Requirements for Virtualization of AR Displays within VR Environments

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Abstract. Everybody has been talking about new emerging products in augmented reality (AR) and their potential to enhance our daily life and work. The AR technology has been around for quite a while and various use cases have been thought and tested. Clearly, the new AR Systems (e.g. Vuzix m100, Google Glasses) will bring its use to a new level. For planning, designing and reviewing of innovative AR systems and their application, virtual reality (VR) technology can be supportive. Virtual prototypes of AR Systems can be expired and evaluated within a VR environment (e.g. CAVE).

This paper proposes the virtualization of AR displays within VR environments and discusses requirements. A user study investigates the necessary pixel density for the legibility of a virtual display in order to verify the significance of guidelines given by ISO 9241-300. Furthermore, equations examine the suitability of various VR systems for display virtualization within VR environments. This will enable reviews of various display systems in a virtual manner.

Keywords: Virtual Reality, Augmented Reality, Virtualization, Display, User Study.

1 Introduction

Augmented reality (AR) is a technology, which can be apply to support technicians in their work of operating and maintaining technical products by the depiction of instructions, status and warnings through mobile devices (e.g. handhelds, tablets, head-mounted displays) [1, 2]. The necessary documents and dialogs should be planned, designed and reviewed within the product development phase in order to provide high-quality manuals at the time of product release. The use of AR technology in virtual reality (VR) [3] is a promising approach, which ensures the quality of AR instructions and enables service training in advance.

The goal of the project "Virtualization of AR systems for maintenance planning in immersive environments", founded by the German Research Foundation (DFG), is to integrate AR technology into the product development process seamlessly. Previous research has investigated the possible combination of AR technology and VR technology (AVR) for the review of AR instruction by developing the prototypes displayed by Fig 1. Fig 1-1 shows AR information being depicted by an AR Display

R. Shumaker and S. Lackey (Eds.): VAMR 2014, Part I, LNCS 8525, pp. 105–116, 2014.

in a VR environment (VRE) [4]. This allows the evaluation of an actual AR System and its dialogs. Another multi-display approach is the use of a tracked mobile device (e.g. tablet, see Fig 1-2) within a VR system [5, 6] enable a high fidelity view into a VRE.

This paper focuses on the possible virtualization of an AR display within a VRE. This virtualization would enable the enhancement of the virtual prototypes by depicting documents and dialogs for maintenance directly within the VRE (see Fig 1-3). The design and review can be achieved without the use of physical AR systems. Within a narrow time frame, issues can be identified and solved in early development stages. Furthermore, a huge variety of AR systems can be tested and even not yet existing/available systems can be evaluated.

Fig. 1. Tree different approaches to bring AR into VREs

2 Investigation of Virtual Displays in VR Environments

According to Azuma [7], an AR system consists of the following functional units: controller, computer and presenter. Since the design of documents and dialogs is primarily visual, the AR display plays an unique role as a presenter. In principle displays are called virtual when the image plane is shifted by optical or holographical system. This technique is used for near-to-eye micro displays (e.g. HMDs) to generate a virtual image, where the perceived distance is larger than the real distance of the micro display. In addition, the representation of an AR display within a VE can be termed a virtual display as well. For this representation the content legibility is fundamentally. The depiction of legible signs, symbols, texts and illustrations essentially depends on the applied VR system. Influencing attributes such as contrast, brightness, viewing distance, pixel density and character properties are described and standardized in ISO 9241-300 [8]. Since the applied rules are based on requirements for electrical visual displays, it is unclear whether the calculated values are applicable for a virtual display within VRE or not.

Essentially, the achievable fidelity of a display depends on its specifications (e.g. contrast, brightness and pixel density). For virtual displays, contrast and brightness are attributes directly determined by the VR system. However, the pixel density of a virtual display depends on the pixel density of the VR system and also on the operator's position in the VR system. Consequently, the AR content is depicted with a altering pixel density, resulting in various virtual display qualities (see Fig 2).

The viewing distance is the distance (d) between the point of sight and a display. In case of virtual displays there are two viewing distances to be considered:

- d_{RD} defines the distance to the physical screen of the VR system.
- d_{VD} is the distance between point of sight and virtual display.

