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Virtual Reality Tool for Human-Machine Interface Evaluation and Development (VRHEAD)*

Anna Aldea, Angelica M. Tinga, Ilse M. van Zeumeren, Nicole van Nes, Doris Aschenbrenner

Abstract— **Higher levels of vehicle automation come with new challenges for designing safe systems. The Human Machine-Interface (HMI) plays a key role in mediating the interaction between the human driver and vehicle automation. By providing the driver with appropriate feedback, the HMI has the potential to increase mode awareness and situational awareness. For the development of appropriate HMI solutions, usability assessments are essential. Immersive Virtual Reality (VR) technology enables researchers and designers to construct realistic virtual prototypes and immersive evaluation scenarios with less time and resources. The current study presents a VR evaluation tool called VRHEAD, which is designed to facilitate an iterative design process and support the rapid implementation of virtual prototypes to evaluate of an automated vehicle's HMI. Initial results indicate that VRHEAD is a promising approach for the rapid implementation and evaluation of design concepts. The use of VR tools, like VRHEAD, can reduce the time and costs associated with developing high-fidelity prototypes and provide more flexibility in modifying a design according to new research findings, thus broadening the exploration of the HMI design space.**

Keywords—virtual reality, HMI, Human Centered Design, design for experiments, human-machine interaction, design evaluation, iterative design process, rapid prototyping, mode awareness, automated driving

I. INTRODUCTION

Automated systems are on their way to gradually taking over the driving task. To define different steps in the transition toward higher levels of automation, the Society of Automotive Engineers International (SAE) has distinguished six levels of vehicle automation [1]. Those range from zero automation, in which the human driver is in charge of the complete driving task (SAE Level 0), to full automation, where the automated system performs the complete driving task (SAE Level 5). In each of the automation levels in between, the driving task is shared in some capacity by the human driver and automated system. In these levels, the responsibilities of the driver can range from continuously monitoring the driving task (SAE Level 2), to being able to engage in non-driving related activities (NDRAs) but ready to take over the driving task when needed (SAE Level 3). In the near future, it is likely that distinct levels of automation will be available in the same vehicle, depending on the driving conditions [2]. This development entails that the driver must switch between driving modes at various points during a ride, taking on more or less responsibility for the driving task.

The shared responsibility for the driving task poses severalchallenges to the safe operation of a system and increases the risk of human error [3]. Such problems may arise when the human driver is confused about the state of the automation, about his own responsibilities, or believes that the car is driving in a different mode, thus reacting inadequately or slowly [3]. Establishing a good cooperation between driver and automation is important to counteract these problems [4]. Good cooperation requires an understanding of the driving environment by both agents, which is referred to as situational awareness [5], as well as the driver's understanding of the different available automation levels and the currently active mode, defined as mode awareness [6]. In addition, both human and automation must be aware of each other's abilities, limitations, and responsibilities. This knowledge is embedded into a 'mental model' of the human-machine system, or an internal image of the system and it's functioning [7], and it is based on previous and current experience [6, 8]. Successful cooperation between humans and automation depends on the consistency of the mental models of each other's abilities and responsibilities and an understanding of how the driving task is shared [8]. For example, understanding who has control over a specific function at any given time enables both driver and automation to act appropriately and, if needed, allows either one of the actors to safely take over (part of) the driving task without causing conflicts. Therefore, errors could be prevented by facilitating the interaction between humans and automation and providing the drivers with appropriate feedback [9].

Being the primary means of communication between driver and vehicle, the Human Machine-Interface (HMI) plays a crucial role in helping drivers understand the capabilities of the automation and how they are expected to act as automated functions vary over time. Besides traditional visual and auditory displays, the HMI includes all vehicle controls that allow human input to the vehicle and vehicle feedback to the driver [10]. The HMI is tasked with conveying appropriate information to the human driver and moderating all interactions between the driver and automated system, thus ensuring mode awareness, consistent mental models, and situational awareness [10, 11]. In order to develop safe and reliable HMI concepts, it is essential to understand how different interfaces can affect the interaction between the human driver and automated vehicle. This requires new

