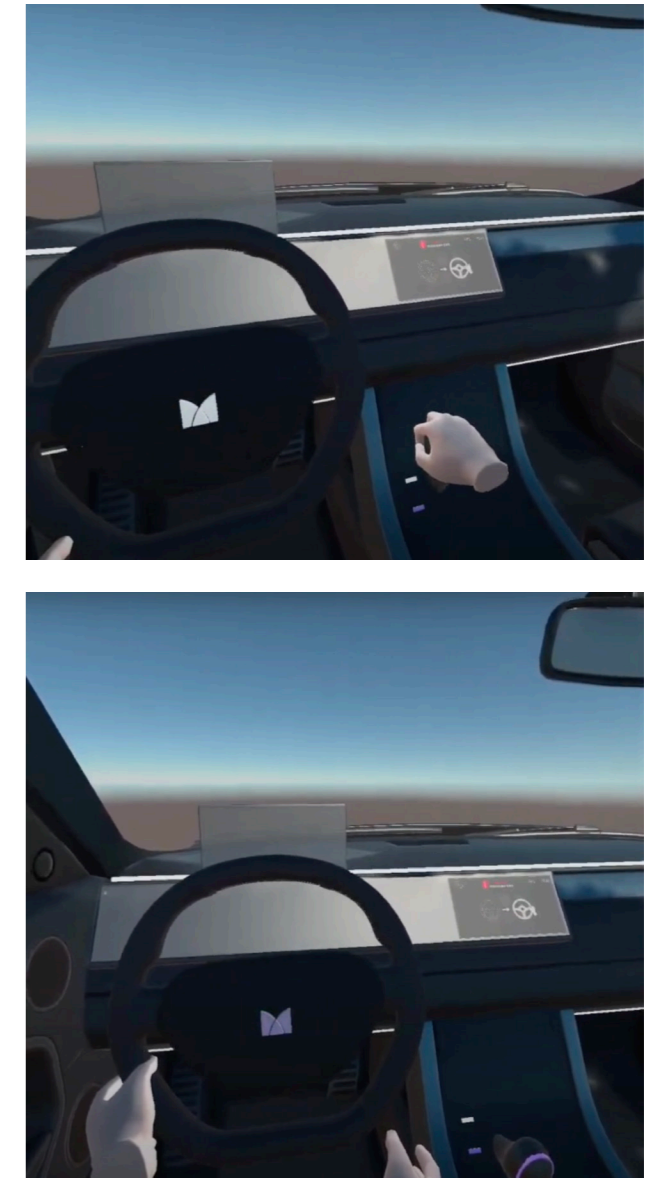
Figure 27 and 28: Examples of the scenes created in MVP3.

As mentioned previously, the test participants were given a choice to confirm or deny the transfer of control request during each scene. This interaction is made possible through the gear lever in the Mediator System. However, due to time constraints and to avoid potential issues caused by a faulty interaction system, during the evaluations, **we opted for the use of the Wizard-of-Oz system that was designed previously. Each time a participant attempted to move the gear lever, the correct interaction would be activated by the test leader.**

Besides activating the gear interaction, the Wizard-of-Oz system was used to manage various parts of the VR application during the experiment. **This system was used to manage the high number of scenes and different timelines that created the scenario in each scene.** Using Unity's Input Action Manager system[1] a series of input actions were created to activate the scenes, which were mapped onto the keyboard keys Q, W, E, R, T, Y and activated scene 1 - 6 respectively. In the same way, keys 1 - 6 were used to play different timelines within each scene as needed, based on the actions of the test participants.

To improve the participant's experience with the first time use of VR equipment and allow them to get accustomed to the interaction with the environment, an empty "preparation scene" was also built in the applications used for the evaluation.

6.4.3 Testing

The evaluation of MVP3 was conducted with the other student. At the end, participants were asked to evaluate both the HMI design concept and their experience with the VR application.

GOAL
The goal was to observe the interaction of the test participants with the virtual environment, particularly with attention to the new features added to the prototype (audio feedback and interaction with the gear lever).

PROCEDURE
The evaluation of the design concepts and the VR experience was conducted with a sample of two participants. As we did not have access to a more suitable space, the evaluation took place in a home environment, and participants were seated on a regular dining chair, as shown in figure 29.

After a brief introduction to the use of VR, allowing the participants to comfortably position the head-mounted display onto their hand and experiment with the interactions available in the VR space, the participants experience each scene, answering the questions posed by my colleague about the design concept after each one. The student led the evaluation with the test participants, and also managed the scenes through the Wizard-of-Oz system, while I observe the interaction of the users with the virtual environment.
When the experiments were over, participants were asked to fill in a questionnaire and answered a few open questions (see Appendix 6) about their experience with the VR prototype.

Figure 29: MVP3 evaluation set-up. The test was lead by the TU Delft student who collaborated with me on the development of the prototype.

1: Unity Input Action Manager: https://docs.unity3d.com/Packages/com.unity.inputsystem@0.9/manual/ActionAssets.html

6.4.4 Main Takeaways

VR PROTOTYPE USABILITY EVALUATION

Generally, the participants reported a positive and immersive experience with the virtual prototype. Similar to the other evaluations, the lack of an exterior environment was cited by both, indicating that it influences the realism of the experience. One participant noted *"I feel like I am watching a wall"*. Other observations concerned the delay caused the use of the Wizard-of-Oz method to fake the interaction with the gear lever. **The delayed response from the object was sometimes confusing to the participants, who did not immediately understand whether they performed the correct action.** Furthermore, this caused the experience to feel less immersive, as they felt like the environment was not responsive to their actions. **The audio feedback given by the HMI was a positive addition, as it helped participants predict the events they would experience in the scenes.** However, it accentuated the lack of other audio stimuli in the VR environment. When asked about the experience with the auditory aspects of the virtual environment, one participant expressed *"In the beginning there was not much audio, it should be included"*. Finally, because of the limited interactions possible with the wheel component (only two parts on the lower side of the wheel could be grabbed using the virtual controllers), the interaction mechanism was considered less natural.

COLLABORATION INSIGHTS

While a user test was not conducted to evaluate the use of the VR tool to construct a custom experiment scenario by the TUDelft graduation student, **our closer collaboration in defining the structure of the scenes and constructing them, as well as in leading the experiments, provided several insights into the way in which a Mediator designer/researcher could use during the set-up and evaluation moments.**
The successful use of the VR tool in this experiment proved its value for this type of application. In a rather short time, three days, the concept could be fully integrated into the VR prototype, which included the creation of custom content (animations, videos and audio files) and the six custom scenes. This resulted in an arguably more immersive and interactive experience than could have been achieved in the same amount of time using other prototyping methods. As a result, the student used the VR tool to evaluate further concepts (Shan, 2021).

Furthermore, **collaborating with a designer who had no prior experience of Unity development revealed what type of information is necessary and useful for a designer to independently navigate the Unity interface when creating their own evaluation scene.** After the experience, the student was invited to participate in a brainstorm session in which we explored the information that should be included in a manual to support the users of the VR tool through this process. More information on the outcomes of this exercise is included in chapter 8.1.

7

Final Design | Mediator VR Evaluation Tool

The insights gathered from both the research activities and the evaluation of the MVPs were translated into the final design concept for the Mediator VR Evaluation tool, which will be described in the following chapter. The final subsection describes the prototyping of the final product developed throughout the course of the graduation project.

7.1 Design Concept

The final design outcome is a VR tool that will facilitate researchers and designers in the evaluation of the Mediator HMI, at different stages of the design process. The concept serves two general functions:

- **Firstly, it allows test participants to experience the Mediator HMI in an immersive environment and in a simulated context, eliciting realistic reactions to the interaction with the design.**

- **Secondly, it allows designers/researchers to evaluate various parts of the Mediator HMI, as well as the holistic design concept, by supporting various evaluation activities.**

The image on the right (figure 30), represents the system architecture of the Mediator VR Evaluation Tool concept, showing the different parts of the system and how they relate to each other.

The final design can be considered in terms of two distinct parts:

1. **The VR Tool's Interface**, which includes the used VR devices, and the Unity 3D project, which is used to build the application.

2. **The virtual environment**, which contains all the elements that make up the simulation that participants experience during the evaluation.

These are represented in figure 30 and will be explained in more detail in the following subchapters.
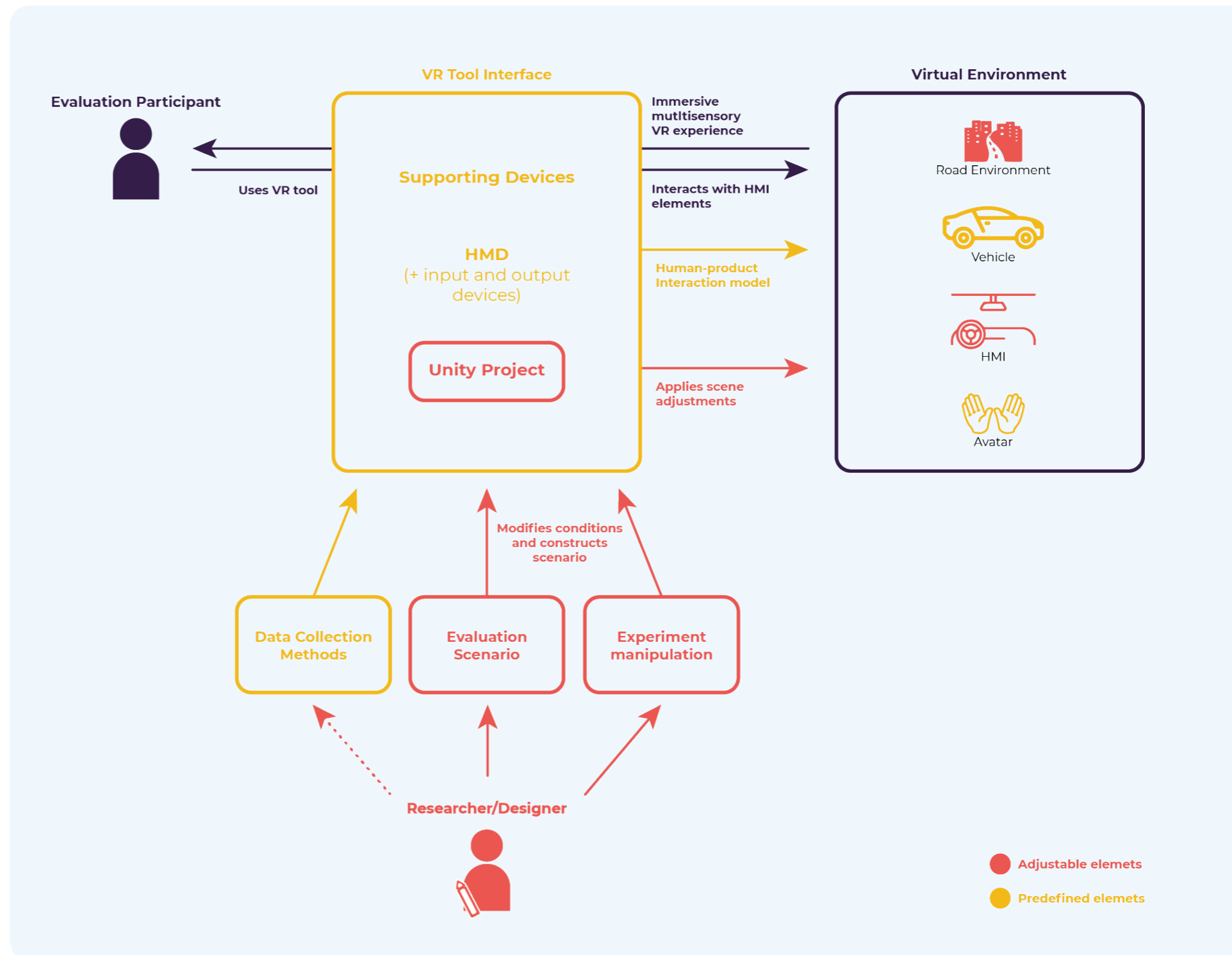
Figure 30: System Architecture, Mediator VR Evaluation Tool

7.1.1 VR tool's Interface

The Interface is the means through which evaluation participants interact with the virtual world in which the use of the Mediator HMI is simulated. The VR devices, including the head-mounted-display, controllers and other tracking devices, are part of the interface and dictate the way in which users can interact with the virtual world. The choice of input/tracking devices that are used for any VR application can bring specific benefits or limitations. For example, using the regular controllers of a commercial VR device comes with reliable tracking of the users' hands position, but it provides a less natural interaction and impedes the possibility of recreating a realistic tactical experience of the evaluated design.

To enhance the potential of the VR Interface, a number of supporting devices can be used. These are described as devices which are paired with the head-mounted-display to provide additional feedback to the user or to allow for different interaction models to be set in place. These can range from regular physical objects which the users can interact with in the real world to match the experience of the virtual world to other input/output devices through which users can interact directly with virtual objects. **An ideal set-up for the Mediator VR Evaluation Tool includes the use of several supporting devices: a real car seat, to give the illusion of seating inside a vehicle; a connected wheel, the rotation of which is tracked and mimicked into the virtual space; a physical prototype of the Mediator gear lever, which is connected to the VR application, allowing users to influence the events in the virtual space in real time; haptic devices, such as vibrators placed on a seatbelt, to give haptic feedback as per the design of the Mediator HMI.** Only through the use of such supporting devices can test participants experience the Mediator design on a holistic level.

Also part of the VR tool's Interface is the software through which the virtual space is rendered and the interactions are defined. **The Mediator VR Evaluation Tool was created with the Unity 3D Game Engine**, which was used to build the virtual environment and recreate the experience of interacting with the HMI design concepts.

7.1.2 Virtual Environment

The Virtual Environment is the digital space and all of the elements within it, which the users view and interact with through the use of VR head-mounted-display and peripheral devices.

The Virtual Environment designed for the evaluation of the Mediator HMI contains four key elements: **the HMI components, the vehicle, the road environment and the users' avatar.**

The HMI components represent the digital prototypes of the evaluated designs and are consistent with various parts of the HMI design, such as the LED lighting, the instrument panel screen, the gear lever, etc. The VR tool includes all Mediator HMI components in order to support the evaluation of the holistic design. These components are developed in a way that allows users to experience the design to the highest possible degree of realism. As such, they accurately reflect the form and behavior of the HMI, being animated to display specific characteristics in different usage scenarios.
When experiencing the virtual environment, test participants will be able to view the behavior of these components in various driving scenarios, and also to interact with them, affecting the virtual space by being able to move objects or influencing the course of events in a given scenario.