If d_{RD} and d_{VD} are equal, the pixel densities are corresponding (d_{RD1} in Fig. 2). Since the viewing distance (d_{VD}) remains constant (e.g. virtualization of HMDs), a larger screen area is used for depicting the virtual display by increasing the distance to the VR screen (d_{RD}). Therefore the achieved pixel density of the virtual display increases (d_{RD2} and d_{RD3} in Fig. 2).

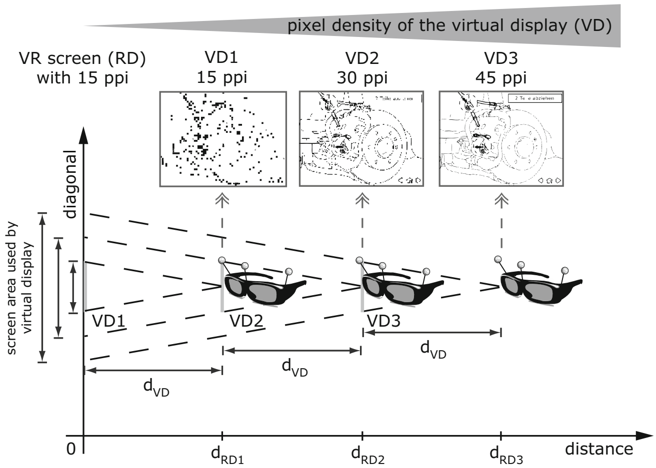

Fig. 2. Dynamic pixel density of virtual displays

In principle the pixel density of a display (ppi_{RD}) is calculated by the quotient of the display height/width and its resolution. However as presented in the graph above, the dynamic pixel density of a virtual display (ppi_{VD}) is defined by the ratio of the current viewing distance to VR screen (d_{RD}) and the specific viewing distance of the virtual display (d_{VD}) is multiplied by the actual pixel density of the VR system (ppi_{RD}):

$$ppi_{VD} := ppi_{RD} * \frac{d_{RD}}{d_{VD}} \tag{1}$$

To support the upcoming investigations, introduces examples of AR and VR systems with their specifications. The four VR systems distinguish in their resolution, but not in their dimension, resulting in different pixel densities. The dimension of the VR projection corresponds to the CAVE available at our facility. The SVGA AR display is based on the specification of the Nomad ND2000 [9], also available at our facility. A system with an higher SXGA resolution is assumed to the second AR display.

Table 1. Illustrative AR systems and VR systems

VR screen	Screen diagonal	Pixel density	Viewing distance
1.6K	4500 mm	11,29 ppi	< 3600 mm
2K	4500 mm	14,45 ppi	< 3600 mm
4K	4500 mm	28,90 ppi	< 3600 mm
8K	4500 mm	57,80 ppi	< 3600 mm
AR Display	**Screen diagonal**	**Pixel density**	**Viewing distance**
SVGA	200 mm	127,00 ppi	400 mm
SXGA	200 mm	203,20 ppi	400 mm

The diagram in Fig. 3 compares the introduced systems to illustrate the described dependence between the achievable pixel density of virtual displays and the viewing distance to the VR screen. For a successful review of a virtual display and its content, the quality and legibility of the virtual display is imperative. The achievable pixel density of a virtual display is a key factor and depends on the operator's position in the VR system. In order to gain the pixel density of the SVGA display of ND2000, the viewing distance to the ultra-high definition 8K VR screen has to be at least 0,9 meters. By using VR screens with lower pixel density, the achievable pixel density of the virtual display diminishes (compare Fig. 3). Assuming a 4K multi wall projection with a square base (e.g. CAVE), the maximum pixel density will be achieved by standing in the middle of this base. The virtual pixel density cannot be raised on one screen without being diminished on another screen. This shows that ultra-high definition VR screens are required for high fidelity virtualization of common AR displays in a VRE.