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designs to go through extensive usability testing to assess the effects these can have on user experience, efficiency of the HMI/driving performance [12], and driving safety [2]. Researchers have developed and evaluated various in-vehicle HMI elements or proposed HMI design principles for automated vehicles [10]. However, further research is still needed to explore the effects of an HMI on human factors and draw conclusions regarding the suitability of HMI design concepts. Currently, the exploration of the design space for in-vehicle HMIs is limited. Cabrall et al. [3] found that most research studies investigate the usability of HMIs through manipulations of simple interface elements and many decisions regarding the HMI design are limited to heuristic expert evaluation and design principles, resulting in a gap in research that does not encourage the exploration of novel solutions in this area. This could be partly be attributed to the limitations given by current evaluation methods used in automotive research, which will be discussed in a later section.

In the current paper, we explore a solution that can facilitate the design and evaluation process of HMIs for automated vehicles using immersive Virtual Reality (VR). Existing literature was examined on three main topics: 1) Weaknesses of current approaches, 2) the benefits of VR in design and evaluation, and 3) the required features for a VR tool. In Section 2, we present the most relevant findings related to the current development and evaluation of HMI designs for automated vehicles and to the use of immersive VR systems in various stages of the design process. VR allows virtual prototypes to be implemented rapidly and at a low cost. It enables an immersive simulation of the HMI design and use context counteracting the weaknesses of more common HMI evaluation methods. We propose VR as a solution to facilitate the development of safe HMIs for automated vehicles. In Section 3, we describe the characteristics of a VR evaluation tool and its intended benefits for the users. Further, in Sections 4 and 5, we detail the design and development process of VRHEAD, **V**irtual **R**eality for **H**uman Machine Interface **D**evelopment **a**nd **E**valuation, a VR tool designed to facilitate the evaluation of HMI concepts for automated vehicles. This tool was developed through collaboration with experts in the field of automotive research and design. Finally, in Section 6, we describe the evaluation of VRHEAD and in Section 7, we discuss the implications of the results for future work.

II. RELATED WORK

A. HMI Development and Evaluation

Developing solutions for new technologies (i.e., automated vehicles) require extensive exploration and research to understand how to best tackle the novel challenges that these bring forth and reduce the risk of producing ineffective and unsafe designs. Current research on the usability and effects on human factors of automated vehicles' HMI designs is focused on evaluating simple HMI concepts, mainly consisting of visual (e.g., presenting information on an instrument cluster or Head-Up-Display) and auditory (e.g., speech and non-speech warnings) interfaces and less often haptic (e.g., vibrations and counterforce feedback) interfaces [3]. Many studies conclude on the effects of the HMI on the driver's user experience by analyzing subjective (e.g., perceived workload) and objective (e.g., reaction time) measures and making a comparison by manipulating one or more HMI factors, such as the output and input of information, the duration/urgency with which information is conveyed or the driver state. However, decisions regarding the design of the HMI are often supported by design principles and expert knowledge, which leaves a gap in the explorations of novel problems and solutions [3]. This issue is often addressed by using an iterative design and evaluation process. An iterative process entails implementing multiple ideas into prototypes and testing of those concepts from the early stage of the design. In this way, the interactions with the product can be refined until an adequate solution has been found [13]. However, multiple iterations of a design can be challenging to implement and evaluate due to the limitations of evaluation methods commonly used.

Different methods are used for the evaluation of in-vehicle HMI design concepts. These range from low-fidelity prototypes (e.g., video and paper prototypes) to on-road studies with instrumented vehicles. Each of these methods presents specific benefits and drawbacks. In terms of external validity, on-road studies are preferred, while low fidelity prototypes are regarded to lack sufficient realism [2, 11]. Driving simulators are often proposed as a suitable method for assessing HMI usability [14]. However, some researchers still challenge their external validity [2, 11] as these often lack the immersion of test subjects into the evaluation scenarios, which can affect their reactions to and interaction with the HMI concept [15]. Evaluation methods also differ in terms of the cost and time required to produce the prototype. While on-road evaluations give the highest amount of realism, preparing such an experiment can be very time-consuming and costly and is limited by the risks associated with testing in an unsafe environment [15]. On the other hand, simulators can be easily adapted to a variety of experimental manipulations at a low cost [16]. Simulator studies also offer a higher degree of flexibility, allowing researchers to manipulate certain parts of the HMI design easily. However, this is only true for simulator studies that include simplistic HMI elements such as displays and sounds. As we can observe in the literature, studies that include more complex interventions on the HMI often require physical prototypes of HMI elements such as LED bars [17] or modifications of the steering wheel [18], which again increases costs and time and limits flexibility.