To add a context to the HMI design, it is displayed inside **a realistic-looking 3D model of a vehicle**. This allows users to experience the Mediator system in a believable way, helping them feel immersed. Viewing themselves inside of a car is not enough, however, for the test participants to fully imagine themselves in a real driving situation. To achieve this, it is necessary to include **an environment on the exterior of the vehicle, a road environment**. In order to accurately evaluate the experience with the HMI in scenarios in which users should be involved in the act of driving the vehicle, it is necessary for test participants to feel in control of the vehicle's movement on the road and be able to affect the environment they are seeing outside of the vehicle. Therefore, the road environment responds to the user's action of steering of the virtual wheel, simulating a turn in the vehicle's direction.

For users to be able to track the movement of their own body in the virtual environment, **a representation of it, or avatar**, is needed. Users of the Mediator VR Evaluation Tool will be able to see their hands in an anatomically correct yet stylized image. This simplified view of the body in VR is sufficient for users to perform interactions with the objects in the space naturally, as they are able to see the position of their hands and their movement, which is consistent with their experience of reality. The hands are given a set of animations, including gripping or tightening the hand into a fist. This hand gesture indicates to the user the possibility of specific interactions, for example grabbing and moving objects, like the gear and wheel.

7.2 Design Scope

Given the short timeframe dedicated to this graduation project, it is clear that the development of a final prototype that would satisfy the vision for the Mediator VR Evaluation Tool was not possible. As such, a narrowed down scope for the design needed to be defined.

The definition of the design scope started by considering which aspects of the VR Evaluation tool is most important within the context of the Mediator project. The intention is to develop a prototype that can be used for the evaluation of the HMI design in the months following this graduation project, with minimal changes or improvements. Therefore, more importance was given to including the HMI components within the virtual environment and animating them in order to recreate various scenarios of possible interactions with the Mediator system.

LIMITATIONS

One limitation for the intended development of the tool is posed by the devices that were available for the prototyping of the final product. **While the concept indicates a need for the use of supporting devices to enhance the interaction with the Mediator HMI components, these could not be included during the course of this project.** The development of such features requires a significant amount of time for the creation of physical prototypes that can be connected to the VR application. Because of this, **it was decided to continue with the use of the VR controllers,** which were also used for the development of the three

MVPs, to facilitate the interaction with the objects in the virtual environment. *While this interaction is not fully aligned with the experience of physically touching these components, the evaluation of the MVPs indicates that test participants are still able to feel immersed in the experience and to interact with the prototype.* To maintain an element that would stimulate the test participants' tactile sense and hopefully enhance their feeling of being inside of a vehicle, it was decided to use a car seat for the evaluations of the final prototype (chapter 9.1).

Another compromise was made in the development of the virtual environment that is experienced during the evaluation moment. The most important part of the virtual environment is represented by the Mediator HMI components. It is important for those to match, as closely as possible, the design concepts, in order for the evaluation supported by the VR tool to generate relevant and realistic responses from test participants. Therefore, **the design of these virtual prototypes and the recreation of their behaviour through a series of animations was given priority within this graduation project.** However, due to time constraints and the need to adapt the VR prototypes to the changing HMI design at various stages of the project, **certain elements were not optimised as desired**. In particular, it was noted during the evaluation of the second MVP that the animation of the HMI instrument panel screen and head-up-display needs to be more fluid and match the way it would appear in real life. Not having access to the final animations of the two displays, it was decided to only show the still frames that were currently designed. Similarly, the form of the HMI gear lever included in the final prototype does not match the design created by a

TUDelft student team in parallel with this graduation project. Taking inspiration from the interaction model designed for the gear lever concept, a similar L-shaped for the selection of the driving mode was recreated. However, in the future, the model will need to be updated to appropriately fit the design.

Besides those details related to the HMI components, **the development of an interactive road environment was defined as being out of scope.** The insight gathered from the evaluation of the MVPs design in the exploration phase of this project indicates a strong desire from test participants to view a road environment on the outside of the vehicle. Because of this, it was necessary to include an element that would give users a sense of being on the road. However, because of the limited time remaining for the project, the possibility of creating a fully interactive world, in which users could drive the vehicle and to which the HMI would respond, was seen as too ambitious. Instead, the addition of a realistic exterior world was limited to a view of a 360-degree photosphere on which an image of a road is projected.

7.3 Tool Customization

To satisfy the need of the Mediator designers and researchers to easily construct custom experiments for the evaluation of the HMI, **some elements of the system are defined as adjustable, while others will be predefined** (see image 30).

Predefined elements are ones that do not need to be adjusted or changed for each evaluation. These elements, which include the VR hardware, supporting devices and data collection models built into the interface could easily be defined, based on identified requirements, to meet the needs for the evaluation of the HMI in different experiments.

Adjustable elements refer to those parts of the system that need to be adapted for each evaluation. In the research phase, it was identified that researchers need to construct customised experiments to answer their research questions. It is necessary for the tool to allow some flexibility in defining the evaluation scenario, or the context of use (defined as a specific exterior road scenario) in which the interaction with the HMI will be tested, as well as in manipulating details of the HMI design in order to test participants' reactions in various conditions.

In order to support this particular use of the tool, the possibility of creating a custom interface, which users could access to easily apply changes to the virtual environment and set it up as desired for each experiment. However, due to the complexity of the prototype that was developed during this graduation project (chapter 7.4) and the extent of changes to the content of the virtual environment that is predicted to be necessary in the future, it was decided to not create this type of interface. It was clear that **this design would have greatly limited the customization choices of the user group and would not allow for the current prototype to be adapted to the constantly changing design of the Mediator HMI,** which was still in the development phase. Furthermore, to build such an interface with all of the necessary features would require a significant amount of time that was not available in this graduation project, therefore it was defined as out of scope. Instead, **the decision was made to instruct users on how to access parts of the virtual designs directly in the Unity Game Engine.**
It was deemed necessary to support the use of the VR tool by researchers and designers by providing them with a user manual, which is detailed in chapter 8.

7.4 Final Prototype

As mentioned previously, the final prototype of the Mediator VR Evaluation Tool was developed using Unity 3D Game Engine. With the final version of the prototype, users can view the interactive virtual environment and interact with it using a VR HMD (head-mounted-display) and controllers. The structure of the prototype can be considered in three parts:

- **The VR interaction system**
- **The virtual environment**
- **The animation system**

7.4.1 The VR Interaction System

The first consideration for building the prototype was setting up the project to allow for it to be viewed using an HMD device. For this purpose, a number of available tools for the Unity platform were used.

One requirement of the prototype was the possibility to run it on multiple VR devices. Specifically, the HTC Vive Pro, which is owned by SWOV, and Oculus Quest 2, which was mainly used thought this graduation project for prototyping and testing. This was due to the restrictions related to the Covid-19 pandemic,

which forced me to work from home with limited access to the HTC devices for the majority of the project's duration. Unity's XR plug-in framework[1] was used to support development for both VR platforms and was combined with the XR Interaction Toolkit[2], a system which allows basic interactions in VR spaces through the use of various input devices (e.g. the HMD device and VR controllers).

The prototype allows the users to move and interact with objects within the virtual scene. All interactions were created using XR Interaction Toolkit's XR Rig, Interactor and Interactable components (see figure 31), which are already set up to allow basic actions (e.g. grabing, moving, throwing) in VR.

Interactors
Interactor components handle the actions of hovering and selecting objects in the world. Any object with an Interactable component is registered with an Interaction Manager and checked each frame for the list of possible objects it can hover or select.

Interactables
Interactables are objects in a Scene that an Interactor can hover, select, and activate. By default, all Interactables can be affected by all Interactors. You can change this behavior by grouping Interactors and Interactables into complementary Interaction Managers. The Interactable defines the behavior of Hover, Select, and Activate. The same Interactor might be able to pick up and throw a ball, shoot a gun, or press a 3D button on a keypad.

Figure 31: Defscription of Interactor and Interactable components, retrieved from docs.unity3d.com [2].

1: XR plug-in framework: https://docs.unity3d.com/Manual/XRPluginArchitecture.html
2: XR Interaction Toolkit: https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@1.0/manual/index.html

The XR Rig represents the head and hands in the virtual world. It contains several preconfigured components, including the XR Controller, that defines which actions should be performed by various controller inputs, as well as an Interactor component on each hand.

Two physical interactions, shown in figures 32, 33.1 and 33.2, are available:

1. **The wheel can be grabbed and rotated by the user** when they perform the grabbing action (by pressing the predefined grab button on a VR controller). The wheel object contains four different grab points (Intractable components). When they are selected using the hand Interactor, they follow its position, rotating the wheel on the y axis, around a fixed point.

2. **The gear lever can be grabbed and moved around a fixed point, whit a limited range of motion around the x and y axes.** When it is released at various points around its path, it will interact with one of four Socket Interactor[1] components, which allow the object to snap a position representing different driving modes (neutral, manual, assisted and piloted). Using the **Interactor Events** it is possible to assign specific actions, for example triggering a different behaviour from the HMI, to happen when one of the four Socket Interactors is selected. Events were also used to give users visual feedback regarding the position of the gear lever by turining on a small LED in the color of the selected driving mode, as shown in figure 33.1 and 33.2.

1: Socket Interactor: https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@0.0/api/UnityEngine.XR.Interaction.Toolkit.XRSocketInteractor.html

Figure 32: Wheel interactions. Users can grab the wheel from one of the four grabpoints using one or both hands.
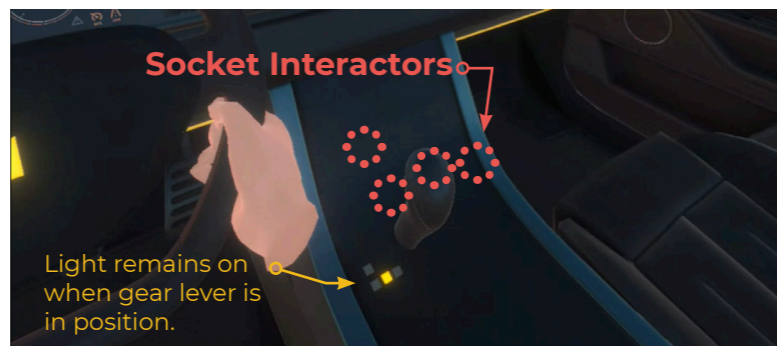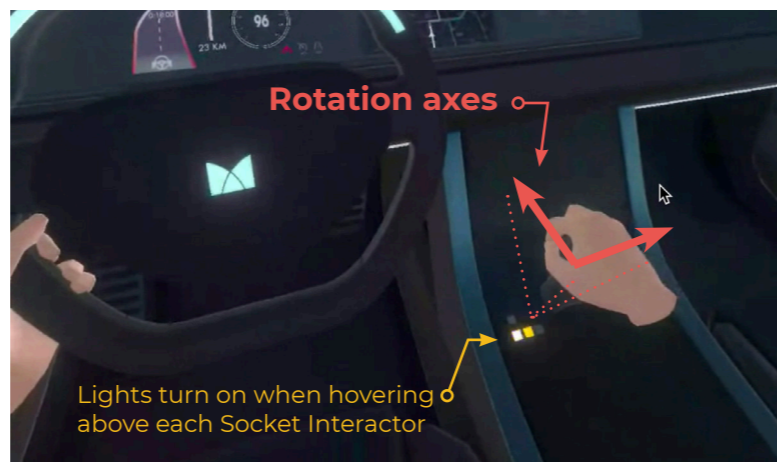
Figure 33.1 and 33.2: Gear lever interaction. Users can grab the lever and rotate it as showin in the image. As the lever hovers over the Socket Interactors, the lights turn on. When the lever snaps into one position, the light will remain on.

7.4.2 The Virtual Environment

The final product includes five elements that represent different parts of the HMI, as shown in figure XX:

- **The Wheel**
- **The Gear Lever**
- **The Screen**
- **The HUD (head-up-display)**
- **The LED lighting strips.**

These objects are constructed as Prefabs, or prefabricated objects, in Unity. They are complete with components and properties that give them the look and functionality of the HMI design.

Other elements included in the scene are the realistic vehicle 3D model, which was discussed in chapters 6.2.2 and 6.3.2, and an exterior environment (see figure 35).

To give the users the illusion of being inside of a three-dimensional world, I opted to display a panoramic image around the users (see figure 34). The 360-degree images are projected onto an inverted sphere, meaning that the faces of the inside of the three-dimensional model are rendered rather than those on the outside.

Figure 34: Exterior environment included in the final prototype.