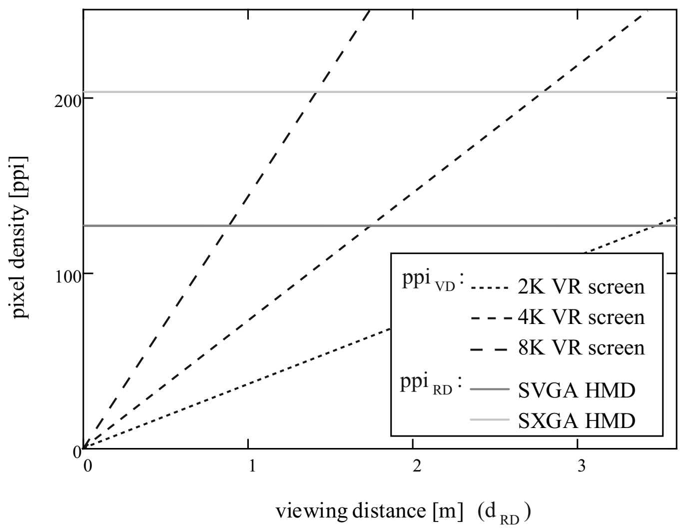

Fig. 3. Achievable pixel density of a virtual display

Illustrations consist of graphics, symbols and text and are presented within VRE by the virtual display. A low pixel density reduces the fidelity of the display. For legibility of single characters a guidance is provided by ISO 9241-300. Considering this the width to height ratio of the character matrix has to be at least 7 by 9 pixels to ensure the legibility. Another requirement for legibility is a character subtense of at least 11 minutes of arc (rms). The chosen character size in the illustration determines the necessary pixel density of the virtual display to guarantee the legibility of the depiction. Taking into account the character matrix requirement, an equation can be introduced to calculate the necessary pixel density of the virtual display (ppiVD), ensuring the legibility of a certain character size within a virtualized AR display:

$$ppi_{VD} := \frac{px_h * d_{VD}}{\frac{inch}{72} * \mathrm{pt} * ppi_{RD}} \tag{2}$$

This ensures the legibility of a certain character size within a virtualized AR display. For the calculation of $ppi_{VD,}$ the constant viewing distance of the virtual display (d_{VD}), the pixel density of the VR system (ppi_{RD}) and the character height (pt) must be given. The character height in pica point can be converted into the metric system by the multiplication with 1/72 inch [10]. In correlation with ISO 9241-300, the height of the character matrix (px_h) is set to 9 pixels.

Considering the CAVE in our facility with 1600 by 1200 pixels per screen and the virtualization of a Nomad ND2000 (), the following results appear for various character subtenses. The viewing distance (d_{RD}) is calculated by using equation (1):

Table 2. Calculated minimum viewing distance to the VR screen for various character subtense

Parameters					**Results**		
min. character matrix	**pixel density (ppi_{RD})**	**viewing distance (d_{VD})**	**character height (pt)**		**character subtense**	**pixel density (ppi_{VD})**	**viewing distance (d_{RD})**
9 px	*11,29 ppi*	400 mm	22 pt	*7,46 mm*	47,3‘	29,46 ppi	1,04 m
			16 pt	*5,64 mm*	34,4‘	40,50 ppi	1,44 m
			11 pt	*3,88 mm*	23,6‘	58,91 ppi	2,09 m

Larger character subtenses allow a shorter viewing distance to the VR screen. By virtualizing the Nomad ND2000 in our CAVE and by depicting a character height of 16 pt, the viewing distance to the VR screen as to be at least 1,44 meter ensures legibility. This distance allows a movement range of 0,36 meter relative to the CAVE center, considering the width of the CAVE, which is 3,6 meter. Within this area the legibility is guaranteed. Provided that all parameter stay the same, the movement area escalates as the VR screen resolution increases.

3 User Study

Since the calculation is based on ISO 9241 for electrical optical displays, it will be investigated whether equation (2) can be applied to the virtualization of displays. A user study aims to clarify this question using the setup described in Table 2.

As former studies [11–13] have shown, the stereoscopic view is the most unfavorable for legible depiction of content. So the eye charts used for the study are depicted in stereoscopic manner. Eye charts containing different sized single characters, word groups or illustrations, are used to determine the necessary viewing distance for legibility. The eye charts are depicted through a virtual display into the participant's field of vision. The parameters of the virtual display correspond to the Nomad ND2000, which is virtualized within our CAVE. Fig. 4 shows a participant during the experiment observing a chart in our CAVE.