To facilitate the evaluation and development of HMIs for automated vehicles, a solution is needed allowing prototypes to be rapidly implemented and modified. VR systems represent a potential solution, as they allow for high-fidelity and immersive simulation development, but do not require the time and resources needed for on-road evaluations [19].

B. Virtual Reality

VR is a broad area with several definitions within the literature. While there are various types of VR systems, including non-immersive and semi-immersive VR, the term is most often used to refer to an immersive VR system [20]. Immersive VR systems are computer-generated experiences that enable users to achieve a high sense of immersion (the feeling of being part of or absorbed by the virtual environment) and presence (the feeling of being physically present in a simulated environment), resulting in a highly realistic experience [21, 22]. Due to recent technological advancements, VR has become more accessible to consumers and has gained interest in various research fields. Today, the prices of VR Head-Mounted-Displays (HMDs) are relatively low. Moreover, game engines such as Unity 3D and Unreal engine offer users the possibility of quickly creating VR applications with few resources. As such, VR technology has been adopted in many industries and has been successfully used to facilitate different design processes. From the early design phases, VR can be used for brainstorming and concept development, and co-creation. In contrast, while in later phases, we can find examples of the use of VR for prototyping and simulation, for the evaluation of a product, for educational purposes, or training. VR has also been employed in automotive research [15] and design [23], enhancing interactions with HMI components in the virtual environment. The degree of immersion and presence, which VR systems can provide, play a significant role in the successful application of this technology in the design process [24]. Furthermore the degree of presence is correlated to a participant's physiological [25] and emotional [26] responses. Eudave & Valencia [27] found that a driving simulator that used immersive VR evoked a more robust physiological response than a traditional simulator due to the increased sense of presence given by the technology. VR also allows the simulation of various scenarios and environmental settings, which helps transport evaluation participants into the context of use. Besides providing a higher degree of immersion and presence, VR prototyping has proven to be more efficient in terms of time and costs than other prototyping methods [28, 29]. Overall, VR provides multiple advantages within an ample design space making the technology very suitable for an iterative design process.

III. Current Work

A VR tool, VRHEAD, was developed to support an iterative design process and the rapid implementation of virtual prototypes to evaluate of an in-vehicle HMI. The goal is to provide a solution that would allow experts in automotive design and research to explore the in-vehicle HMI design space more broadly using immersive VR. In the development of such a tool, it is essential to address the needs of two distinct user groups involved:

Researchers/designers: Researchers and designers working on developing automotive HMIs will be implementing and manipulating designs in the VR tool.

Naive participants: Participants who will experience the HMI design in the virtual environment while data on their experience is being collected to gain insight into the effects of the HMI design.

With VRHEAD, researchers and designers alike can perform assessments of complex HMI concepts in a controlled environment by manipulating different parts of the interface. Exploiting the benefits of virtual prototyping and VR realism, we focused on creating a realistic visual representation of the in-vehicle HMI. The focus of the design was to allow for sufficient flexibility in manipulating different HMI elements and providing a framework onto which designers and researchers could quickly and easily implement their concepts. This is achieved through a combination of predefined assets and features and existing tools within the Unity 3D platform.

IV. Development Process

VRHEAD was developed following a user-centered, iterative design approach, using 1) expert interviews and 2) rapid testing of low fidelity prototypes with both researchers and designers and naive participants. Researchers and designers working on designing of an HMI for automated vehicles within the European Union's Horizon 2020 'MEDIATOR' project (No 814735) were involved throughout the complete development process. The MEDIATOR project aims to develop an HMI that mediates the transition of control between human drivers and automated vehicles based on who is most fit to drive. The MEDIATOR researchers and designers provided insight into the design and development process of an in-vehicle HMI. This collaboration led to the development of the final iteration of VRHEAD, which was designed to support the researchers and designers in answering research questions regarding the MEDIATOR HMI during the project's design phase.