Head-Up-Display (HUD)

TURN
RIGHT

200 M

Screen

LED strips

TURN
RIGHT

200 M

96

14°C　10:39

Gear Lever

Wheel
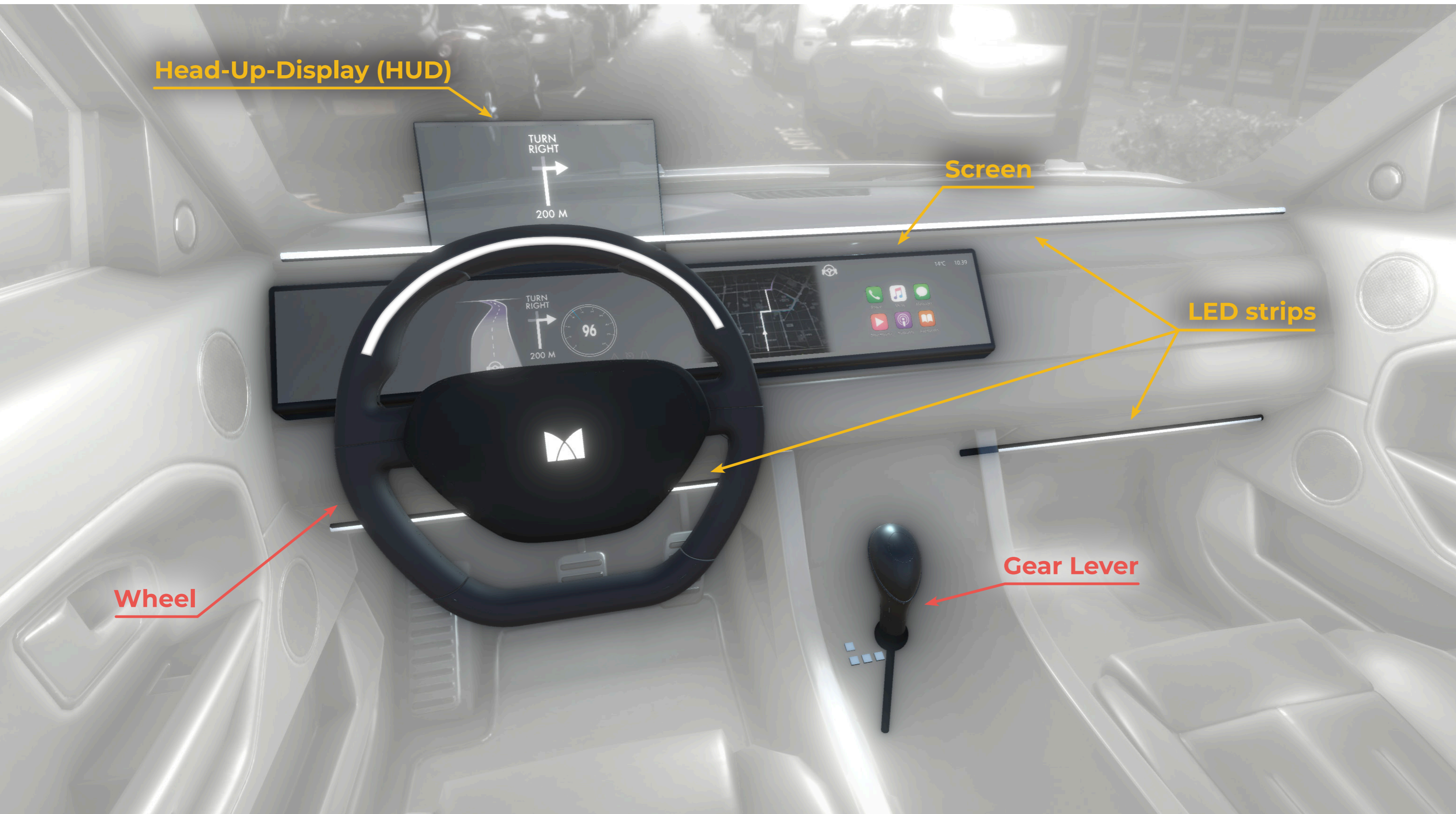
Figure 35: HMI prefabs included in the final prototype.

7.4.3 The Animation System

An important feature of the prototype is the animation of the Mediator HMI components. Animations allow changes to be applied to each object, recreating the way they would behave in various driving modes and use cases (chapter 3.3) for example, displaying different information of the screen, changing the colour of the ambient lighting, etc. Throughout a driving scenario, multiple changes are reflected across the various elements of the holistic HMI design in a synchronised way. To manage all the required animations I chose to make use of the Unity Timeline tool[1]. **This tool allows creating complex animation sequences of multiple objects within the scene**, by simply laying out animation clips in the desired order along a time axis. The use of the Timeline requires little to no coding, which made it an ideal solution for the rapid implementation of multiple scenarios throughout the project. Furthermore, the Timeline editor (figure 36), which resembles other video-editing of animation software, allows for each sequence to be easily modified, which is of importance for the future use of the VR tool.

The Mediator VR Evaluation Tool includes multiple Timeline assets, which represent different driving modes and use case scenarios (chapter 3.3), as defined by the Mediator HMI design.
Multiple Timeline assets can be included in a single scene, allowing for the construction of complex scenarios.

Figure 37 explains the logic for the use of multiple Timeline sequences in a Unity scene. **As we can see, the use of multiple Timelines also allows creating interactive sequences, in which the actions of the user affect the next sequence of events.**

Two different solutions are available to activate the correct animation sequence after a user interaction. As mentioned previously, this is possible by using the interaction with the gear lever object. **When users move the lever into one of the Socket Interactors, an event can be set us to play the correct Timeline.** Another possibility is the use of the Wizard-of-Oz method, described in chapters 6.3.2 and 6.4.2, which allows the test leaders to activate the correct timelines
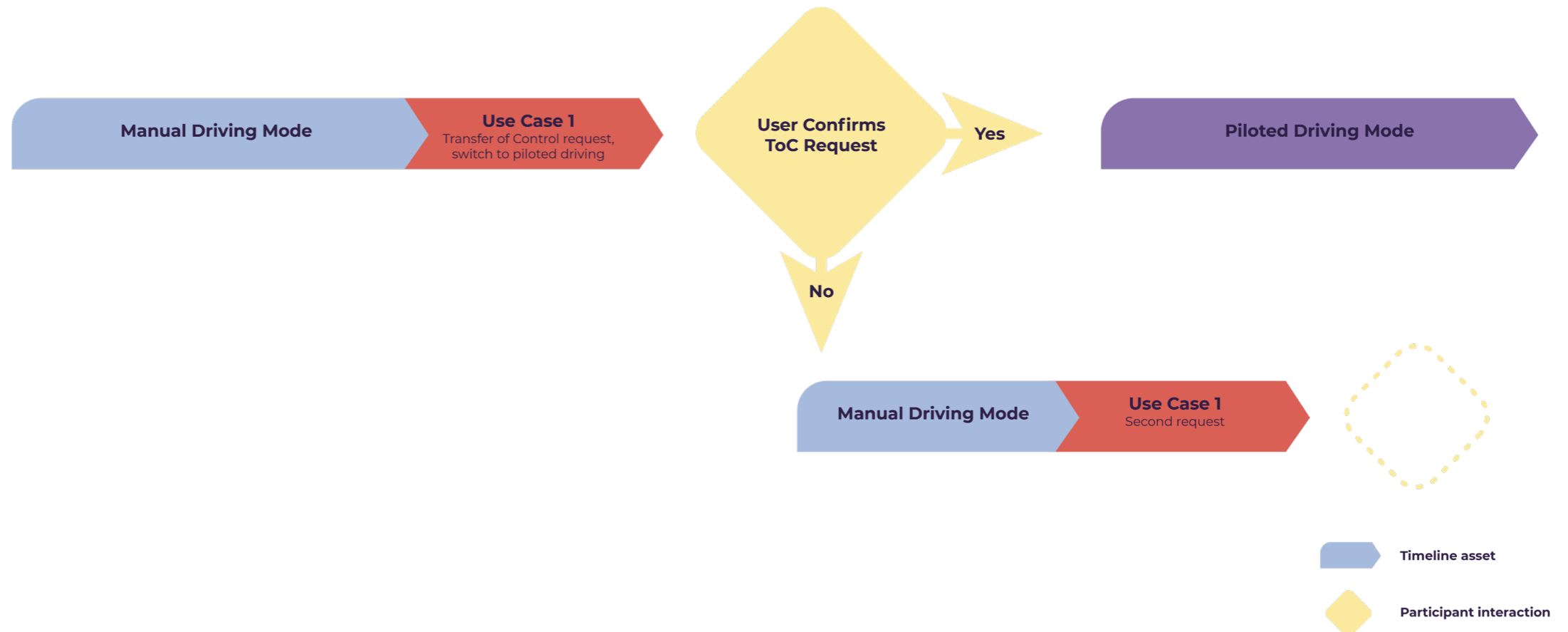
remotely through the use of a Bluetooth keyboard. These solutions are described in higher detail in the User Manual, which is included in Appendix 7.
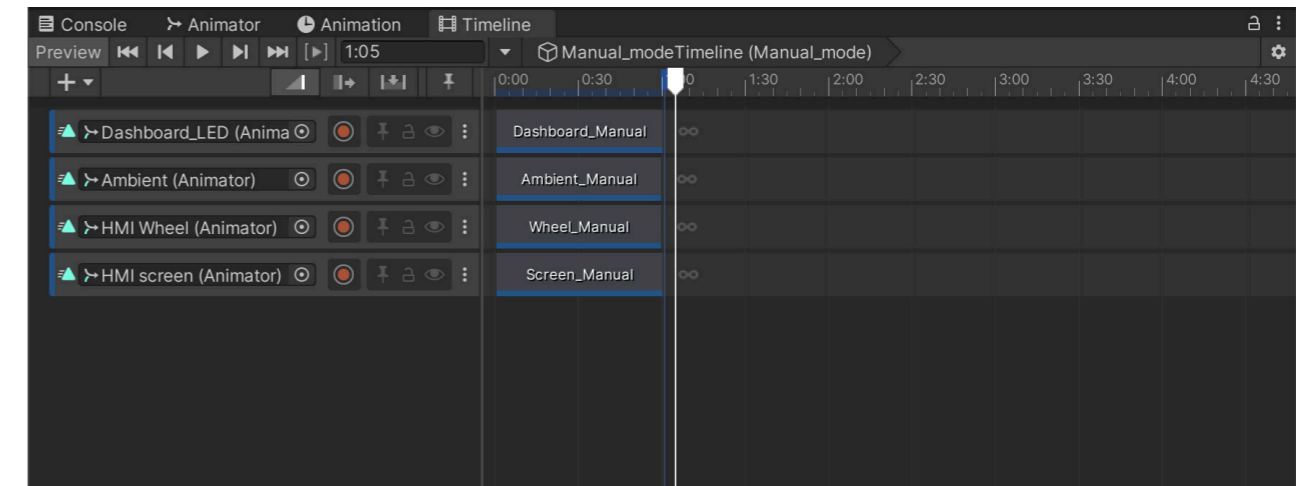
Figure 36: Timeline editor window.

Figure 37: Constructig scenarios with multiple Timeline sequences.

1: Timeline tool: https://docs.unity3d.com/ Packages/com.unity.timeline@1.2/manual/ index.html

8

Final Design | User Manual

To support the customization of the experiment scenes by Mediator designers and researchers, a solution was needed to guide them through the use of the Unity Game Engine.
In the following chapter, the process of ideation and design of the User Manual and supporting video tutorials will be reported.

8.1 User Manual Requirements

The Mediator VR evaluation tool is intended to be used to conduct several experiments in the following months, within the Mediator project. Because of this, it is necessary that the tool can allow users to easily implement changes and build custom scenes that will fit the purpose of each experiment.

As it was previously discussed, the intention is to allow the researcher and designer to access the prototype directly through the Unity Game Engine and modify the existing elements of the project using the tools available within the editor. **As most of the users of the VR evaluation tool are expected to have a very limited or no prior experience with Unity, it was deemed necessary to support them in using and navigating this interface by creating a User Manual.**

Before moving on with the design of the User Manual, a small brainstorming session was conducted to identify what sort of information could support the use of the VR tool and should be included. This is described in the following subchapter.

8.1.1 Brainstorming

As described in chapter 6.4, for the development and evaluation of the third and final MVP1 I had the opportunity to collaborate with a fellow graduate student, whose graduation project (Shan, 2021) involved the design of the Mediator HMI's negotiation system. **During this collaboration, the student had the opportunity to use the VR tool and adapt the contents of the virtual scene to include her own HMI design concepts. In this process, she got acquainted with the Unity Game Engine's interface and the structure of the Mediator VR Evaluation Tool's Unity project.** Her experience made her the ideal candidate to give input into what sort of information would be needed for a Mediator designer to successfully use the tool. A small brainstorming session was organized to map out the requirements for the User Manual.

During the brainstorming session, two general questions were explored:

1. *What could improve the experience of setting up a custom experiment using the VR evaluation tool and Unity Game Engine?*
2. *What could improve the experience of using the VR tool during the evaluation moment?*

