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STATE OF THE ART BARRIERS IN VALIDATION OF DIGITAL MOCK-UPS IN IMMERSIVE VIRTUAL ENVIRONMENTS

Konstantin Wall[1], Wilm Tomaszek-Staude[1], Sandra Poeschl[2] & Nicola Doering[2]

[1]Volkswagen AG, Wolfsburg, Germany, [2]Technische Universität Ilmenau, Germany

ABSTRACT

This contribution addresses state of the art barriers from a user perspective in validation of digital mock-ups in immersive virtual environments. A qualitative one-shot case study was conducted with (n=12 vehicle experts) of an immersive validation tool and process in a car manufacturing company. Data collection was performed by means of semi-structured interviews and analyzed by method of Mühlfeld et al. (1981). The results show major challenges when VR technology is used in operational environment. Several users reported symptoms of cybersickness caused by poor system performance or usability of VR devices. A rather surprising result was the self-assessment of experts that were asked to validate from "end customer's point of view". Shortly after the start of validation they unconsciously resumed their expert's role. Another result shows a disparity in perception of digital (DMU) and physical mock-ups (PMU) incorporated in the validation. Users have adjusted the PMU like a real car (seat, steering-wheel, mirrors) but only a minority has done this with the DMU. Insights were provided into needs and expectations of IVDMU users. In the consequence more applied research should be conducted for example to understand effects of perception disparities of PMUs and DMUs (e.g. treated like a real car vs. treated like a visual presentation) under the aspect of validation reliability. The self-assessment of the expert's role in IVDMU should also be further examined. Further research should be conducted on factors contributing to cybersickness in order to raise user acceptance of IVDMU.

1. INTRODUCTION

Virtual Reality (VR) has become popular when it comes to the evaluation or validation of digital mock-ups (DMU) [1]. Due to the increased available computational power, the used 3D-models can have an immense amount of detail (as described in 4.5) and be experienced in immersive virtual environments (IVE). Immersive validation of digital mock-ups (IVDMU) has become very attractive for some industry branches like aviation, aerospace and automotive industries [2][3][4]. These industries benefit from the agility of VR during the product development process (PDP) as well as of the lower costs of DMU in comparison to physical mock-ups (PMU) [5]. Although VR technology has made some serious progress for decades, there are still caveats when it comes to the reliability and usability of IVDMU (e.g. lack of physical correct real-time lighting calculation, unsatisfactory usability of VR devices etc.).

This paper presents a qualitative case study of an IVDMU process and system (as described in 3.2 and 3.3) from a user perspective. The purpose of the study was to explore factors that play a role in the validation of virtual and physical mock-ups (PMU), the perception of DMUs in immersive virtual environments (IVE) with the focus on the user's point of view and daily operation conditions. Further current problem areas of IVDMU should be identified. Results of our study may help to understand the recent requirements of such systems in production operation conditions.

2. RELATED WORK

Several definitions of digital mock-ups in different contexts have evolved over the years [1]. In the presented work, we relate to the definition proposed by Dai & Reindl in 1996, whereby a "Digital mock-up (DMU) is a realistic computer simulation of a product with the capability of all required functionalities from design/engineering, manufacturing, product service, up to maintenance and product recycling" [6]. In the presented work mock-ups of vehicles were the point of interest. In the following the terms DMU and *virtual vehicle* are used synonymously to describe the digital representation of a vehicle, displayed in the IVE. The term physical mock-up (PMU) is referring to a design model (1:1 scale) of a vehicle project (e.g. a functional interior representation model).

As mentioned before, DMUs in combination with VR are playing an important role in the PDP. The development of a new product in the automotive industry takes up to four years. In this period, many engineering and design processes run in parallel and even before a first PMU can be build, product decisions based on construction data need to be made [7].