Semi-structured interviews were conducted with a researcher and the lead designer of the HMI in order to start with the expert interviews used in designing VRHEAD. These experts described the types of research activities they were conducting and the characteristics of the HMI concept, which consists of several elements and multimodal interactions. Based on the input from the expert interviews, the first concept for VRHEAD was proposed. This consisted of a primary virtual environment, including a realistic vehicle model in which different interactive HMI prototypes could be easily manipulated and tested. In the design of early prototypes, features were added iteratively, based on feedback from both researchers and designers (N = 3) and naive participants (N = 9), representing the two different user groups of the tool. The vehicle model and fundamental interactions within the virtual space (e.g., avatar movement, object grabbing) were extended in the following prototypes with an exterior environment and more complex interactions based on the identified needs of the two user groups. Each prototype was tested with naive participants who were shown various manipulations of HMI concepts. Following the experiment, qualitative data regarding their experience with VRHEAD was collected through semi-structured interviews. These activities contributed to the improvement of the realism of the scene and the user experience and feelings of presence and immersion in VR. The experience of the MEDIATOR designers and researchers was also evaluated and served to improve how HMI elements could be manipulated and evaluation scenarios customized as needed. Results of these early evaluations defined the final design of VRHEAD.

A. Software

The tool was built using Unity 3D game engine, version 2020.2.6f1. This platform was chosen because it offers an abundance of tools and assets that can facilitate the rapid development of interactive virtual environments and their implementation with various mixed reality (XR) devices.Unity's XR Management Toolkit was additionally utilized. This toolkit provides a framework for 3D interactions using inputs from various XR devices, including commercial VR (e.g., Oculus Quest, Oculus Rift, HTC Vive, etc.) and AR devices (e.g., HoloLens). The XR Management Toolkit contains a library of components necessary to manage movement in the VR space and create fundamental object interactions such as hovering and grabbing. Therefore, this toolkit facilitates the quick set-up of interactions with various virtual elements and allows for the development of cross-platform VR applications.

In combination with the Timeline Tool plug-in, the Unity Animation System was used to create various test cases by animating the HMI elements present in the scene. The Timeline Tool offers the possibility of creating complex events within a scene, being able to manage multiple animations, audio, and events simultaneously. Furthermore, creating or modifying such events does not require any coding skills, making the tool easy for various users.

B. Hardware

VRHEAD was implemented and tested using the Oculus Quest 2 Head-mounted-display (HMD) and controllers. The Oculus Quest 2 offers 6 degrees of freedom of movement in the virtual space with tacking of the user's head (through the HMD) and hands (through the controllers).

V. VRHEAD

Figure 1 shows a schematic overview of VRHEAD resulting from the development phase and its use.Through VRHEAD, naive participants can experience the HMI in different use casesand respond to the HMI through an interaction with certain HMI elements. For example, a researcher or designer can run VRHEAD through Unity and use it to create customized evaluation scenarios by integrating animations of individual HMI elements onto a Timeline sequence. Besides animations, researchers and designers can also independently modify the various parts of the virtual environment, which are described below. After finalizing the modifications, the scene can be exported to be used during an evaluation session. A Wizard-of-Oz system was created to allow those leading the evaluation session to control the scenes and animation sequences the participant views through a connected Bluetooth keyboard.

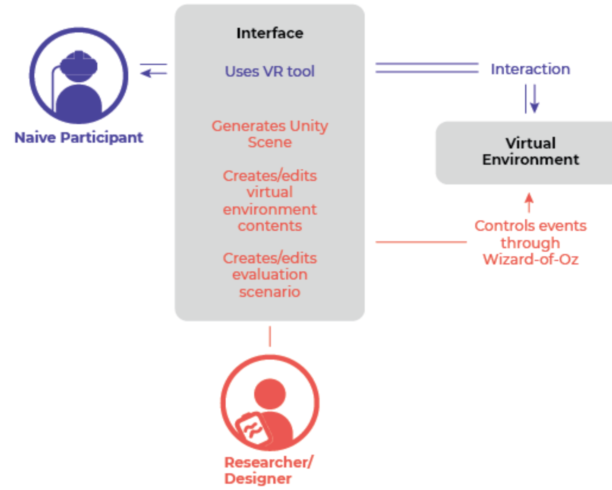

Figure 1. Overview of VRHEAD. Elements of VRHEAD that apply to naive participants are listed in blue text and elements that are important for researchers and designers are listed in red text.