Figures 38.1 and 38.2 detail the main insights gathered from the brainstorming exercise. These were used as a basis for the design of the User Manual.
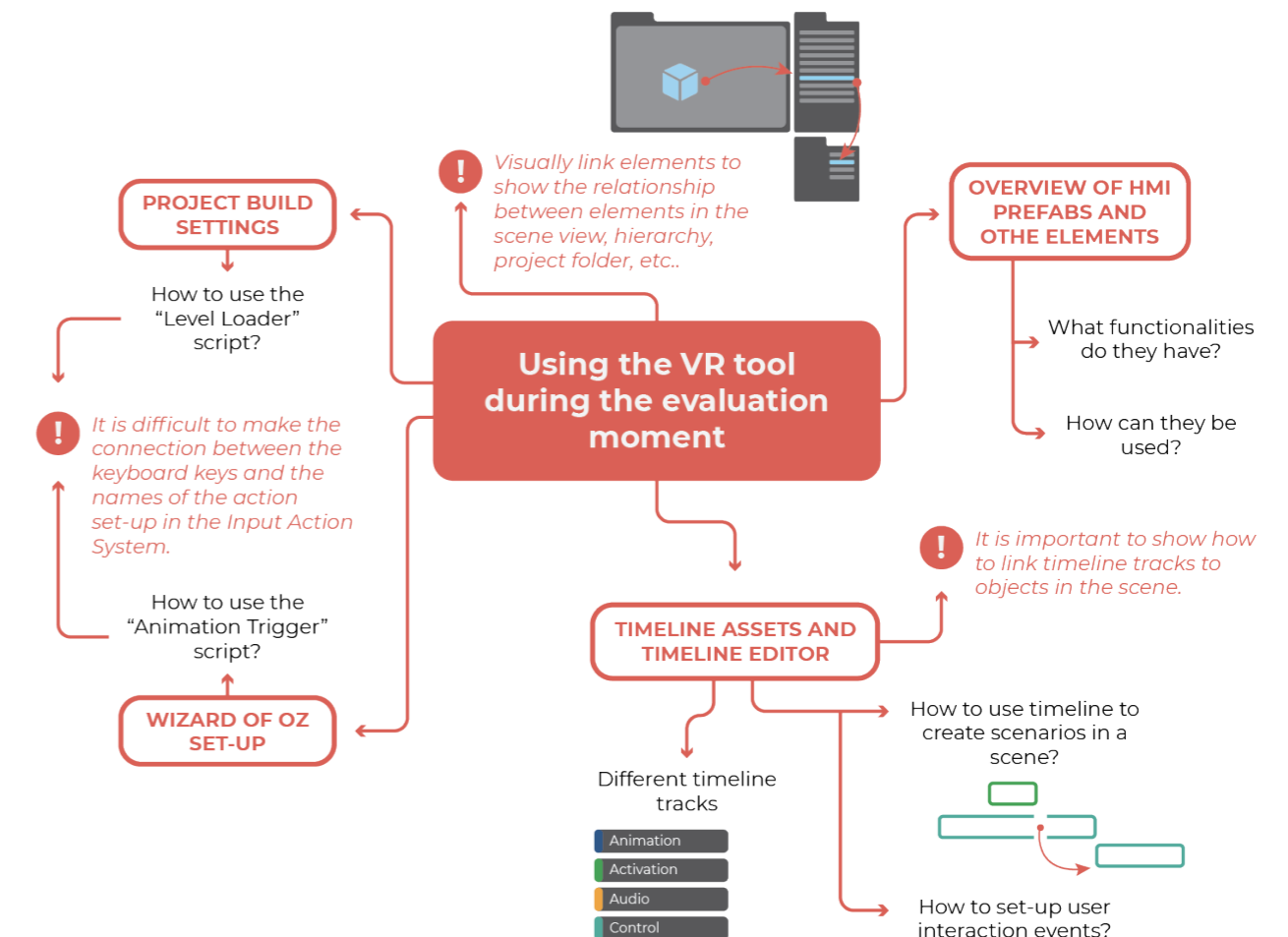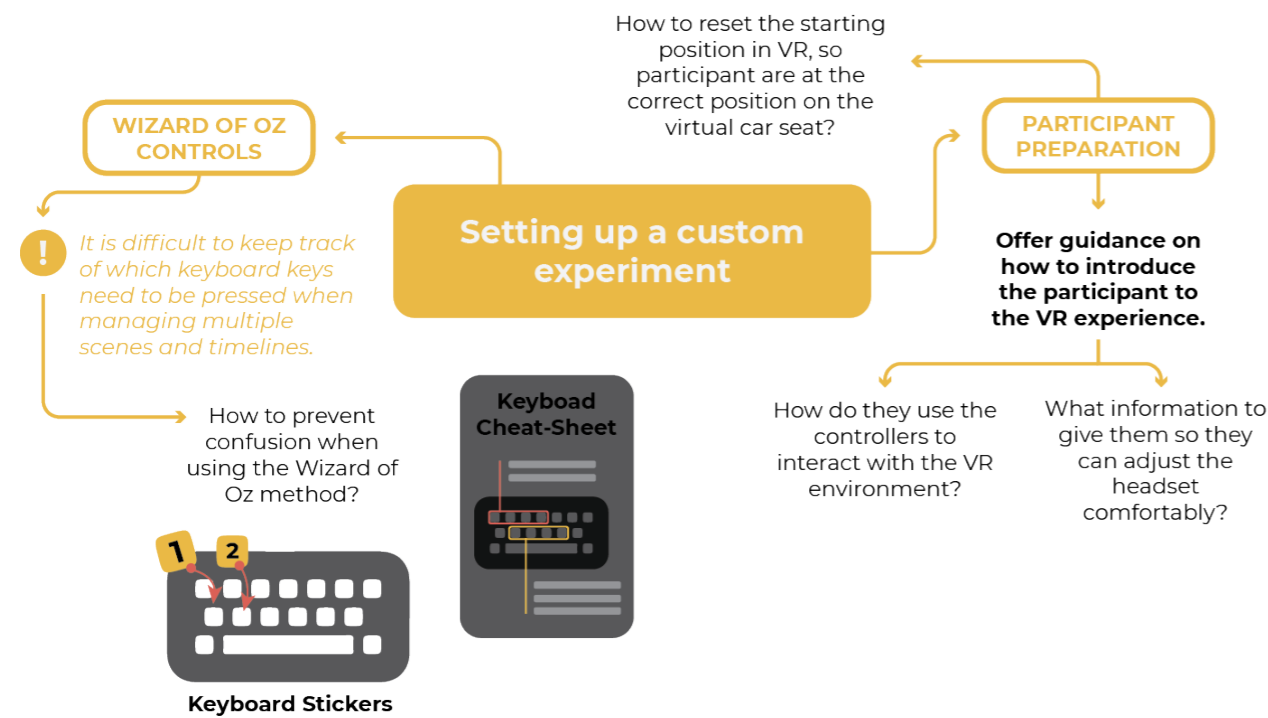
Figure 38.1 and 38.2: Insghts derived from the brainstorming session.

8.2 User Manual Design Concept

Considering the insights gathered from previous explorations (see chapter 6.3, ideation and testing of MVP2), and the brainstorming session mentioned above, it was clear that both the amount and the difficulty of the information required for a user with no previous experience of the Unity Game Engine to independently make changes to the project are very big. As such, **the focus of the design of the User Manual of the Mediator VR Evaluation Tool was to simplify the task of creating a customized scene and provide only the necessary information required to complete it.** This was done by creating a step-by-step (see figure 39) walkthrough to guide the process.

Each step shown in figure 39 is transformed into a sub-chapter in the User Manual, containing detailed information of all actions that must be completed to properly set up the VR tool.

However, in the previous collaboration with the Mediator student, as well as in the evaluation of the guide created as part of the second MVP, it was observed that users still had a hard time following direct instructions, as they were unfamiliar with the Unity interface, and could not intuitively navigate it. For example, because they were unsure of what certain terms were referred to or because they could not find specific elements in the cluttered windows. Because of this, **it was still deemed necessary to give users an initial overview of the Unity 3D interface, the prefabs which were created for the Mediator VR Evaluation Tool and the Timeline tool, which was heavily used in the project and offers the greatest opportunities for the customization of a scene** (see figure 40).

The User Manual was structured into two chapters:

1. **Introducing the Mediator VR Evaluation Tool**: giving an overview of the Unity interface, tools and contents of the project, as shown in figure XX.

2. **Creating a Custom Scene with the Mediator VR Evaluation Tool**: explaining the steps to creating a custom scene in Unity, shown in figure XX.

Because of the complexity of the information that has to be communicated to the users, I decided to supplement the written instructions with a set of video tutorials. **In video format, it is easier to explain the relationship between multiple elements present in the Unity interface, by showing how certain actions will manifest in the various windows.** For example, in explaining how a game object that is visible in the scene view can be affected by inputting new values in the transform component in the inspector view, showing the changes in real-time will help users make the connection between

the two much faster. On the other hand, watching an entire video can be more time-consuming if the user is only missing a part of the information required to complete a task. Therefore, the combination of a written guide and video tutorials is expected to be most efficient as it offers enough support in understanding complex information but also allows users to quickly reference the needed information on a page.

A complete overview of the User Manual and its contents is included in Appendix 7.

Steps to creating a customised evaluation scene in Unity 3D

1. Creating a new Scene
2. Customising the scene Content
3. Using the Unity Timeline
4. Building/exporting the Scene
5. Using the VR Tool during the evaluation moment

Figure 39: Step-by-step process of creating a custom evaluation scene with the Mediator VR Evaluation tool. The stept also represent the sub-chapters in the second chapter of the User Manual: Creating a Custom Scene with the Mediator VR Evaluation Tool.

Contents of Chapter 1: Introducing the VR tool Unity project

Unity Interface:
- General introduction to Unity editor.
- Unity version used for the VR evaluation tool (2020.2.6f1)
- Editor layout and windows: how to navigate the project.

Prefabs:
- Detailed description of prefabs: what elements they are composed of, animated elements, interactions.

HMI Wheel prefab   **HMI Gear Lever prefab**   **HMI LED prefab**

HMI Screen prefab   **HMI HUD prefab**
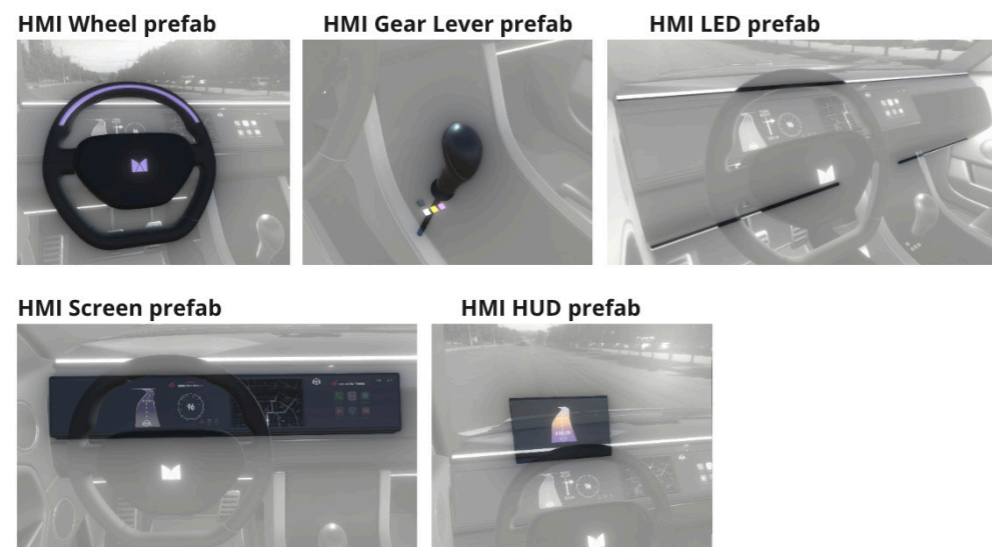
Timeline:
- Timeline editor window: introduction to tracks and controls.
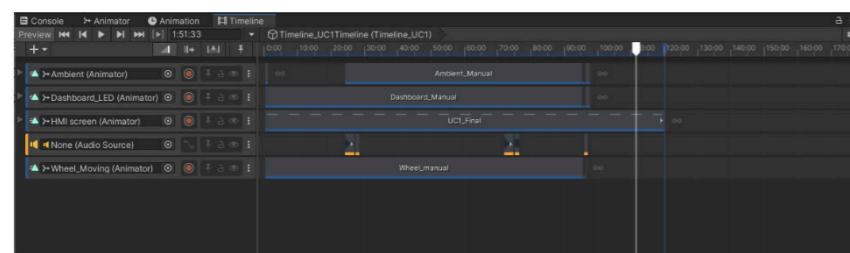
Figure 40: Content structure of the User Manual chapter: Introducing the Mediator VR Evaluation Tool.

An important part of the design of the User Manual is represented by the visual language which is used to help the users rapidly find the needed information on the page, but also to aid in the understanding of the relationship between the various instances of an object within the various windows of the Unity interface. **Brightly colored arrows were overlaid on top of images of the Unity interface to help the reader identify and make connections between the components referenced in the text** (see figure 41).

Other information was laid out in yellow boxes, as shown in figure 42, to highlight its importance and guarantee that it would not be missed by the readers.

Figure 43, on pages 116 - 117, gives an overview of the final User Manual design.
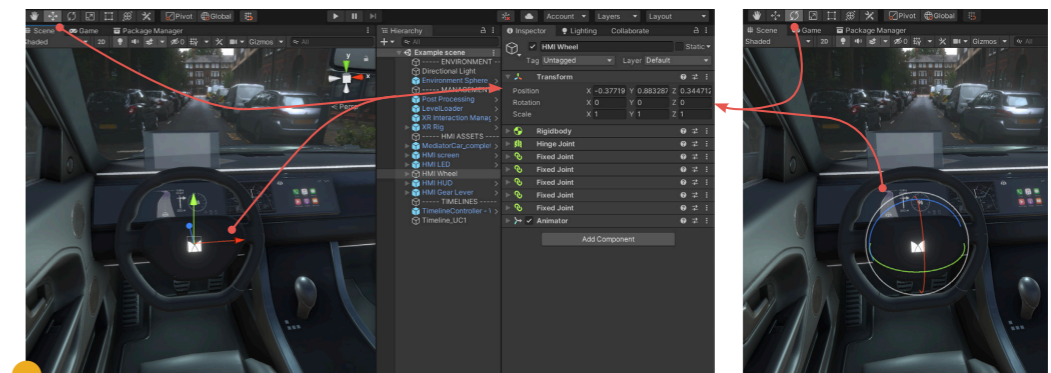
The position, rotation and scale of objects can be change in the transfrom component that is found in the inspector when selecting an object.
Using the gizmos on the screen, changes can be made directly by dragging the arrows and lines in the scene view.

Figure 41: Example of visuals used in the User Manual.

Note: When an existing Timeline asset is added to a Scene, it is important to recreate the **bindings between the tracks and the correct objects** (see image below). An exception to this is the audio track. While audio tracks can be linked to an audio source in the Hierarchy, these are not necessary.
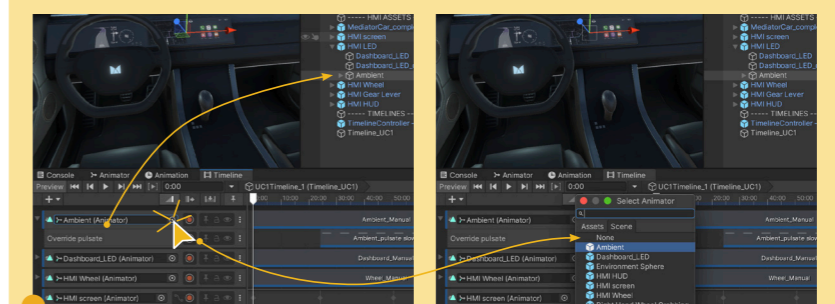
Creating bindings between tracks and objects in the scene.
On the left, we can see the relationship between the a track and an object in the hierarchy window. In order to link the track to the binding we can click the icon next to the track name and choose between the components available in the scene (right).

Figure 42: Example highlighted information in the User Manual.

Figure 43: User Manual pages. The full user manual is included in Appendix 7.

9
Product Evaluation

This chapter details the evaluation process and results of the final Mediator VR Evaluation Tool prototype, and the supporting User Manual.

9.1 Evaluation: Mediator VR tool

9.1.1. EVALUATION GOALS

To validate the use of the tool developed as part of this graduation project, a final evaluation was conducted, during which a sample of 10 participants were invited to experience two scenes in which they were presented with various conditions of the Mediator HMI. The goals set out for this evaluation are as follows:

1. **To observe whether participants are able to express genuine opinions on the Mediator HMI design they interact with through the VR interface.**

2. **To measure the user experience of interacting with the VR tool.**

9.1.2 EVALUATION PROCEDURE

During the evaluation, participants were asked to take part in two different experiments modeled on those that the Mediator VR Evaluation tool was designed to support. The first being a target experiment, during which participants are asked to view and evaluate specific parts of the Mediator HMI design. The second, an interactive experiment that captures users' realistic interaction with the HMI in a given scenario (figures 44.1 and 44.2).

In the first experiment, they were shown the Mediator HMI designs in four different driving states (Manual, SB, CM, TtS), mentioned in chapter 3.3. In between each state the screen fades to black, giving participants the opportunity to describe the experience.

In the second experiment, participants were presented with a scenario in which they had to perform a transfer of control, initiating the transfer through an interaction with the gear lever. The communication of the HMI is consistent with the design of Mediator Use Case 1.

DATA COLLECTION

Data was collected through a variety of methods.
During the evaluation, participants were asked to express their thoughts using the "think aloud" method. Observing their interaction with the HMI virtual prototype as well as the overall VR tool, notes were taken regarding their actions and thoughts.