Using visualized digital data instead of building hardware prototypes helps companies to shorten the time-to-market of a product and can accelerate the start of production, which means an earlier return of investment [8][3]. The lifecycle of a complex product can even last up to 30 years, for example in aircraft development.

At Volkswagen the use of VR technology has started in 1994 [7]. While in the beginning, DMU were mostly displays of monitor screens, soon after the first immersive virtual environments were arising incorporating Head-Mounted-Displays (HMD), Data Gloves or CAVE setups [9].

In such IVEs the user has a sense of being in the virtual world (and can experience the DMU instead of just looking at it) [10], [11]. There is a common understanding in the literature that the experience that the user has in an IVE depends on the simulation fidelity, which is provided by a VR system. It also depends on the subjective factors of the user itself (adaptability, experience and practice, motivation etc.) [12], [13]. In our work, we use the terminology proposed by Mel Slater back in 2003 where *immersion* is defined as the level of sensory fidelity provided by the VR system and *presence* is a sense of 'being there' in a virtual environment (VE), as a psychological response to a VE provided by a VR system [14].

For the process of IVDMU, this means that "The VR system simulates and renders all characteristics relevant to the particular context as precise and realistic as possible in an immersive environment" [15].

Over the last decades, a lot of effort has been put into the research of immersion and presence factors and their relation [12], [16]. Furthermore, collaborative research projects between industry and research (like the AVILUS project) have been looking into particular needs and requirements of IVDMU, like *visual* and *functional* validation[1] of product characteristics for industrial use with the result of further development of applicable technologies [5]. However,

[1] In terms of quality assurance.

most research has been done in laboratory conditions focusing on one or few aspects related to IVDMU.

In our work, we investigated an IVDMU process and system to get a status quo of the challenges we face in 2014 when it comes to daily operational use of such technologies. Our goal was to identify recent user requirements on technology and its operation.

Therefore our research questions were:

> ***RQ1a****: What factors play a role in the validation of virtual and real vehicles from the user's point of view?*
>
> ***RQ1b****: What factors play a role in the perception of a vehicle in IVE/VR from the user's point of view?*
>
> ***RQ2****: What current problem areas are present in IVDMU technology?*

3. METHOD

3.1 Case Study

A qualitative one-shot case study with automotive experts that performed an IVDMU was conducted to shed light on these questions. An explorative qualitative approach was chosen, because little is known about the user's needs and expectations of IVDMU in relation to recent VR technology. Data collection was performed by means of semi-structured interviews (see 3.5). The semi-structured interview is well suited for this study because it allows the users to dynamically and flexible bring in their own thoughts and therefore contribute to the richness of data.

3.2 Validation Process

The VR DMU validation process in general is used to hedge various properties of the later vehicle from the end customer's perspective. For this purpose project related vehicle experts are invited to participate in the validation process from this particular role while several presentation modalities of a vehicle project are provided to them. These might incorporate a PMU, real cars (e.g. current model) and the combination of the DMU and the VR seating buck (VRSBUCK) as described in 3.3. The displayed data of the latter are more recent than the PMU's data – due to shorter preparation times – and thus more accurate as well as of a higher importance for the project.

To meet the different versions of data, it is intended to assess each particular aspect (e.g. visibility through the rear window) once in each form of representation (PMU / DMU / RC). Some aspects cannot be assessed in every condition, either because of the absence of some presentation modalities (e.g. no haptic feedback is given in the DMU / VRSBUCK) or the presence of some options, that are not feasible in the other conditions (e.g. presentation of abstract data, like an overlay of different versions of rear view mirrors). The ratings are stored in a database for a later analysis. It is up to the vehicle experts in which sequence they will make their assessment in order to ensure an optimal use of the resources.

3.3 Technical Setup

The IVDMU system consists of (1) a seating buck (see Figure 1), which can be thought of as a minimal car-interior mock-up, (2) a Head-Mounted-Display, (3) an optical tracking system, (4) a VR cluster for computation and (5) the VR Software including the DMU.