1) Virtual environment content

The virtual environment consisted of the following main components: 1) Vehicle model, 2) HMI elements, 3) environment model, and 4) hand models. These components will be described in more detail below.

Vehicle model – A 'stripped down' vehicle model onto which various HMI components can be added. The vehicle is a modified version of a 3D asset that was retrieved from the Unity asset store and chosen due to its visual realism. Elements of the existing HMI were removed to provide a blank slate onto which new designs can be added.

HMI elements – Five in-vehicle HMI elements were included divided into two categories. The first refers to conventional in-vehicle HMI components such as a wheel, a shifter, a Head-Up-Display, and audio feedback. The second includes novel components, which were added based on the design of the MEDIATOR HMI, such as ambient lighting, and LED bars. These assets were created as prefabricated objects and are composed of separate 3D and 2D (e.g. screen UI elements) models, which can be easily duplicated and manipulated. In addition,the HMI elements were animated to create various test scenarios and managed by the Timeline Tool. An overview of the HMI elements is presented in Fig. 2.

Environment model – A simplistic exterior environment was used to enhance the realism of the experience and give users a feeling of being inside a moving vehicle. This consists of an inverted 3D sphere, onto which an image, animation, or video of a road can be projected. In addition, environmental audio, consisting of the sound of a moving vehicle and engine, was also included to enhance the immersion of the experience.

Hand models – Providing users with functional hands in the virtual world improves their sense of presence and can shape their perception of affordances in the virtual space [30, 31]. Therefore, virtual models of human hands were included. The hands are controlled by the VR controllers, through

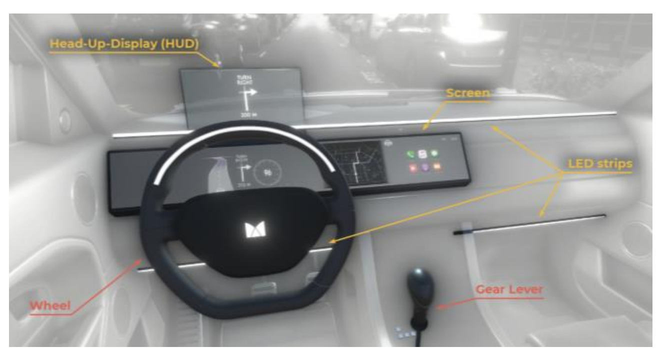

Figure 2. An overview of the HMI elements in VRHEAD. The HMI elements indicated with red text include physical interactions, allowing users to grab and move the objects with the controllers, the elements indicated in yellow are only conveying information visually.

which users can perform grabbing and pinching actions.

VI. Evaluation

Two experiments were conducted to evaluate VRHEAD. First, the tool was evaluated with a group of naive participants (Experiment 1). Then, the tool was evaluated by a MEDIATOR researcher and designer (Experiment 2). In Experiment 1, the aim was to examine the naive participants' experience in the virtual environment and with the simulations. Experiment 2 concerned the usability of VRHEAD for the customization of virtual prototypes of various HMI designs by a researcher and designer with moderate and no experience with Unity 3D or similar software respectively.

A. Experiment 1: Evaluation with naive participants

Experiment 1 was conducted following the Rapid Iterative Testing and Evaluation method (RITE). This evaluation method is typically used from the early stages of a design project to perform usability tests and gain insights that lead to rapid iterations of a design by finding and fixing issues [32]. In the current experiment, RITE was used to evaluate and improve the user experience.