Both qualitative and quantitative data related to the participants' experience was collected.

Three quantitative questionnaires were used:
NASA-TLX questionnaire: participants filled in the questionnaire evaluating the task of simulated driving in VR. The results are compared to those registered in other studies where users performed similar tasks (Grier, 2015). This test was given to participants directly after the VR experience. They were asked to think about the mental workload required to scan the VR environment and understand what the HMI is communicating to them, while trying to act as they would in a real driving situation (if in manual, CM or SB modes, see chapter 3.3).

The **ICT-Sense of Presence Inventory** questionnaire (Lessiter et al., 2001) was used to evaluate the feeling of presence experienced by users after they are exposed to the VR content. Four factors related to the users' experience with the digital media are analysed:
- Spatial presence: indicates a sence of physical presence in the virtual environment.
- Engagement: indicates a tendency to feel psychologically involved andto enjoy the content.
- Ecological Validity: indicates a tendency to perceive the mediated environmentas lifelike and real.
- Negative Effects: indicate adverse physiological reactions to the virtual content.

User Experience Questionnaire[1] was used to evaluate the prototype on the six scales that are included in the questionnaire:
- Attractiveness: Overall impression of the product. Do users like or dislike the product?
- Perspicuity: Is it easy to get familiar with the product? Is it easy to learn how to use the product?
- Efficiency: Can users solve their tasks without unnecessary effort?
- Dependability: Does the user feel in control of the interaction?
- Stimulation: Is it exciting and motivating to use the product?
- Novelty: Is the product innovative and creative? Does the product catch the interest of users?

Finally, a small interview was conducted to collect qualitative data of the participants' experiences.

PARTICIPANTS

The experiment was conducted with a sample of 10 participants (7 female and 3 male) that had no prior knowledge of the Mediator system or HMI design. Within this group 8 participants have driving experience and 7 had previously used a VR system at least once.

Due to time constraints and limitations posed by the Covid-19 pandemic, participants were recruited mainly amongst other TU Delft student and personal connections, resulting in a homogenous group with similar education background and age.

1: UEQ: https://www.ueq-online.org

EVALUATION SETUP

During the evaluation, participant were seated in a real car seat while wearing the VR headset. The VR device that was used during the experiment is the Oculus Quest 2. The device was wirelessly connected to a laptop, allowing the researcher to view the virtual environment through the participants' perspective in real time. The different evaluation scenes was activated remotely through the used of a Bluetooth keyboard. The entire evaluation setup is show in figure 45.

Figure 44.1 and 44.2: Overview of the scenes and the changes in the HMI experienced by participants during the two experiments.

EXPERIMENT 1 : MEDIATOR DRIVING MODES

| MANUAL DRIVING | CONTINUOUS MEDIATION (CM) | STAND BY (SB) | TIME TO SLEEP (TTS) |

EXPERIMENT 2 : MEDIATOR USE CASE 1

The test participant is viewing and interacting with the virtual environment though the **Oculus Quest 2** system.

The view of the virtual **environment is cast onto the laptop**, where it can be monitored and recorded by the test leader.

The test participant is **sitting on a physical car seat**, in the position that matches the one they would expect to have in the virtual environment.

A **Bluetooth keyboard**, connectd to the VR devices, is **used to activate the different evaluation scenes.**

Figure 45: Evaluation setup.

9.1.3 METHODOLOGY

For this evaluation, the RITE, or Rapid Iterative Testing and Evaluation, Method was used. This evaluation method, which usually spans across the entire course of a design project, is used to perform usability tests and gain insights that can be used to rapidly iterate on a design, by finding and fixing problems (Medlock et al., 2002).

This method was adapted to fit the time-frame dedicated to the three-week period that was reserved for the evaluation of the prototype. **The participant sample was divided into three groups of three to four participants, and evaluation with each of the three groups was scheduled one week apart. Following each**

evaluation, the qualitative insights gathered from the user tests were reviewed and used to improve on the prototype.

This method was used to observe whether an improvement in the ratings given by participants on the quantitative questionnaires mentioned below could be achieved by implementing fixes to the issues identified by participants.

In figure 46 the changes made to each prototype iteration are shown. The results of the RITE method are discussed in detail in subsection 9.1.5.

Iteration 1

In Experiment 1, participants are given a timeframe of 1 minute to evaluate each driving mode, with 30 second breaks in-between.

The exterior environment is static, displaying 360-degree images.

Iteration 2

In Experiment 1, participants are given a timeframe of 3 minutes to evaluate each driving mode, with 30 second breaks in-between.

The exterior environment is dynamic, displaying a looping animation, created with 360-degree images retrieved from Google Street View.

Iteration 3

In Experiment 1, participants are given a timeframe of 3 minutes to evaluate each driving mode, with 30 second breaks in-between.

The exterior environment is dynamic, displaying a looping animation, created with 360-degree sketches of an abstract road environment.

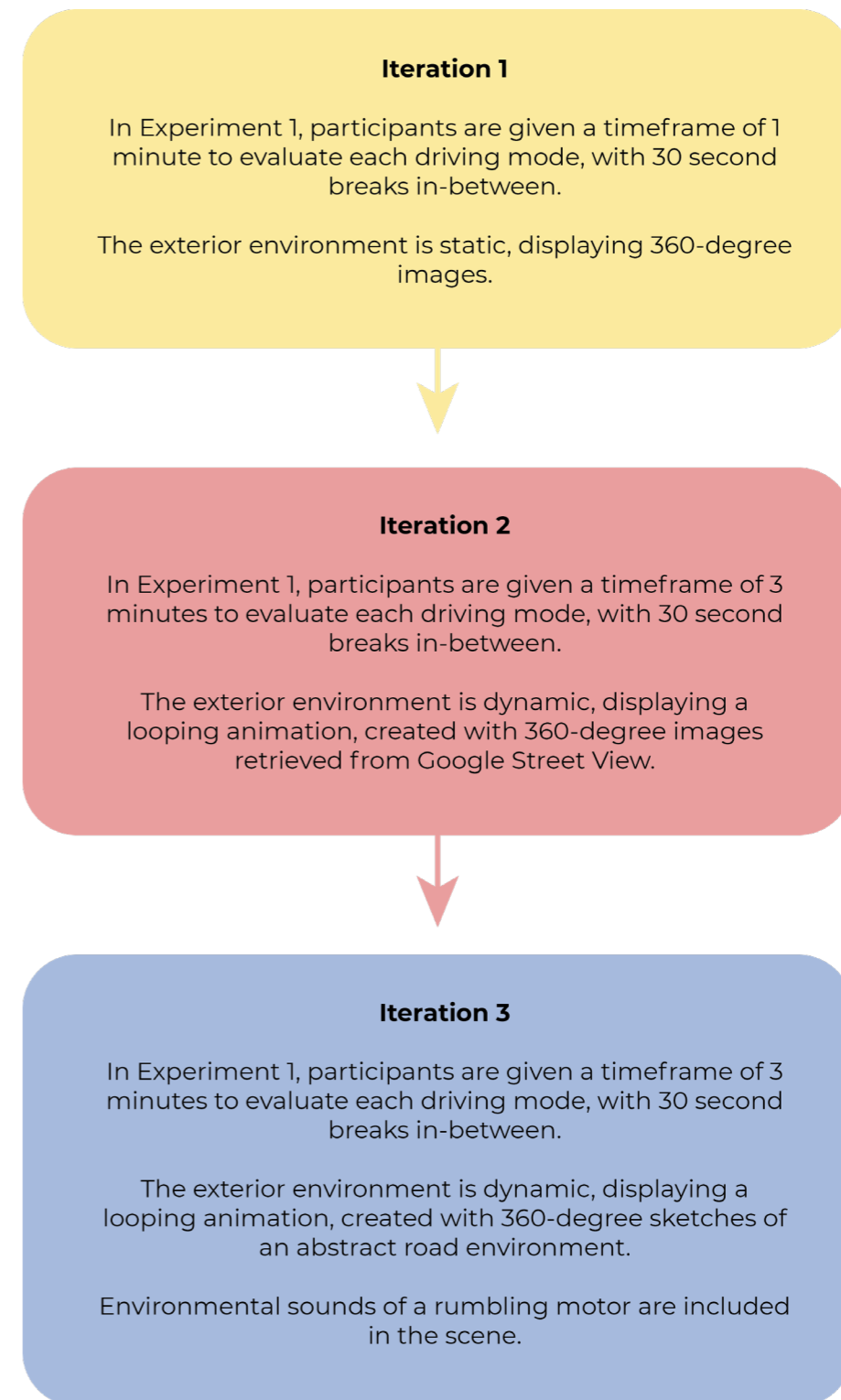Environmental sounds of a rumbling motor are included in the scene.

Figure 46: Overview of changes made to the three prototype iterations.

9.1.4 RESULTS

QUALITATIVE RESULTS

After the evaluation with each of the three participant groups, a list of the most important insights, shown on the right, was created by the analysis of the observation notes taken during the experiment, and the responses given by test participants to the interview questions, which can be seen in appendix 8. The points written in bold text represent noticeable differences from the other groups.

These qualitative insights were used to determine the changes made to the following prototype iterations, as shown in figure 47.

Figure 47: Overview of the main insights derived from the observation and interviews during the three evaluation cycles.

Main insights

Gained from participant observation/ think aloud mehod and interviews.

Group 1

- All participants were able to correctly interpret the displayed driving modes in experiment 1.
- Participants noticed most details of the HMI design which communicate information related to driving mode and driver responsibility.
- **All participants felt rushed and were often unable to complete the task (observing all design elements) in the one minute timeframe dedicated to each driving mode in experiment 1.**
- All participants were able to perform the transfer of control (on the first or second attempt) using the gear lever interaction in experiment 2.
- **2 out of 3 participants failed to simulate the act of driving (e.g. by holding the wheel and looking at the road) when instructed to do so in experiment 2.**
- **All participants expressed that the lack of movement of the road environment failed to simulate the experience of driving.**

Group 2

- All participants were able to correctly interpret the displayed driving modes in experiment 1.
- Participants noticed most details of the HMI design which communicate information related to driving mode and driver responsibility.
- **One participant noted inconsistencies in the navigation communication displayed on the HMI screen (GPS and navigation arrows).**
- All participants were able to perform the transfer of control (on the first or second attempt) using the gear lever interaction in experiment 2.
- **During the second experiment all participants held the wheel to simulate the act driving. 1 out of 3 of the participants let go of the wheel during the experiment.**
- **All participants noted negative side effects (e.g. dizziness, nausea) when looking at the moving road during the experiments. 2 out of 3 participants requested a break after experiment 1, due to the negative side effects.**
- **All participants expressed the lack responsiveness from the road (the car turning as they turn the wheel) rendered the experience less realistic.**
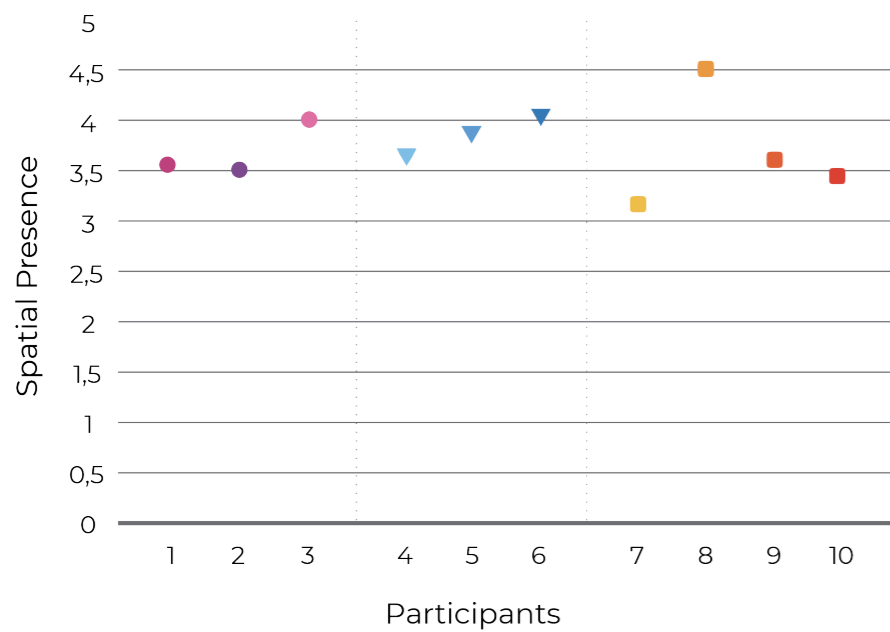
Group 3

- All participants were able to correctly interpret the displayed driving modes in experiment 1.
- Participants noticed most details of the HMI design which communicate information related to driving mode and driver responsibility.
- **One participant noticed the retracted wheel in TtS driving mode in experiment 1.**
- All participants were able to perform the transfer of control (on the first or second attempt) using the gear lever interaction in experiment 2.
- During the second experiment 3 out of 4 participants held the wheel to simulate the act driving. 1 of the participants let go of the wheel during the experiment.
- **All participants noted a sense of being in a moving vehicle given by the animated road environment and environmental sounds.**
- **None of the participants experience negative side effects from the animated road environment.**
- 2 out of 4 participants expressed the lack responsiveness from the road (the car turning as they turn the wheel) rendered the experience less realistic.

ICT SOPI (PRESENCE QUESTIONNAIRE)

The results of the ITC SOPI questionnaire were analyzed by separating the items into four factors that describe the users' experience of the media or, in this case, the virtual environment. Scores for each of the four factors were determined by calculating the mean of the items answered by each participant.

Figures 48.1 - 48.4 show the results for each of the factors: **spatial presence**, **engagement**, **ecological validity (or naturalness)** and **negative effects**. Test participants' scores are clustered into the three groups that evaluated different iterations of the VR prototype. Each group is represented by a specific color scheme.