Seating bucks are common for various development evaluations in the automotive industry [17]. The used seating buck is based on a chassis which houses a steering wheel, a car seat and pedals from real car models. Each of these elements is electronically adjustable. Thus, the physical and virtual elements are superimposable during the validation process and further proportions can be adapted to a variety of car models. The virtual vehicle (DMU) was placed into a photo-realistic road intersection.

The IVE was created with RTT DeltaGen 11 (incorporating RTT *Scale* and RTT *Immersive* modules) and powered by three Dell Precision T7600 workstations, equipped with 2 x Intel Xeon E5-2687W 3,8 GHz CPU; 256 GB of RAM and 2 x nVidea Quadro 6000 GPU. The HMD was a NVIS nVisor ST50 HMD with a resolution of 1280x1024px on each eye with a total HFOV[2] 40° and VFOV[3] of 32°. The HMD and an additional interaction device are tracked with an ARTTRACK2 system.

Figure 1: Schematic representation of the VRSBUCK.

3.4 Sample

The sample (n=12) consisted of automotive experts – with different backgrounds – who were regularly involved in the IVDMU of the particular vehicle project at Volkswagen. Eight subjects were male (66.6%) and four were female (33.3%) with an average age of 38 years (SD=9.26). Five participants had previous experience with VR or 3D-content at work or at home (e.g. computer games, 3D-movies etc.). Four participants have used the HMD in combination with glasses.

3.5 Measures

The interview outline was divided into three main topics and several subtopics. We wanted to identify which IVDMU factors are relevant from the user's point of view and which might be negligible. Further, we were interested in the perception differences among physical and virtual vehicles and prototypes. And last, we tried to identify problematic IVDMU areas in order to be able to improve the system and process as well as offer the user a better possibility of validation (e.g. reduce causes of cybersickness, enhance interaction with the DMU etc.).

[2] HFOV: Horizontal field of view

[3] VFOV: Vertical field of view

3.6 Procedure

The interviews were carried out right after the IVDMU. The data collection was performed by means of semi-structured interviews after obtaining an informed consent from each participant. Relevant observations that were made during the use of the VRSBUCK (e.g. the subject was supporting the HMD with one hand) were addressed during the interview. The average interview duration was about 18 min (SD=04:49min). The interviews were recorded, transcribed and analyzed by the method proposed by Mühlfeld et al. (1981) [18].

4. FINDINGS

In this case study, we aimed to get a status quo of our seating buck setup and the related validation process from the user's point of view. Our goal was to gain an understanding of how the users perceive and use the DMU and VRSBUCK as a validation tool within the IVDMU and to identify current challenges. The results point us in directions we believe are relevant and transferable to similar IVDMU tools and processes and should be discussed among the scientific community.

4.1 Predisposition towards PMU/DMU

Numerous users stated that they had had (or acquired during the first IVDMU) a clear predisposition towards the assessment of particular vehicle aspects either in the PMU or the DMU/VRSBUCK condition. Subsequently they named several pro or contra arguments towards or against either the "virtual" or the "physical" validation. On the one hand, aspects of reachability, spatial perception (e.g. sense of space), size estimation (e.g. of compartments) are preferably made in the PMU. The mentioned advantages were for example the intuitive and sensually more complete interaction with the mock-up (e.g. assessment of reachability of elements by reaching out and touching with a hand), usage of natural given measures (e.g. size of own hand) for size evaluation of compartments, estimation of sense of space (e.g. straighten the body and check the distance to roof lining) and the presence of haptic feedback (e.g. grasping a door handle). On the other hand, some aspects related to the view out of the windows, mirror fields of view as well as the visualization of textures or variants of modules are rather made in the DMU / VRSBUCK condition.