1) Methods

a) Participants

Ten participants were included in Experiment 1, of which three were male and seven female with ages ranging from 24 to 28, mean age = 26, *SD* = 1.33. Participants were recruited amongst university students at the TU Delft.

b) Measures

ITC-SOPI – The participants' sense of presence and their involvement in the virtual environment, whether the content is perceived as lifelike or realistic, and the occurrence of negative effects when exposed to the VR scene were measured with the ITC-SOPI spatial presence, engagement, ecological validity, and negative effects scales [33].

NASA-TLX – The NASA-TLX [34] was used to evaluate the subjective workload experienced by the participants as they were monitoring and processing the information communicated to them by the HMI.

UEQ – The subjective user experience with VRHEAD of the test participants was measured by the use of the User Experience Questionnaire [35].

Semi-structured Interview – A semi-structured interview was conducted, asking participants which aspects of the virtual environment felt less realistic and negatively affected their sense of immersion in the scene. They were also asked to express their opinion on how the experience could be improved.

Think-aloud – The concurrent think-aloud method [36] was employed in which participants think out loud what they see and experience.

c) Procedure

The duration of the experiment was circa one hour for each participant. 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 to allow for fixes to issues to be implemented. Following each evaluation, the qualitative insights gathered from the user tests were reviewed and used to improve 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.

Two different scenarios were evaluated. These scenarios represented different types of use cases that were deemed important in the MEDIATOR project. In the first use case, participants were shown an HMI design that changed four times to give different information regarding the state of the vehicle automation (i.e., presenting four different driving modes). Participants were asked to observe and interpret the visual information conveyed by the HMI by thinking aloud. Each driving mode was shown for 3 minutes with 30 seconds breaks in-between, during which the screen was black and a countdown was displayed. In the second use case, participants were exposed to a driving scenario in which they were prompted to perform a transfer of control through an interaction with the virtual shifter.

The study included the following steps:

General introduction/informed consent procedure – Participants were given an introduction to the experiment and were asked to sign an informed consent form.

Preliminary questionnaire – Participants answered demographic questions.

VR familiarization – Participants familiarized themselves with the VR equipment and the virtual environment. They were given an explanation on how to properly wear and use the Oculus Quest 2, after which they were given a chance to adapt to the virtual environment. At this moment, participants were immersed in a virtual scene similar to the scenarios (i.e., a car interior and a simple exterior environment), but which did not include any of the evaluated HMI components.

VR use cases – The participants were exposed to both use cases in VR while following the think-aloud procedure. Participants were seated in a real car seat, helping them feel immersed in the given scenario. The VR device was wirelessly connected to a laptop, allowing a test leader to view the virtual scene from the participants' perspective in real-time. The different evaluation scenes were activated remotely.

Questionnaire and interview – Participants completed a questionnaire (including the measures discussed above) and a semi-structured interview.

2) Results

The content of the virtual environment was modified after each evaluation session based on the most relevant insights gathered from the semi-structured interviews. The main issues noted by participants during the first evaluation session were related to the short time they were given to view and interpret HMI feedback during the first use case and to the static road in the virtual environment. The latter was thought to reduce the realism of the scene. Participants expressed a desire to view a dynamic/moving road to simulate the experience of driving. This was integrated into the subsequent prototypes through 360-degree animation to simulate the movement of the vehicle on a straight road. In the second iteration, the road environment consisted of images captured from the top of a moving vehicle, retrieved from Google Street View, presented at a low frame rate of 5 frames per second. This change introduced unwanted negative effects for the participants, including dizziness and nausea. Simulation-induced sickness symptoms can be caused by moving objects in the virtual environment and inconsistencies between a realistic visual stimulus and other stimuli [37]. To reduce the chance of such symptoms, in the third iteration of the prototype, the road animation was changed to a stylized/abstract looping animation, with fewer moving objects (e.g., only some trees and bushes on the road) and a stable horizon line. This was enough to induce a feeling of movement in the vehicle while not causing dizziness or distracting the participants from the subject of the evaluation. To further match the experience to the real scenario, an environmental sound of a driving car was added. Fig. 3 shows

Figure 3. Images of VRHEAD in the first (left) and last (right) iteration. In the first iteration, the environment consisted of a static 360-degree photograph, while in the last iteration it is an abstract looping animation.

two images of VRHEAD captured in the first and third sessions.