As we can see by looking at the four graphs, there are no significant differences in the scores given by participants of each of the three groups. A slight difference can be noticed in the scores given by the seconds group related to the negative effects factor. The mean score given by this group 2 (2.77), is significantly higher than the other two groups (mean scores of 1.38 and 1.41).
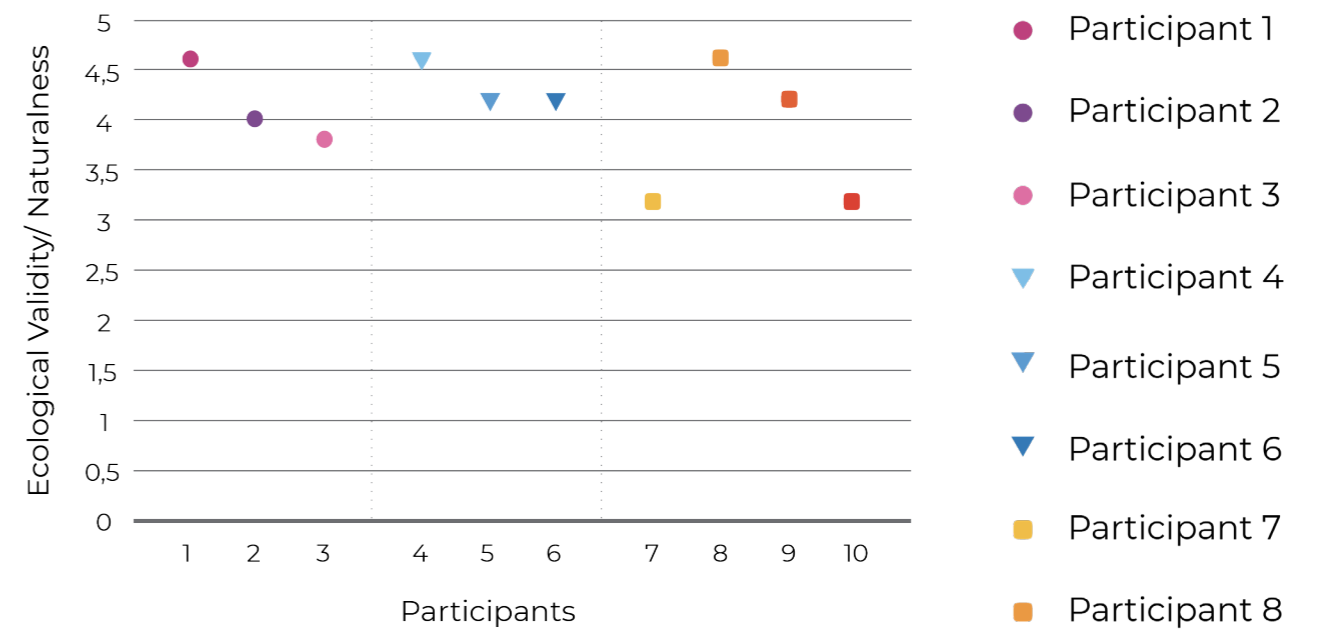

Figure 48.1: Mean scores recorded per participants on the items related to the spatial presence factor.
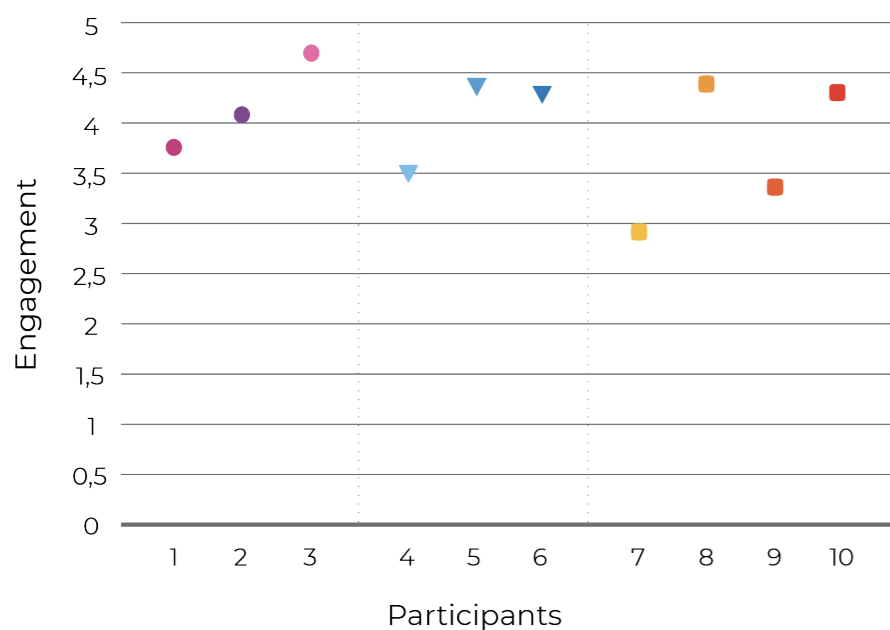
Figure 48.2: Mean scores recorded per participants on the items related to the engagement factor.

Figure 48.3: Mean scores recorded per participants on the items related to the ecological validity factor.
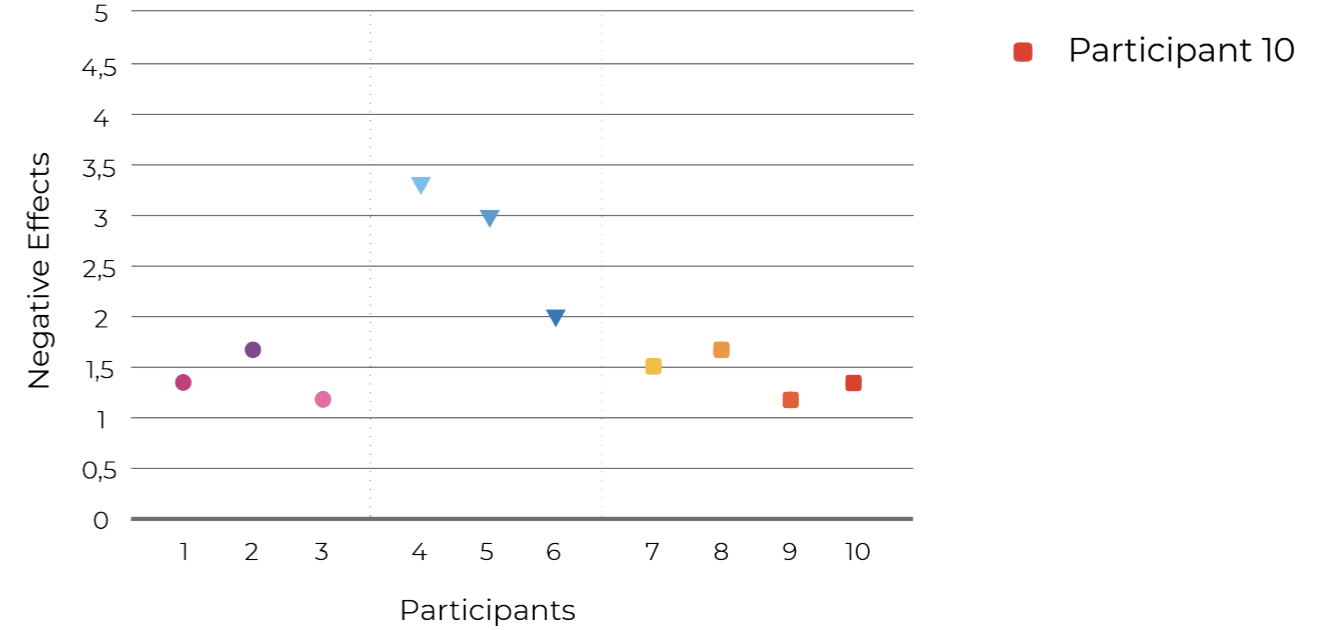
Figure 48.4: Mean scores recorded per participants on the items related to the negative effects factor.

- Participant 1
- Participant 2
- Participant 3
- Participant 4
- Participant 5
- Participant 6
- Participant 7
- Participant 8
- Participant 9
- Participant 10

USER EXPERIENCE QUESTIONNAIRE

The scores of the User Experience Questionnaire were analysed by calculating the mean value of the items related to each of the six scales of the questionnaire. Each participant's answers are shown in figures 50.1- 50.3. Figure 49 shows a comparison of the mean scores per each evaluation group.

Looking at the 5% confidence intervals represented on the graph, we notice that there is no significant improvement in the ratings between the tested iterations. The only exception is the perspicuity scale, which shows a significant improvement between the first and last iteration.

Overall, group 3 recorded the highest scores, suggesting an improvement in the users' experience with the VR tool in the final iteration.
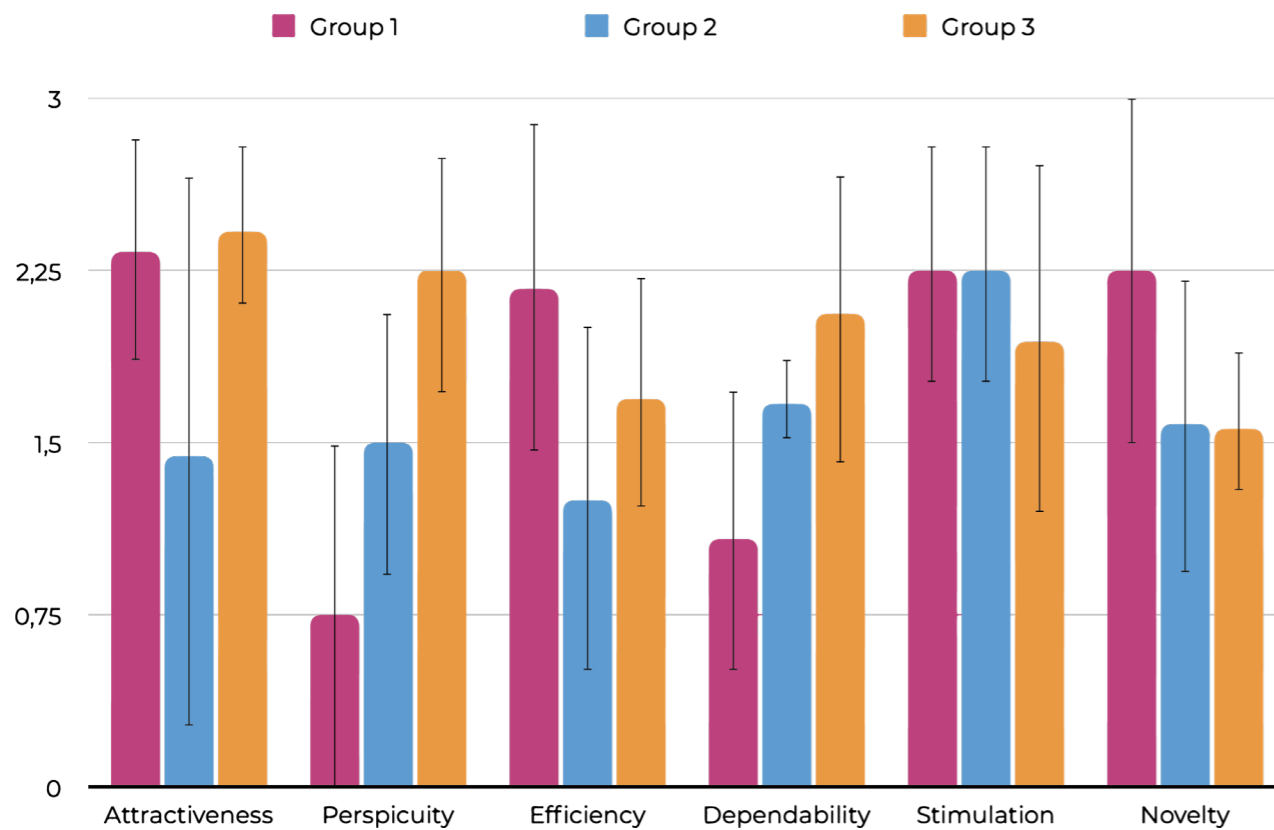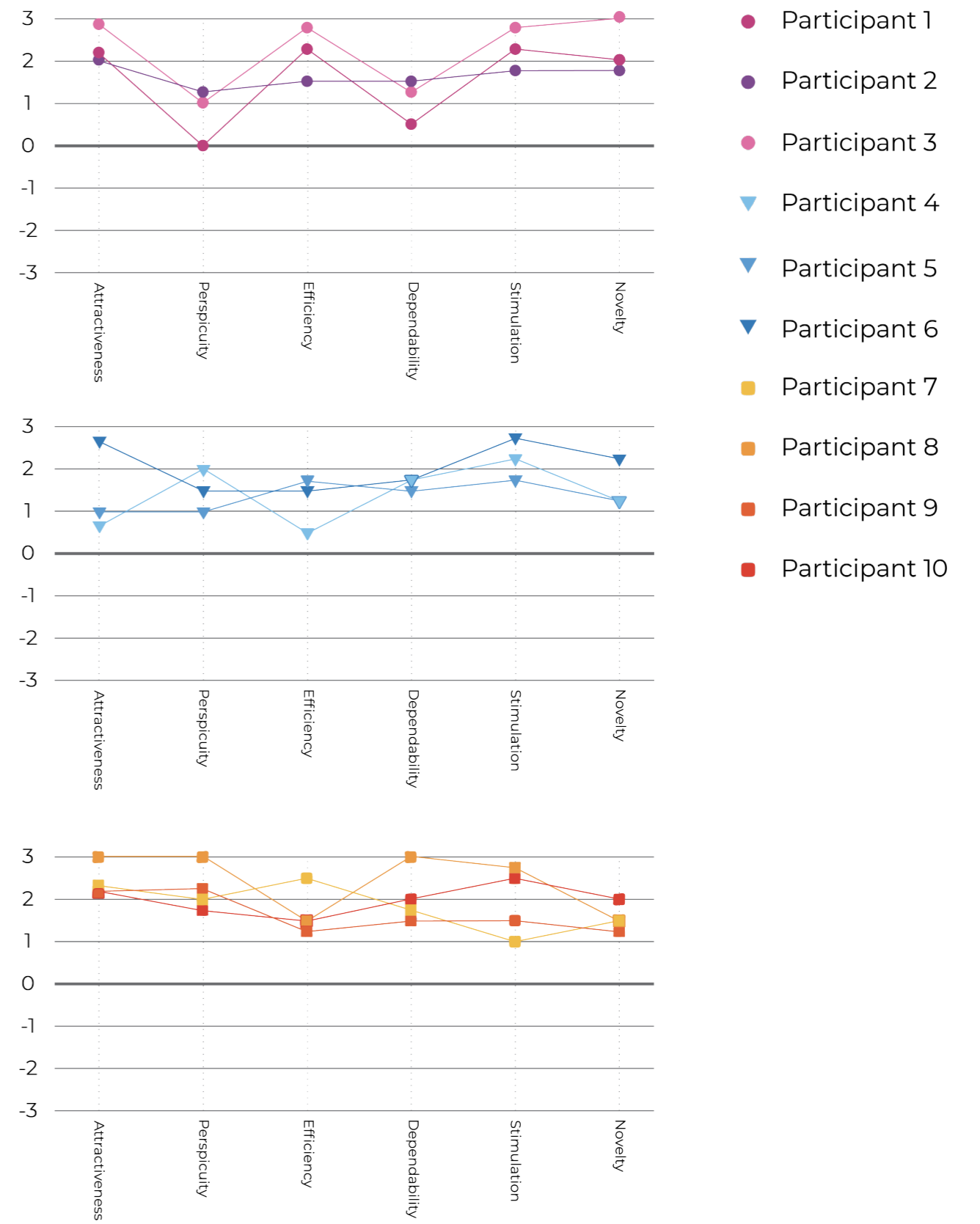

Figure 49: Comaprison between the mean scores recorded by each participant score.