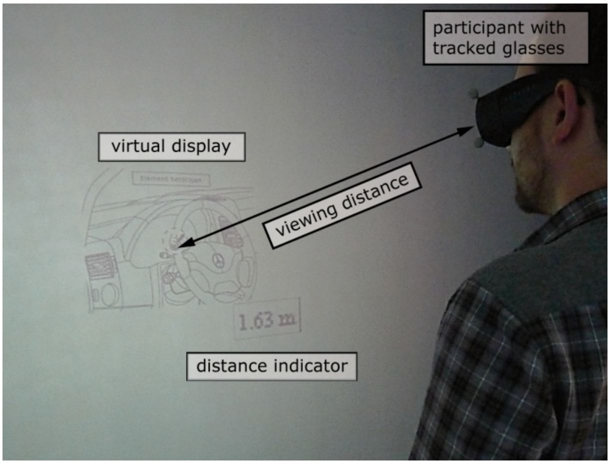

Fig. 4. Setup of the experiment

The chart is a texture mapped on a plane rendered in an independent viewport. Since this viewport does not swap the color buffer but only the depth buffer of the graphic renderer, all mapped textures will overlay the VRE depicted by the screen viewport. This effect of virtual information overlaying other objects emulates the behavior of information depicted through an AR display. While the tracked participant is moving through the CAVE, the relative position and orientation to the virtual display and its information does not change. The chart´s content always appear to be fixed 400 mm in front of her/him. Considering that the screen area facilitated by the virtual display fluctuates depending on the participant´s position in the CAVE, one may conclude that the pixel density (for depicting the chart information) will also vary . The label below the virtual display indicates the current viewing distance to the VR screen. The distance is calculated by the tracked position of the participant and the known dimensions of the CAVE. A larger viewing distance to the screen results in a higher pixel density. For the experiment different combinations of charts and viewing distances are investigated. The used charts are static slides without animations.

The experiment in the CAVE can be divided in 4 parts:

- PRT0: Participant moves freely to get an idea of virtual display and its behavior,
- PRT1: Validate the calculated viewing distance for legibility with an eye chart,
- PRT2: Determine the individual viewing distance for legibility with an eye chart,
- PRT3: Validate and estimate the legibility of an illustration for the calculated viewing distance.

A total of 20 people aged between 20 and 34 years (avg. 23 years old) participated in the experiment and just 20 % of them were females. Most of the participants are fifth semester students of mechanical engineering and had not yet experienced a CAVE. During the 30 minutes of experiment, participants observe a virtual display and its content depicted into their vision. In order to guarantee sufficient eyesight for legibility under normal conditions, all participants had to perform a standard vision test which has shown the following outcomes:

35% had a weak but corrected vision; all participants passed the test with 100 % or more sight (normal or better vision); just one participant had an impair stereo vision (50‘) and however it remains unclear if or how this condition has an impact on his ability to read in VREs, his results were considered and not separated from the other participant´s results.

3.1 Experiment PRT0

At the beginning (**PRT0**) of the experiment the participant can move freely in the CAVE to get a feeling for how the virtual display is depicted and behaves. In order to demonstrate the dependency between viewing distance and legibility, participants are asked to look normal to screen and to step close (~0.5 meters) to the VR screen of the CAVE. The virtual display depicts some characters with a height of 22 pt. Closely to the screen the participant is not able to read the characters. Then he steps further away slowly until the distance is about 1 meter. At a determined distance she/he is able to recognize and to read the characters and understand the basic issue, which was addressed.

3.2 Experiment PRT1

After completing the introduction, the main experiment starts. In the first part, (**PRT1**) the calculated viewing distance for legibility is validated (compare Table 2). To start, the participant looks straight and keeps a viewing distance of 1,44 meters to the VR screen. The first sequence of charts shows lines with single characters or word groups of 16 pt height. All charts in this experiment used the font Verdana, optimized for digital depiction and natively supported by various OS. The participant tries to read each sequence. Fig. 5 shows two complete sequences. The second sequence of charts also shows single characters and word groups with a height of 11 pt. As represented by Table 2, the viewing distance is 2,09 meters.

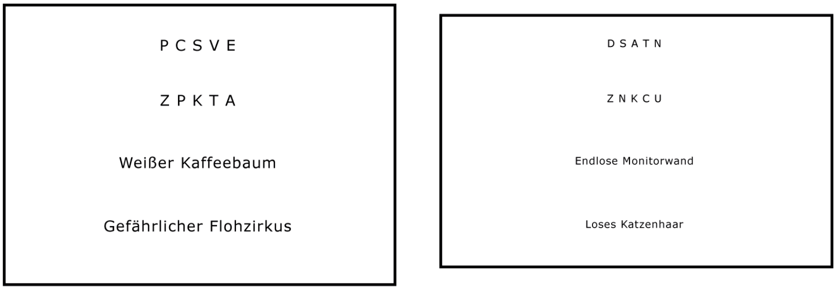

Fig. 5. Chart examples for 16 pt (left) and 11 pt (right)

Considering that all participants were able to read each sequence, we can generally assume that the guidance of ISO 9241-300 may be applied to virtual displays. The diversity of the individual viewing distance for legibility remains unclear up to this point.