Overall three sessions, the average rated spatial presence while immersed in the virtual scene was 3.73 (*SD* = 0.38). Engagement with the VR content was rated 3.97 (*SD* = 0.55) and the ecological validity was rated 4.06 (*SD* = 0.52). The negative effects experienced by participants during the experiment were averagely rated at 1.81 (*SD* = 0.76). Note that all these scores are on a scale from 1 to 5. The scores suggest that VRHEAD offers an adequate presence and engagement with the viewed content while not inducing many negative effects for the user.

The workload was given an overall raw/unweighted score of 28.58 (*SD* = 22.96) on a scale from 1 to 100 across the three sessions. This score is comparable to the lower scores recorded in other studies and is associated with driving and visual search [38].

The user experience was rated from -3 to +3, where -3 represents the most negative and +3 the most positive answer. The results were examined over all three sessions according to the six items included in the UEQ: Attractiveness was given an average rating of 2.10 (*SD* = 0.74); perspicuity 1.57 (*SD* = 0.82); efficiency 1.70 (*SD* = 0.65); dependability 1.65 (*SD* = 0.62); stimulation 2.12 (*SD* = 0.60); and novelty 1.77 (*SD* = 0.55). These averages indicate that VRHEAD was rated relatively positive in all aspects.

When examining the scores recorded in each session separately, we noticed an increase in the ratings related to the negative effects given during the second session. The mean score given by the second group of participants was 2.77, while in the other two sessions, the mean scores were 1.38 and 1.41. No noticeable differences occurred in workload and user experience between the three sessions. The second session's higher score on negative effects can be attributed to the road environment animation presented during this experiment.

The semi-structured interview and think-aloud data indicated that the virtual environment was sufficiently immersive as participants expressed feeling as though they were in a real vehicle. However, participants indicated a lack of interactivity with the virtual environment. Even with the introduction of the movement of the vehicle participants indicated a desire to have control over the steering and acceleration of the vehicle. Another observation from the semi-structured interview is related to the use of VR controllers for the interaction with the virtual prototypes. Participants indicated that interactions with certain parts of the HMI design which involve the sense of touch could be more realistic.

B. Experiment 2: Evaluation with researchers and designers

1) Methods

a) Participants

A researcher and a designer, both involved in the research and development of the MEDIATOR HMI, participated in the study. The researcher had a moderate experience with Unity, while the designer had none.

b) Measures

Questionnaire – A short questionnaire was administered to gain insight into the experience of the researcher and designer. The questionnaire was formulated using four items from the QUESI questionnaire [39], one of the following factors: Perceived achievement of goals, the perceived effort of learning, workload, and familiarity. In addition, three items were developed for the purpose of the current experiment and were included in the questionnaire. These were related to the ability to locate information within the user guide, the clarity of the information and the availability/completeness of the information.

Semi-structured interview – Three open questions were asked regarding the understanding of the information and experience with customization of the virtual environment.

Think-aloud – The concurrent think-aloud method [36] was employed in which participants think out loud about what what they saw and experienced.

c) Procedure

The researcher and designer were asked to complete several of tasks to construct a custom evaluation scene with VRHEAD within 120 minutes. They were provided with a user manual and a set of instructional videos, which included essential information pertaining to the use of Unity 3D and, specifically, the VRHEAD Unity project. Through the manual, instructions were provided on performing several actions that would lead to the customization of an HMI element (Unity prefab object) or a scenario (Unity Timeline sequence). While completing the tasks, the researcher and designer were asked to describe their actions and what they were thinking out loud in order to gain insight into the understandability of the instructions provided and the reasoning behind their actions.

2) Results

The ratings regarding the experience of the researcher and designer (on a scale from -2 to 2) are presented in Table 1. The ratings indicate a difference between moderate experience and no experience with Unity. Compared to the ratings of the moderate user, indicating a relatively good overall experience, the ratings of the novice user indicate a relatively negative experience.