Our concern about this predisposition is that the PMU is of course a geometrical correct representation of a vehicle interior but has for example no material textures. Therefore, it is well suited for reachability validation, but might not reflect the correct sense of space because of its monochrome surfaces, which are usually kept in a dark color. If the users only prefer this type of mock-up from a gut feeling or simply because they do not suffer from any symptoms of cybersickness, there is much room for biased validation results.

One Example may be found in unnatural lighting conditions. Usually PMU validations are set up indoors in factory halls with artificial light where the mock-ups can easily be moved around. Because of their incomplete and fragile mock-up character it is frequently not feasible to put them on a real road. For the IVDMU we still lack software solutions to generate physical correct lighting in real-time to perform reliable validations without PMUs.

Another example is the representation of oneself. While users are able to see their own body in PMUs and use it as natural measure, they are not in IVDMU with HMD. This results from the lack of eligible solutions for body tracking and virtual body representations for operational business environment. In IVDMU the user frequently does not have any "live" body representation that could serve as a virtual natural measure.

At present, body tracking systems require time-consuming setup and calibration processes of each user. The preparation in most cases would take more time than the validation task. Therefore, such solutions are not practicable for validations with large user groups. The same limitations still counts for hand-tracking and hand representation.

According to this, we propose that both mock-up types have to be biased when it comes to the assessment of the sense of space in a vehicle interior. The PMU may be inappropriate for optimal validation in terms of unnatural appearance (due to monochrome interior color, no textures etc.) and the artificial light conditions (due to the indoor placement). The DMU may be inappropriate because of the physical incorrect lighting calculations and the lack of virtual body representation.

Both the stated predisposition and the illustrated differences in these two types of mock-ups should be considered in future research.

4.2 Self-assessment of the user's role / DMU validation from customer's perspective

A rather surprising observation was the self-assessment of the subject's role within the validation process. The subjects were invited for a validation "from an end-customer's point of view" and confirmed their role as such in the beginning of the interview. However, they later declared those aspects of the DMU, as the most important for the end-customer, to which they were related in their professional function in this particular vehicle project.

On the one hand, these experts are often asked to mime end-costumers and conduct a validation from this particular role. On the other hand, our results indicate that they frequently resume their expert role shortly after the start of a validation. They then tend to focus and judge isolated aspects from their operational field of activity (e.g. readability of symbols on a rotary light switch). Nonetheless if asked how a friend who asked them for advice on how "to get a good impression of a car that he or she is going to buy" they frequently suggest to go through some everyday scenarios (e.g. to load the car with goods and groceries or sport utilities, to make a test drive). None of these scenarios was requested by the participants for both types of mock-ups.

A lot of customer related product functions are validated by experts nowadays. The reason for this may be the need to keep prototypes confidential and retain competitive advantages or be justified from an economic point of view. In both cases it is important to keep in mind that experts who are asked to validate from an end-customer's point of view might unconsciously perform otherwise.

4.3 Perception of the virtual vehicle / DMU

Another result was related to the manner in which the subjects are interacting with the seating buck and the virtual vehicle. While some subjects have used the possibility to set up the PMU into a comfortable driving position (seat, steering-wheel position, and mirrors) – even though it is just an interior mock-up and has no proper wheels attached – none of the subjects have done this in the VRSBUCK, after getting in, even though it has comparable adjustable physical elements (see Figure 1).

This result illustrates that there is a different perception of a DMU in comparison to a PMU that represents the same future product. The virtual vehicle in the VRSBUCK was not treated like a car, even though it had all the familiar physical elements. In future studies it therefore may be relevant to evaluate how a virtual prototype needs to be presented to the user in IVDMU to be perceived as the represented product. Further, it is important to research the effect of the perception disparity of PMU (e.g. which is treated like a real vehicle) and DMU /

VRSBUCK (e.g. which is treated like a visual presentation, even though in has the same physical elements) on the reliability of an IVDMU.