3.3 Experiment PRT2

The next part (**PRT2**) addresses the individual viewing distance for legibility. In this second phase, the participant stands 1 meter away from the VR screen and looks straight to it. Once again, sequences of single characters or word groups are depicted. Three different types are distinguished:

1. Single upper characters (*ABC* type)
2. Single lower characters (*abc* type)
3. Word groups (*txt* type)

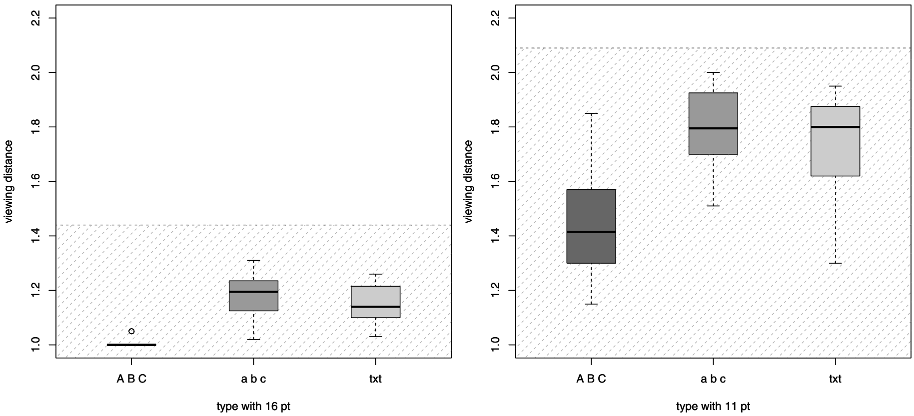

Fig. 6. Results for individual viewing distance (PRT2)

For each of these types, the participant increases the viewing distance step by step until he/she can read the first line of the sequence. In order to ensure the legibility at this point, additional lines of the same type are depicted. If the participant is unable to read the additional line, the viewing distance is increased. The described procedure is made for both character sizes 16 and 11 pt of each of the types separately. The determined viewing distances (for 16 and 11 pt) are shown in Fig. 6.

Over all, the determined viewing distances are below their expected value of 1,44 meters for 16 pt and 2,09 meters for 11 pt (compare Table 2). The *abc* type was the most difficult to read, since less pixels were available for depiction in comparison to *ABC* type. This fact has lead the median of the viewing distance for *abc* type to be higher in comparison to the other tested types.

Despite the presence of lower characters the legibility of the *txt* type is better than the legibility of *abc* type. This is caused by the contextual support of the words and word groups.

The upper characters (*ABC* type) are legible within a smaller distance than the other types, which is not surprising. Regarding the ISO 9241, the character matrix must be at least 5 by 7 pixels in order to ensure the legibility of alphanumeric and upper characters. Based on this assumption the calculated viewing distance for this type is 1,12 meters (16 pt) and 1,62 meters (11 pt). Most of the participants can identify the *ABC* type with 16 pt already at the initial distance of 1,0 meter. Only one participant exceeds the calculated viewing distance.

For a stereoscopic setup the legibility depends also on the personal ability to focus the virtual display plane properly. This plane appears distant form the real display (VR screen) and can cause an ambiguous reception. Therefore the charts were provided with a frame to support proper focus. Furthermore the proper focus can be supported by placing a hand near the virtual display plane. With further distance it is harder to focus properly. If the participant's focus is not proper, the chart appears blurry and it is illegible. For this reason the distance variation for the chart with 11 pt is larger.

3.4 Experiment PRT3

At this point there is still no statement on the quality of the depiction and how well the participants can read the content following the guidance of ISO 9241. At the last part (**PRT3**) of the experiment the participants rate the legibility of an illustration including text and symbols. The viewing distance is once again 1,44 meters. The different elements are displayed in the following order: text field, edge image, highlighted image elements, symbols and arrows. When a new element is displayed, the participant is expected to describe the change, its content and rate its legibility. The illustration in Fig. 7 shows the complete chart with all elements.