TABLE I. QUESTIONNAIRE RATINGS

	Moderate experienced user	Novice user
Perceived achievement of goals	2	1
Perceived effort of learning	1	-2
Workload	1	-2
Familiarity	1	-1
Ability to locate information	2	0
Clarity of information	2	1
Availability of information	1	-2

a. The table shows the ratings on the seven questionnaire items rated on a scale from -2 to 2.

The data from the semi-structured interview indicate that the researcher and designer were able to follow direct instructions and perform minor changes (e.g., altering the position and duration of animation clips within a timeline, modifying the scale or position of HMI elements in the scene). However, they both encountered difficulties when attempting to alter the content in ways which were not directly described in the manual and instruction videos and only achieved these goals with some additional help. Before independently using VRHEAD, a user must be familiar with the functioning of several elements included in the tool, such as the animation system, prefabricated objects (prefabs), and the structure of the hierarchy. Processing this amount of information requires a significant amount of time. Therefore, while novice and moderately experienced users can perform minor changes to the scene if provided with step-by-step instructions, the assistance of an experienced Unity user is recommended for larger changes.

VII. DISCUSSION

This paper explored a solution to overcome limitations in the development and evaluation of automated vehicle HMI design throughVR technology. The following research questions were the focus of our background literature research: a) *What are the weaknesses of current approaches to developing and evaluating of HMI solutions for automated vehicles?* b) *How can VR support the design and evaluation of HMI concepts for automated vehicles?* c) *What are the required features of a VR tool and which benefits does it provide its users?* Based on the literature and a user-centered iterative design approach, we developed VRHEAD, a tool intended to facilitate researchers and designers in the design process and to broaden the HMI design space. Two experiments were performed to evaluate VRHEAD: In the first experiment, we measured the user experience of naive participants, representing those who will virtually experience an HMI design. In the second experiment, we measured the usability of the tool to create of custom evaluation scenarios with researchers/designers, representing those who work on the development of HMIs and that will be implementing and manipulating designs with the tool. The findings indicate that VRHEAD is a promising solution.

With VRHEAD, we could simulate parts of an HMI being developed within the MEDIATOR project, which would have otherwise been difficult to implement at an early stage of the design process. In-vehicle HMI designs for automated vehicles often include several interactive elements that must work simultaneously. These are often difficult and expensive to replicate through a physical prototype. They require the sourcing of various components (e.g., moving parts, displays) and time-consuming programming to replicate the intended interactions. Even more challenging is the implementation of future technologies in working prototypes. For example, a semi-transparent Head-Up-Display can be challenging to recreate with existing technologies. In contrast, VR tools for prototyping and evaluation allow for the simulation of complex interactions with the HMI. Multiple HMI components can easily be programmed to work in a synchronized manner and can be modeled to recreate any shape and visual effect without additional resources. This demonstrates how tools such as VRHEAD could benefit researchers looking to simulate complex HMI designs.

While we recommend using VR technology to develop and evaluate novel HMI designs, we recognize that tools such as VRHEAD cannot fully substitute other evaluation methods. In particular, high-fidelity on-road studies are still needed to accurately assess advanced HMI designs' usability and safety.

The current work represents an initial concept using VR technology to support the development and evaluation of novel HMI solutions. Further research is required to assess how VRHEAD could support the design and evaluation of HMI designs in different projects and identify additional features required for its use in various usability assessments. Further exploration is needed into the implementation of interaction modalities between users and different elements of the virtual environment. The addition of haptic feedback (e.g., through haptic gloves or physical prototypes) could lead to significant improvements to VRHEAD, as it would allow users to experience the HMI through multiple senses and be further immersed in the experience. While in the current work on improving the visual representation of the HMI elements, implementing a more realistic driving scenario and the ability to drive the vehicle is advisable depending of the purpose of each project.

VIII. CONCLUSION

In this study, a VR evaluation tool called VRHEAD was presented to support the development and evaluation of an in-vehicle HMI. VRHEAD showed to be a promising concept for a tool facilitating the development of an intuitive in-vehicle HMI through an iterative design process. Implementing HMI prototypes in a virtual environment in rapidly and cost-effectively opens the possibility of exploring the design space more quickly and broadly. Moreover, effective interaction design solutions such as these could make the difference in achieving a safe and successful transition to higher levels of vehicle automation on our roads.

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