4.4 Head-Mounted-Display

Some frequently reported problems were addressed towards the VR system. Some subjects have reported the HMD as inconvenient for the given task because of its weight (of 1050g) and the uncomfortable cable routing on the back, which limits the user while turning their head. Another mentioned problem is the narrow total field of view of the display.In our case, we use the most convenient HMD on the market and yet lack of sufficient field of view, have a low resolution and an unfavorable cable routing and weight. Cable routing of HMDs is a problem that was already formulated since the early days of HMDs [19]. Unfortunately, there are still no satisfactory or flexible solutions in 2014. A downward directed routing is designed for upright standing use mostly. However, this type of routing is not suitable for seating scenarios. The cable frequently collides or even interlocks with the seat and in our case exclude the possibility of using a head restraint (as shown in Figure 2). In addition the weight of the cable hose (including 2 x HDMI, audio, and power cords) encourages a tensile load and in consequence causes a slipping of the HMD.

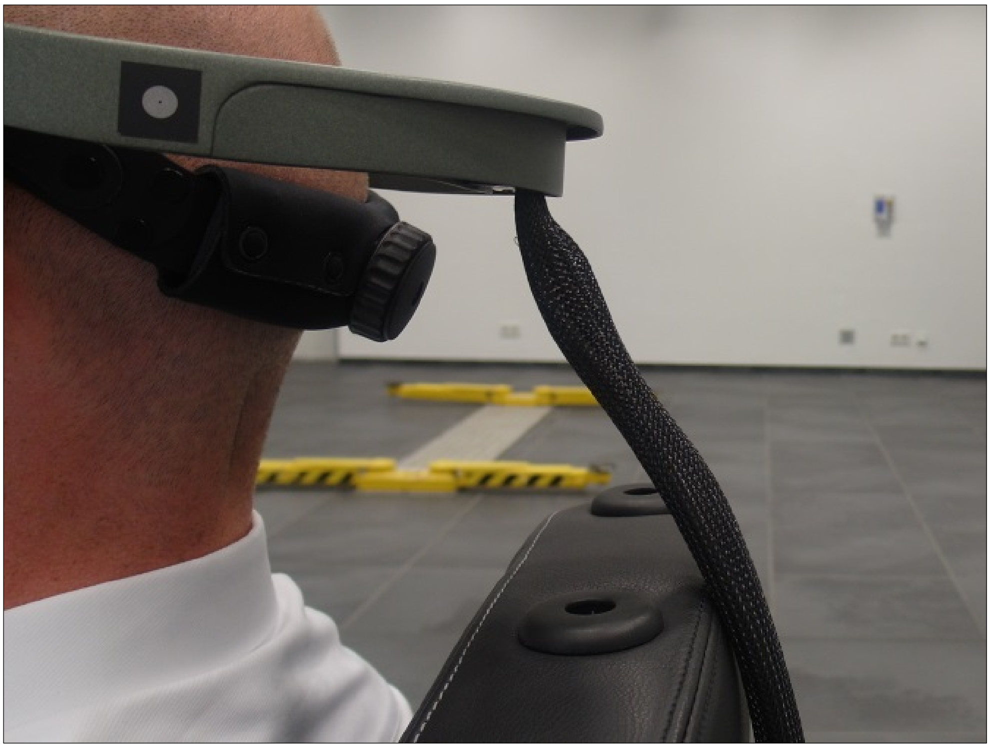

Figure 2: Cable routing of the NVIS nVisor ST50 HMD.

The narrow field of view of this HMD is often discussed in the literature. However, one point that is often forgotten in discussions and is important for validation contexts is the fact that the narrow field of view may force the user to move in an unnatural way. One subject stated that during the task of rating the reachability of the safety belt, he subsequently turned his head to locate its position. With the narrow HFOV of the HMD he was forced to rotate his head further than he would have needed to do in real life to get the seat belt into his range of vision. This inconvenience in turn may be misleadingly rated and transferred as an uncomfortable aspect of the validated product (e.g. vehicle) and not as a characteristic of the HMD and lead to biased validation results.