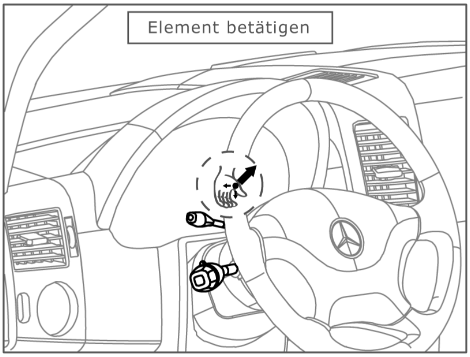

Fig. 7. Chart with illustration and additional elements

All elements were correctly identified by the participants. For the assessment of the legibility, a scale of 1 to 6 was applied (scale see Fig. 8). Most participants have perceived the text field with a character size of 16 pt as "*well legible*" (2). Only one of the participants has rated the text field with a grade of "*legible*" (3). The assessment of the graphic shows similar results. Just one participant has rated the legibility as "*very well*" (1). The rest of them has perceived the graphic as "*well legible*" (2). A larger variation of the assessments has occurred in the case of the symbol and the arrow. Some of the participants described the symbol and the arrow as legible, where others described the legibility as well or even very well. Fact is that with the available pixel density of 40,50 ppi, the hand symbol (as illustrated in Fig. 7) can be perceived but not all of its features. Some participants were not able to detect the arrow head. The average grade for the symbol was 2,3 and for the arrow 2,6. In a situation where the operator is acquainted with the symbol library, the perception and identification of symbols are possible even if they are not depicted in every detail.

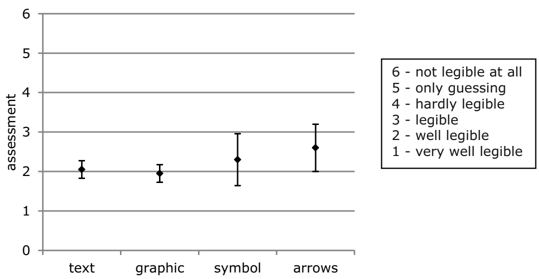

Fig. 8. Results for legibility of the illustration (PRT3)

4 Conclusion

Essentially, the user study has shown that the legible depiction of AR displays in VREs is possible. In order to guaranty legibility, the guidance of ISO 9241 has to be considered. This paper has investigated the relationship between pixel density and legibility for virtualization of displays and its dynamic behavior. Besides the pixel density, the motion blur and display parameters (e.g. contrast, brightness and response time) also influence the legibility but have not been further discussed in this paper.

The introduced equations may be used to estimate the pixel density for the virtualization of a display by a VR system. For the virtualization of state-of-the-art AR displays with full pixel density, ultra-high definition VR screens with at least 8K are required. VR screens with 4K and less resolution can still provide the legibility of virtualized displays, although with less details. Besides the evaluated CAVE System, other systems such as video glass and powerwall can be applied. The requirements described by this paper apply to these systems as well. Another alternative to enable virtualization of displays with low definition screens is to adopt a multi-display approach by employing tracked high definition mobile devices to depict high fidelity content in low definition VR systems.

The paper has mainly described the virtualization of head mounted displays, however the equations may also be used to estimate the achievable pixel density of a virtualized stationary display (e.g. dashboard, control panel). In contrast to head mounted displays, the viewing distance between this display and the operator may change. The achievable pixel density depends on the current position of the operator and also on the fixed position of the display in the VRE. For a valuable estimation, the achievable pixel density has to be calculated for each crucial position of the design review.

For full comprehension of the visual effects for virtualization, further influential display parameters for legibility shall be investigated (e.g. contrast, brightness, response time). For most immersive planning, designing and reviewing processes, the complete AR system must be modeled in VREs. Therefore all components and their relations to each other must be mapped. It is not necessary that all components are virtualized but connected. These tasks were not discussed in this paper, but investigated as part of the project “Virtualization of AR systems for maintenance planning in immersive environments”.

Acknowledgments. The authors gratefully acknowledge the German Research Foundation (DFG) for funding this research (grand STE1451/12-1). Furthermore, the authors acknowledge the Mercedes-Benz Commercial Vehicles Division of the Daimler AG for providing product data and prototypes for the creation of the test scenario. The support of the Daimler colleagues Gregor Tauscher and Tea-Soo Kim (Virtual Reality Support Center) was particularly greatly appreciated.

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