Figures 50.1 - 50.3: Mean scores recorded per participants in each of the three groups.

NASA-TLX

Figure 51 represents the average scores recorded by each participants group on the NASA-Task Load Index questionnaire. The mean on the unweighted scores recorded by participants of a group on each item of the questionnaire was calculated. As we can see, no major differences were recorded in the scores related to the majority of the questionnaire items. An exception is given by the temporal demand ratings given by the participants of group 1. The reason for this particular difference was made clear by asking participants to explain the reasoning behind their choices. In this situation, participants rated the temporal demand high, due to the limited time (one minute) which they were given to observe each driving state in experiment 1.

To better interpret the overall workload associated with the use of the Mediator VR Evaluation tool, the overall mean scores recorded for each group (see figure 52) were compared with those recorded in other studies. Grier (2015), provides an analysis of the global workload scores recorded and categories by the task type. As, during the study, participants were asked to interpret the information giv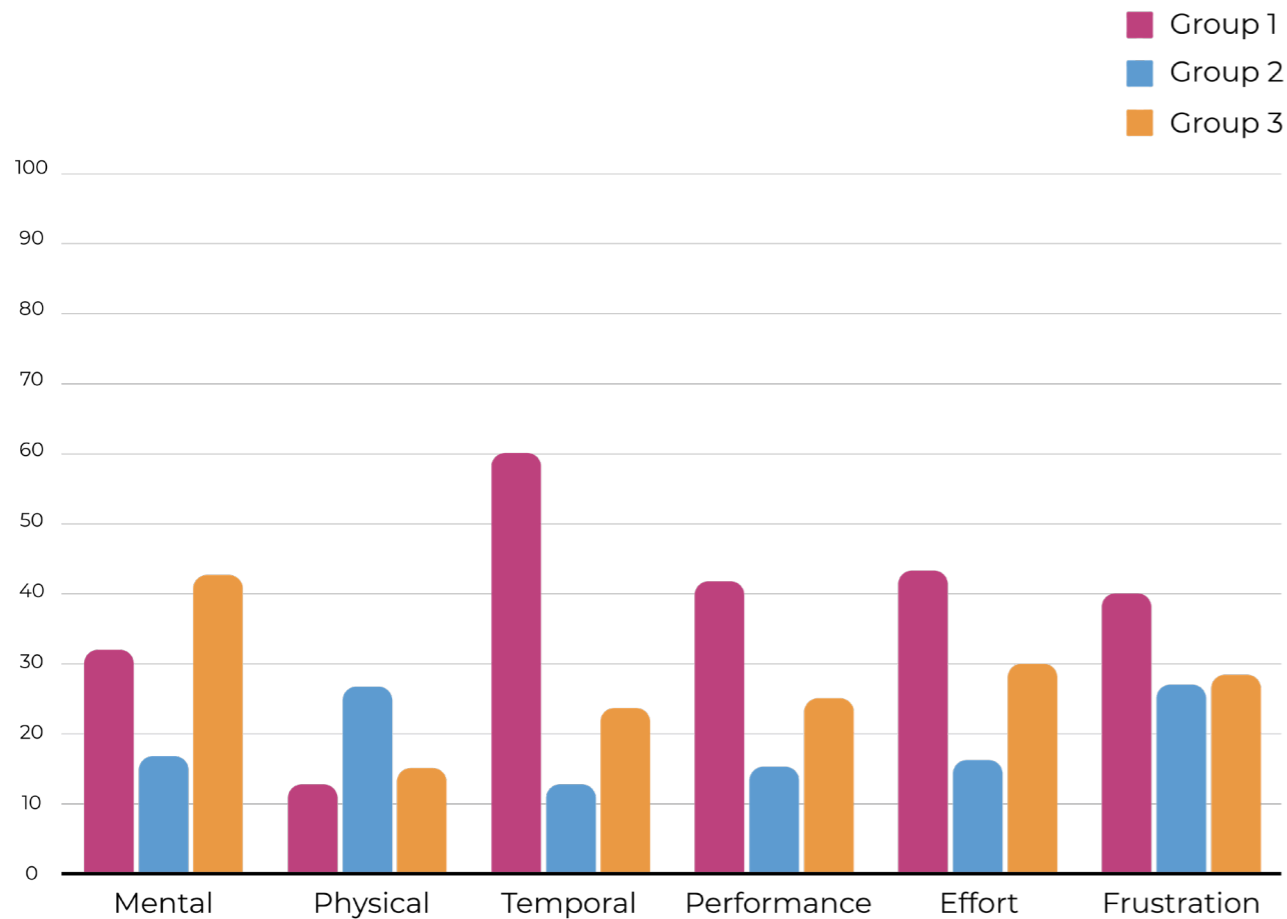en by the HMI, mostly through visual cues, as well as, simulate the act of driving the vehicle, the scores are compared to the "driving car" and "visual search" tasks (see figure 53.1 and 53.2). As we can see, the scores recorded by groups 2 and 3 are lower than 25% of the global workload scores associated with both driving and visual search tasks. Group one, with an overall score of 41.67 falls just above 50% of the scores related to driving, but still below 25% for visual search. Taking into consideration the context of the experiment and the fact that all participants were unfamiliar with the Mediator system, we can deduce that the overall workload associated with the use of the VR tool is acceptable.

	Overall Raw/ Unweighted Scores
Group 1	41.67
Group 2	20.00
Group 3	15.42

Figure 52: Overall workload scores calculated per each group.

Table 3
Description of Task Types

Task Type	Description
Driving Car	Real or simulated control and operation of motor vehicles
Visual Search Tasks	Active scan of environment for particular stimuli

Figure 53.1: Description of task types. Retrieved from Grier (2015).

Table 6
Cumulative Frequency Distributions of NASA-TLX Global Workload Scores by Task Type

Task (n)	Min	25%	50%	75%	Max
Driving Car (36)	15.00	28.05	41.52	51.73	68.50
Visual Search (46)	28.98	51.06	57.89	67.74	79.23

Figure 53.2: Global workload scores, per task type. Retrieved from Grier (2015).

Figure 51: Comparison of the group scores recoreded for each NASA/TLX item,

9.1.5 DISCUSSION

During the first round of user tests, participants were able to perform the required tasks. An issue that was noticed by all three participants, however, was related to the time during which they were able to view each driving mode in the first experiment. Initially, the scene was set up to display each driving mode for an interval of one minute, with a space of thirty seconds in between. The one-minute timeframe was too short for the participants to analyze and describe all details of the design and all of them indicated a sense of being rushed through the experience. To remedy this issue, the timing was increased to three minutes for the second round of evaluations. In this case, participants were able to finish their thoughts before the time was over. Only on a number of occasions, they had run out of things to explore significantly sooner. The three-minute timeframe was maintained during the last round of evaluations with similar results. This indicates that the three-minute timeframe might be suitable for similar evaluations, nevertheless, a system that allows the test leaders to jump to the next scene could be beneficial to avoid situations in which the participant must wait several seconds before they can continue the exercise.

Overall participants were able to evaluate the Mediator HMI with the use of the VR tool. All 10 participants correctly interpreted the driving modes displayed by the end of the first experiment. When asked to describe their understanding of the driving mode communicated by the HMI during the first experiment they did so in detail, demonstrating that the various parts of the HMI design were mostly visible and clear. Errors in the interpretation of the meaning of elements of the HMI design, such as attributing a particular meaning to the colors used in the language of the HMI ("Yellow colour indicates a need to be alert and focused"), were recorded often, but could mostly be attributed to the lack of prior knowledge of the Mediator HMI design. Participants focused mostly on the UI of the HMI screen, such as text information and icons. Inconsistencies in the design of the screen interface, for example in the navigation information (e.g. arrow indicating going straight, GPS indicating a turn ahead), were noticed by some participants and created confusion. This indicates a need to pay close attention to the details displayed in the virtual environment, even when these are directly linked to the evaluated design elements. A single detail of the HMI was missed by all participants but one: the retracted wheel displayed in TtS mode (see figure XX), during the first experiment. The reasons why this change went unnoticed by participants is unclear but could be attributed to several factors. On one hand, participants might have missed the detail because their attention was directed to other elements where changes were previously noticed, such as the screen, and the LED strips. On the other hand, this small change in the position of the wheel might have gone unnoticed due to the visual rendering of the VR system, which due to low contrast in shadows and textures, might not give users a sufficient sense of depth in the environment.

Following the first two rounds of testing, it was immediately apparent that all test participants desired more realism of the surrounding environment. In the first round, the prototype included static images of various road environments. While these helped contextualise the experiences scenarios, all three participants commented on the lack of movement on the road, indicating a decreased sense of realism and immersion. Furthermore, because they did not feel as though they were in a moving vehicle, the participants did not pay attention to the road even when, in the second scene, they were asked to behave as they would in a real driving situation. Instead, all participants focused on the behaviour of the HMI, reacting immediately to the first recommendation of the system to switch to piloted driving, often without attempting to understand the reason behind the request.

In an attempt to improve the realism of driving and to elicit a more natural interaction with the system in the interactive scenario, the second iteration of the prototype was modified to give a sense of the vehicle moving, by displaying a short looping animation of a straight road. An improvement was immediately noted, as participants expressed that they did feel the experience to initially be realistic. Despite acknowledging that the immersion broke as they realised that the environment was repetitive and not responsive to their action of turning the wheel, the participants mainly cited the lack of environmental sounds, such as the rumbling of a motor, as the reason for which the experience was perceived as less realistic. The looping animation of the road, which was created using 360-degree images downloaded from Google Street View (https://www.google.com/streetview/) and had a noticeably low frame rate, created an unwanted negative effect. The photographs created a "shaking" effect, causing participants to feel dizzy and resulting in higher ratings related to "physical demand" on the NASA-TLX questionnaire and to the "negative effects" factor of the ITC SOPI questionnaire, as illustrated in figures XX and XX.

With consideration to the findings from the results of the first two iterations, for the final version of the prototype, the road environment was again modified. To maintain the movement, but decrease the negative side effects, a simplified animation loop was created using abstract sketches of a rural road environment. The sense of movement was created by objects (trees and bushes) moving towards the vehicle, while the horizon line remained static reducing the "shaking" effect noted in the previous iteration. As we can observe in figures XX and XX, the change was successful, resulting in lower scores for "physical demand" and "negative effects". Furthermore, an environmental sound of a rumbling vehicle motor was added to simulate the effect of a moving vehicle in a multisensorial way. Multiple participants expressed that this detail contributed to the perceived realism of the virtual scene.

CONCLUSION

In conclusion, the results of the evaluation suggest that overall the VR tool can facilitate the evaluation of the Mediator HMI, allowing participants to express their opinion on various details of the design concept. With few improvements, the tool can be used in future experiments within the Mediator project.

While the RITE prototyping exercise did not result in an increase or decrease, in the scores recorded on either of the three scales, qualitative insights indicate that participants did experience an increased sense of realism related to the movement of the vehicle.

9.2 Evaluation: User Manual

9.2.1. EVALUATION GOALS

A small scale study was conducted to validate the usability of the User Manual and support video tutorials for the purpose of constructing custom scenes in Unity 3D for the evaluation of the Mediator HMI. The goal for this experiment is:

1. **To evaluate whether the User Manual can facilitate novice users in navigating the Unity 3D interface.**
2. **To observe whether the information provided by the User Manual and supporting video tutorials is sufficient and allows users to independently create a custom evaluation scene.**

9.2.2 EVALUATION PROCEDURE

During the evaluation, participants were asked to use the User Manual (see Appendix 7) and video tutorials in order to complete the following tasks:

1. Get accustomed to the Unity interface and Mediator VR Evaluation Tool project by reading the first chapter of the User Manual.

2. Duplicate the Sample Scene, following the steps provided in chapter 2, sub-section 1.

3. Modify the content of the Scene, following the steps provided in chapter 2, sub-section 2.

4. Add Timeline assets to the Scene, following the steps provided in chapter 2, sub-section 3.

5. Choose a method of controlling the Timelines, following the steps provided in chapter 2, sub-section 3.

    5.a Modify one of the Timeline assets.

6. Build the scenes, following the steps provided in chapter 2, sub-section 4.

7. Read the instruction in chapter 2, sub-section 5.

Participants were given access to the User Manual, video tutorials and the Unity project of the Mediator VR Evaluation tool

DATA COLLECTION

The participants were observed while compleating each of the above-mentioned tasks. The number of failures was recorded, together with notes on type and reasons for the failure.

After the evaluation, participants' experience was recorded through a small questionnaire (see Appendix 9), formulated using four items from the QUESI questionnaire, one per each of the following factors: **perceived achievement of goals, the perceived effort of learning, workload and familiarity**. In addition, three self-formulated items were included in the questionnaire. These are related to **the ability to locate information within the user guide, the clarity of the information and the availability/completeness of the information**.

Finally, qualitative data was collected though a short interview.

PARTICIPANTS

Three participants in total took part in the evaluation of the User Manual. **After the first evaluation, it was clear that the User Manual required several improvements to successfully achieve its goals. Because of this, the design was significantly changed to the final iteration,** which is included in Appendix 7. **Therefore, the rating given by participant 1 will be presented separately from the other two.**

The participants have varying degrees of experience with Unity or similar application, however, none are experienced users.

The participant sample includes two members of the Mediator project: one

TUDeflt designer (participant 1), one SWOV researcher (participant 2). The third participant is unrelated to the Mediator project and was chose to represent a user with no experience of Unity 3D or similar programs.

9.2.3 RESULTS

ITERATION 1

As mentioned previously, after the first evaluation of the User Manual a number of issues were identified. During the evaluation, the participant was not able to complete the majority of the given tasks making use of only the information provided in the first iteration of the manual. Instead, two main issues were noted:

1. Essential information, which was included in the first chapter of the User Manual (see chapter 8.2) was forgotten by the participant by the time it needed to be used in completing the next tasks.