Furthermore, the unfamiliar and in extreme cases non-ergonomic movements lead to muscular tension and fatigue and can promote cybersickness symptoms (as reported in 4.6). Some reported consequences were that users either canceled the IVDMU or begun to support the HMD on the front by one of their hands. This in consequence led to even more unintuitive interaction with the virtual prototype.

The latter "workaround" was also reported by participants with a head circumference outside of the adjustable range of the HMD. Whereby, users with a too small head circumference supported the HMD by hand but were still able to take part in the validation, while for persons with a larger head circumference there is simply no option to omit this limitation.

4.5 Display Fidelity / Simulator Performance

Several factors have been objected to simulator fidelity and simulator performance.

The used scene for this particular IVDMU (consisting of the actual vehicle project interior/exterior model, previous model, surrounding) had about 62 billion polygons. This partly dropped the display refresh rate in the HMD down to 10FPS[4]. In consequence the scene responded very slowly to viewing angle alternation through head movements, which has been often mentioned during the validation (as observed) as well as during the interviews. However, this performance value is not a constant. Due to the fact that the software package incorporates occlusion calculations, the frame rate changes depending on the current viewing orientation. For example, while the users were looking down into the interior or to the footwell, the other virtual car model and the surrounding were excluded from calculations and the scene reacted very fast (the frame rate was above 25 FPS). If the user raised their head so that objects behind the windshield became visible, the frame rate frame rate dropped abruptly and the scene responded very slowly to head movements. This kind of alternation in response behavior of the IVE led to malaise effects.

Concerning scene performance and display fidelity, scene response can be extremely inconsistent. While looking into scene parts with less detail, the scene responses dynamically and smoothly (e.g. 25+ FPS). However, as soon as more details come into play, the scene response can drop dramatically (e.g. 10 FPS) and suddenly begin to stutter. Both conditions for themselves would be something that the user could adapt to but the dynamically changing response characteristics occur unexpectedly for the user and therefore are hard to accustom to. This leads us to the discussion of a more general performance related point. It is often mentioned in related work that at that time the performance was not very well due to the given data complexity but this will change in the future when more computational power becomes available. Though, this is an erroneous belief. While computational power increases, the complexity of data used for DMU does, too. As mentioned before, the scene used in the presented study has 62 billion polygons, which is exceptionally high for validations, but was dictated by certain validation requirements. In 1996, one of the first DMU for similar operational purposes at Volkswagen had about 60 thousand polygons [19][8]. Almost 20 years later the poly count is 300 times larger[5], while we still are struggling with low refresh rates and high latency and operating in daily business somewhere around the recommendations of 15 FPS from 1998 [20].

The display quality itself (e.g. photo-realistic appearance of leather textures etc.) was often rated and described as "very impressive" by the participants.

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[4] FPS: Frames per second

[5] The virtual vehicles used in the described IVDMU have an average polygon count of 20 billion polygons.

4.6 Cybersickness

Further, the results show that, even though the users had a positive attitude and acceptance towards the IVDMU, they rather tended to avoid longer sessions in the virtual environment. Nine of twelve subjects reported side-effects after being in the IVE, which can be assigned to cybersickness symptoms (e.g. eye strain, headache, vertigo) [21]. The subjects have reported some inconveniences with hard- and software of the system (discussed in 4.5 and 4.6) that may have led to these symptoms.

These inconveniences, however, are predetermined by external factors in a certain way. The DMU is based on computer-aided design (CAD) data from construction branches [22]. To ensure data compatibility and efficient workflow, the industry is tied to only a few VR software products available on the market. Our findings illustrates that the fidelity of an IVE is consequently tied to (a) given data complexity and (b) the performance of the software packages. The same applies to the incorporated hardware.

5. DISCUSSION

This contribution addresses state of the art barriers in validation of digital mock-ups in immersive virtual environments. A lot of research in the field of IVE is done in laboratories under experimental conditions where the focus is put on isolated factors or on their interaction. Our goal was to gain a holistic picture of the current limits of such systems in productive operation conditions and from the user's point of view. These findings are important for planning and setting up as well as for further development of such systems. Further discussion within the scientific community will give new impetus for research work. We conducted a qualitative one-shot case study with users (vehicle experts) of a IVDMU process and tool (VRSBUCK) at Volkswagen. The results illustrate that IVDMUs still face a lot of technical challenges in productive operation - some of which are left over from the early days of VR. Considering that these systems need to be optimized to suit a specific purpose, we conclude that there are constrains both of internal and external nature. The internal aspects concern the rising complexity of DMU data, predefined business processes and the overall acceptance of IVDMU. The external aspects are related to suitable hard- and software available for selection. The VR products needed for the validation of digital mock-ups in immersive virtual environments are demanded by a small target group of which every member has individual requirements. This may cause a kind of stagnation in some technologies that still have not achieved a satisfactory state. A prominent example is the choice of suitable HMDs. These are still heavy, which is often the first comment of a user, non-ergonomic and one is forced to decide between either to have a wide FOV in combination with rather poor visual quality or a narrow FOV with better quality. However, the next generation of HMDs (like the Oculus Rift[8] or the SENSICS dSight[9]) is looking promising to resolve some of these problems. Aside of internal and external restraints, we identified two other interesting aspects regarding IVDMU that should be investigated further. First, our users showed a tendency to prefer PMUs over DMUs when given the choice. We discussed possible reasons and stated our concern about the lost opportunity to work with most recent data if users tend to avoid IVDMU. Second, we stated that that there might be a shift in the user's self-concept regarding their role in the validation process. For example, if IVDMU is performed by experts who are asked to assume a different role (e.g. being a normal

[8] Oculus VR: www.oculusvr.com

[9] Sensics: http://sensics.com/head-mounted-displays/

consumer), they tend to unconsciously resume their expert role and validate differently from what they propose how the other role would/should do.

Although the vehicle experts who participated in this study reflected the diversity of the usual VRSBUCK user group, the convenience sample might be biased due to its non-probabilistic character. Furthermore the small sample size and the fact that the data was collected during one particular IVDMU, transferability to other IVDMU and generalization of the findings is limited. It is likely that aspects would be addressed differently depending on the predetermined parameters of another vehicle project (e.g. complexity of data, individual duration in the IVE during the validation process etc.).

It remains to conclude that immersive VR setups in productive environments are subjected to many dependencies that are disregarded in scientific research. Therefore, we hope to encourage the dialog between industry and science to bring new momentum in the technological development and point out white spots for research work in the actual application of immersive VR. We suggest that more applied research should be done for example to understand effects of perception disparities of PMUs and DMUs (e.g. Why is one treated like a real car and the other like a visual presentation, if both have the same physical basic elements). This research should be focusing on the aspect of validation reliability (e.g. Is validation of sense of space is comparable and valid in PMU and DMU?). The self-assessment of the expert's role in IVDMU should also be further examined. Though experts are frequently the usual user group of IVDMU systems, the shift in the self-assessments (e.g. being in the belief to validate mock-ups for later products from the role of an end-customer, but perform from the expert's role). Also research should be conducted on factors contributing to cybersickness in order to raise user acceptance of IVDMU. The results indicate that even with state of the art technology, a lot of aspects are contributing to cybersickness in daily operation.

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CONTACTS

Konstantin Wall, M.A. konstantin.wall@volkswagen.de

Dipl. Inf. Wilm Tomaszek-Staude wilm.tomaszek-staude@volkswagen.de

Dr. phil. Sandra Poeschl sandra.poeschl@tu-ilmenau.de

Prof. Dr. phil. habil. Nicola Doering nicola.doering@tu-ilmenau.de