2. Certain information necessary to complete the steps given in chapter 2 of the manual was only included in the video tutorials linked on the page. As the participant preferred not to watch the videos unless necessary, this information was missed, leading to the tasks remaining uncompleted or complete with errors.

Considering these initial insights it was deemed necessary to improve the design before moving forward with the evaluation. The changes that were made to the design included:

- Adding additional information on the completion of the steps described in chapter 2 of the manual.
- Linking back to important information given in the first chapter.
- Visually highlighting the available video tutorials.

ITERATION 2

The final iteration of the User Manual design was tested with 2 participants: First, with a naive participant (P2 in figure

54) with no prior experience with the use of Unity 3D or similar products as well as, no knowledge of the Mediator project and HMI design. Second, a Mediator researcher (P3 in figure 53) with a moderate experience of Unity.

Despite their differing experience, the scores given by both participants on the questionnaire items (figure 54) are equally high, indicating that, overall, the manual can facilitate the use of the Unity project.

However, during the evaluation, both participants recorded errors in completing the tasks and requested additional information from the researcher. In particular when they encountered functions or components not described in the user manual. For example, while compleating task 3, participant 3 attempted to modify the colour of certain HMI elements. As sub-section 2 in chapter 2 of the user manual does not describe how the material properties of the objects in the scene can be modified, the user required additional information to complete the desired changes. Similar situations were also encountered by participant 2, who explained: *"It depends what I want to create. If it is within the bounds of what is explained in the user manual, then yes. If I want to do something that is not in the guide, then I couldn't."*

The video tutorials were perceived to be helpful, as they could immediately show how a task could be completed, and contain more detailed information compared to the written guide. However, participants did not always choose to watch the videos. Both participants indicated that, while the tutorials were valuable as a first introduction to the tool, they would not go back to watch them every time they need information regarding the use of the tool.
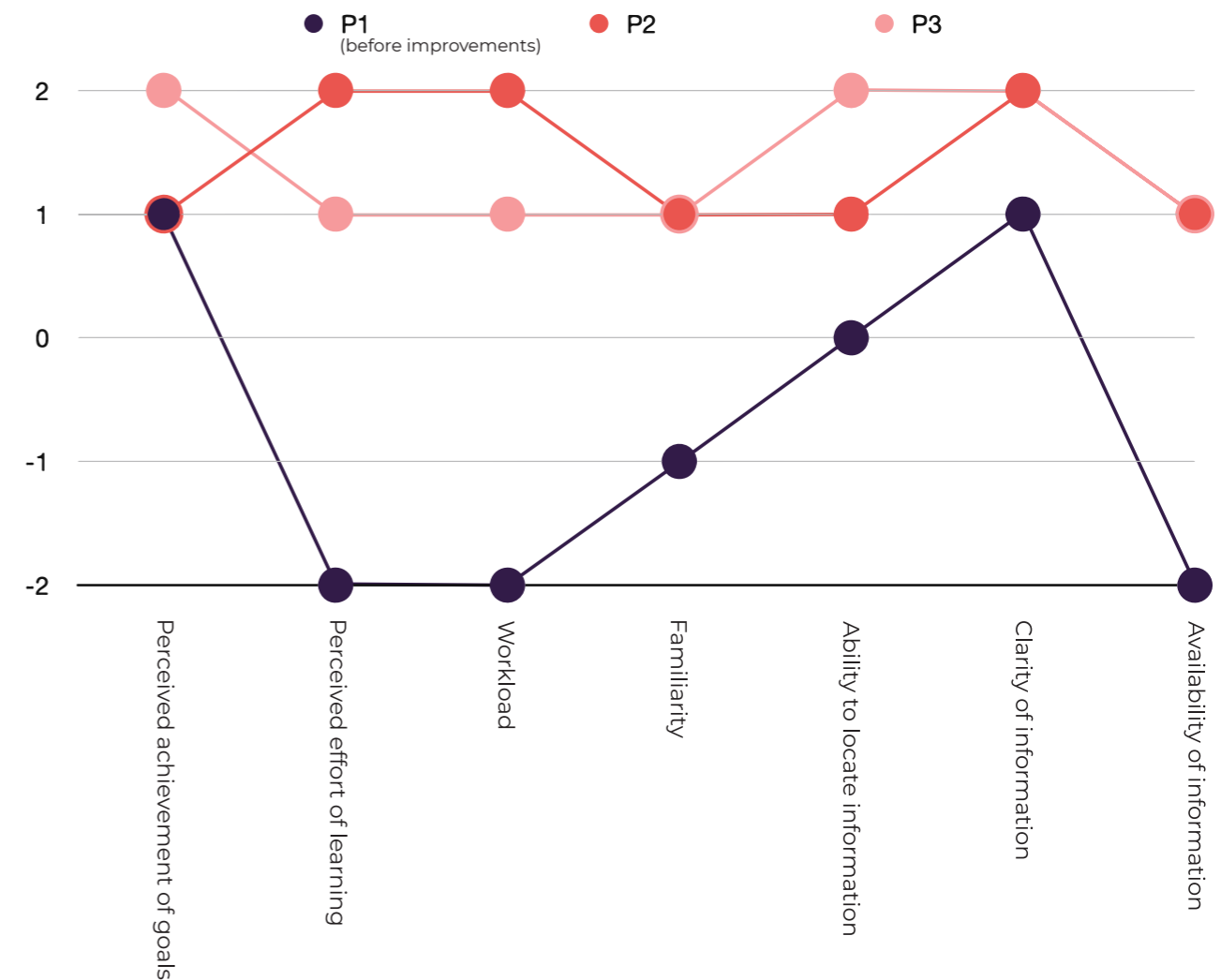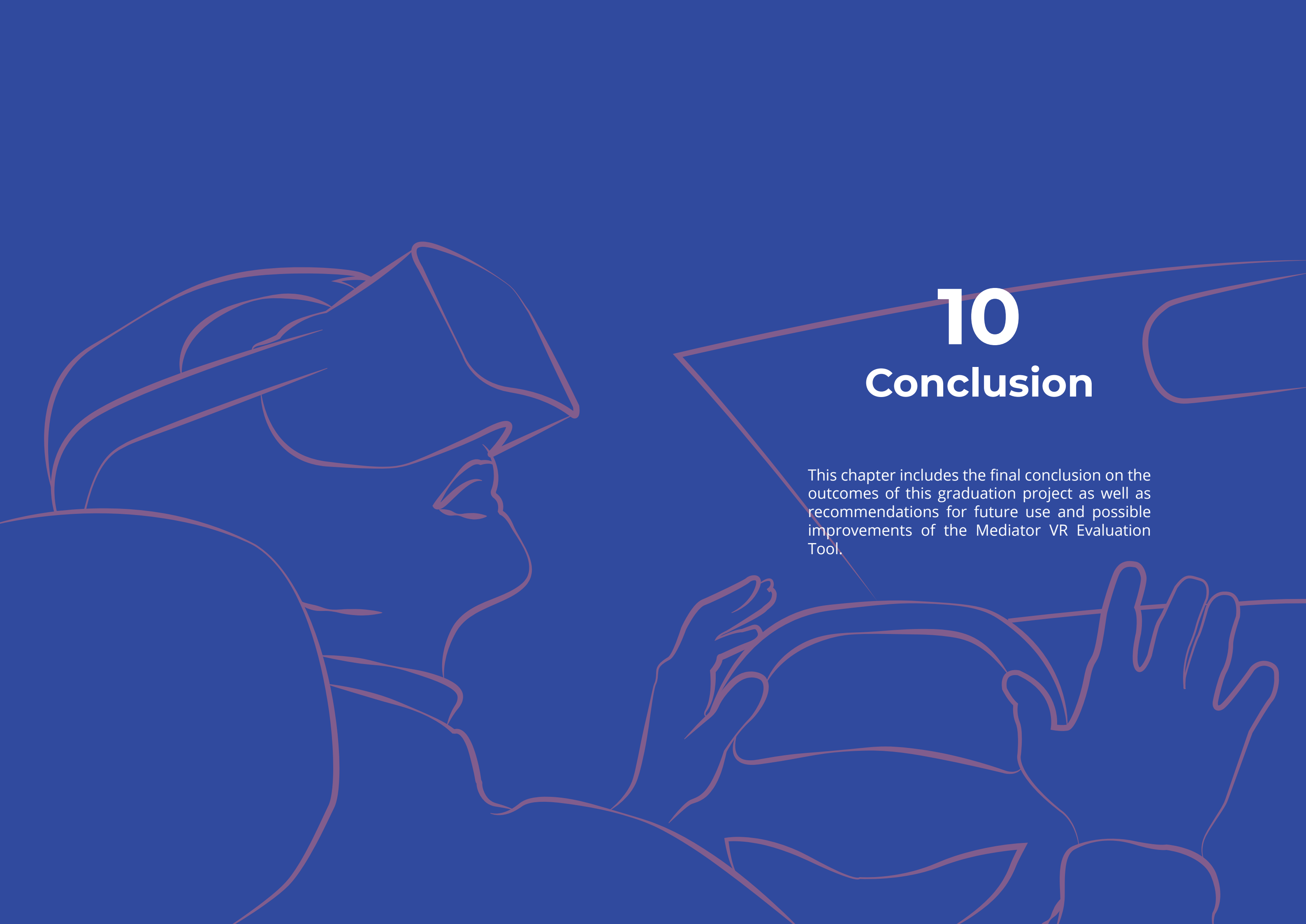

Figure 54: Scores given by each participant on seven questionnaire items.

9.2.4 DISCUSSION

The results of the evaluation of the final iteration of the User Manual indicate that this product, in combination with the additional video tutorial can help a novice user through navigating the Mediator VR Evaluation Tool Unity project.

However, given the amount and complexity of the tools and assets included in the Unity project, the provided information is not sufficient for users to customize a scene beyond what is explained in detail in the User Manual walkthrough.

This suggests that greater changes to the VR tool still require the involvement of an experienced Unity developer.

10
Conclusion

This chapter includes the final conclusion on the outcomes of this graduation project as well as recommendations for future use and possible improvements of the Mediator VR Evaluation Tool.

This graduation project resulted in the development of the Mediator VR Evaluation Tool, an application that simulates the interaction with the Mediator HMI design through the use of Virtual Reality technology. With the User Manual which was designed to support the use of the VR tool, members of the Mediator project will be able to construct virtual environments with customized content and scenarios and conduct experiments to evaluate the holistic HMI design.

The results of the final evaluation conducted in the course of this graduation project prove the use of the VR tool is effective in collecting valuable insights regarding the HMI design concept. Although I expect the VR tool could be used in its current form with positive results, there are several improvements that can be applied to the design, in order to maximise its value. These will be discussed in the next section.

The User Manual and the supporting video tutorials appeared to be helpful in guiding test participants through navigating the Unity 3D interface and the Mediator VR Evaluation Tool project. However, based on the insights gathered in the final evaluation of this product, it is apparent that the amount and depth of information given in the manual are not sufficient to support the customization of the scene, beyond what is explained in the step-by-step walkthrough. Therefore, in the future use of the tool, the collaboration with a Unity 3D expert is expected to be necessary to bring larges changes and improvements to the current version of the product.

10.1 Recommendations

Before the Mediator VR Evaluation Tool can be used in practice, a number of improvements can be made.
The following recommendations concern improvements which can increase the realism of the users' interaction with the virtual HMI prototype and other parts of the virtual environment. These recommendations should be considered in terms of the requirements specific to each experiment that will be conducted and are not necessarily applicable to every type of evaluation.

Realism of the HMI Design Elements

When immersed in a virtual environment participants evaluate the things they see based on their expectations acquired from their experience with the real world. The current version of the VR Tool includes realistic virtual prototypes of the HMI elements. However, certain details of the design of these virtual prototypes do not match the real wold products they aim to simulate. a particular example is represented by the HMI screen and head-up-display elements. Due to the limited time available for the prototyping of the final design the UI of these elements was designed to be rather simplistic. Instead of a continuous animation showing a gradual change in the displayed information, currently, the UI changes abruptly to a different frame. This difference can change, not only the users' sense of immersion in the virtual space, but also the way they interpret the information given by the virtual HMI.

This was observed during the evaluation of the final prototype, where participants had difficulty interpreting the meaning of the time shown on the screen related to the time-budget. As the prototype did not show the time counting down, it was difficult for users to recognize it as a timer. These details can negatively impact the results of an evaluation conducted with the VR tool. Therefore, it is recommended the design of the HMI screen and HUD elements be improved with better animations, to reflect their behaviour in the real world.

Visibility of HMI Design Elements

As discussed in the previous chapter, during the evaluation of the VR tool participants were able to observe the majority of the HMI design details and interpret the information that was given to them by the system. Nevertheless, one important detail was overlooked by the majority of the participants: the retracted wheel during the Time-to-Sleep driving mode. Given the importance of those details for the design of the HMI, it is recommended that the visibility of all HMI elements be revised, ensuring that they come across as intended through the VR devices.
The screen resolution of the VR device which is used during an evaluation plays an important role in the visibility of certain design details. While participants were able to see the icons presented on the HMI screen, this sometimes required them to lean forward in order to get a closer look. A comprise might be necessary, choosing

between maintaining a higher fidelity to the size of those types of elements in the real world or enlarging them to be more visible to the users.

Exterior Environment

Multiple participants of the final evaluation expressed a desire to be able to control the movement of the vehicle on the road. The current solution includes a simplified road environment in which the vehicle appeared to be constantly moving, independent of the actions of the users. This lack of control over the road environment can cause participants to be detached from the driving context, decreasing the immersive ability of the experience. A high degree of interactivity with the exterior environment is not necessary for all types of experiments. However, interactive experiments, that rely on the participants being immersed in the act of driving, would benefit from the integration of a driving system that allows users to steer the car in a three-dimensional road environment.

Haptic feedback

Virtual Reality systems are often limited in their ability to engage users through all of their senses, particularly the tactile and olfactory senses. When using VR in the evaluation of a product, this can have an effect on the way in which participants' understand and evaluate the interaction with the design. To increase the realism of physical interactions with an object of the virtual environment, for example, the gear lever and wheel elements included in the Mediator VR Evaluation Tool, it is recommended to provided users with a form of haptic feedback. This would signal to users that an action was performed.

During the evaluation of the final prototype, it was observed that participants were often insecure in performing physical interactions, particularly when moving the gear lever into a different position. Furthermore, if participants are asked to act as if they are driving the vehicle they are not able to perform the interaction unless they divert their attention from the road. Adding different forms of haptic feedback as users approach and grab the lever could give an opportunity for this interaction to be performed in a more realistic manner.

10 References

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