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Immersive virtual reality as a tool for lighting design: applications and opportunities

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Abstract. Immersive virtual reality offers a wide range of applications. Immersive virtual reality in particular can play an important role in lighting design, thanks to its ability to allow a quick assessment between different design choices based on spaces, colours and light. However, immersive virtual reality has to guarantee a correct reproduction of light behaviour from photometric and visual points of view, in order to be effectively used for lighting analysis. This paper presents a literature review aimed to analyse the activities of the research groups operating in this field that have addressed, with different approaches and points of view, the issue of iVR applications in the reproduction of environments illuminated by either daylight or electric lighting, as well as a combination of them.

Keywords: Immersive virtual reality, Daylighting, Game Engine, Indoor lighting, Energy saving

1. Introduction

Virtual reality (VR), unlike other representation methods, can combine the realistic reproduction of a virtual environment with the possibility of interaction between the user and the virtual environment itself. Depending on the interaction degree between the user and the virtual environment, two categories of VR can be identified. The first category is composed of VR systems that use screens (Desktop VR) [1], or smartphones (Mobile VR) to reproduce the virtual environment that the user can only explore from a fixed position. The second category is composed of immersive virtual reality (iVR) systems that guarantee immersion and interaction between the user and the virtual environment by using a Head-Mounted Display (HMD) and motion sensors [2]. Thanks to its potentialities, the iVR has been the center of attraction in the building domain [3]–[5], education and training [6], as well as in the evaluation of the human behavior in case of emergencies (for example, fires or evacuations) [7]. The starting point in using iVR as an effective design tool is to verify its ability to represent a virtual model as real and to reproduce the physical phenomena correctly. Although many research and industrial sectors use iVR, the reliability of iVR as a tool for lighting design still has to be thoroughly investigated. The present paper consists of a literature review aimed at: i) analyzing the activities of the research groups operating in this field that have addressed, with different approaches and points of view, the issue of the daylight and electric light reproduction through iVR; ii) reviewing the iVR hardware devices, specifically Head Mounted Display (HDMs) available on the market.

2. State of art: research activities

In recent years, iVR and the study of its capabilities have been an increasingly investigated research topic. Indeed, research [8]–[14] was focused on using iVR to perform subjective investigations aimed at analyzing how the light can be reproduced within HMDs. The papers were thoroughly reviewed and organised according to the type of light reproduced. In addition, the parameters able to characterise the light distribution were also taken into account. Finally, Table 1 summarizes the type of light simulated, the main research objectives, the HMD used, the measurements carried out and the virtual environment interactivity for any of the papers analyzed.

2.1. Electric lighting

In [8], the authors investigated the perceived immersivity of a virtual office model, by asking participants to compare the virtual and the real environment. During the tests, the participants had to express their preferences among different electriclighting set ups , in order to vary the task illuminance and the illuminance uniformity of the background wall. To assure all lighting sources were controlled and properly measured, authors considered a room that did not have any daylighting available. Lighting settings were added within 3ds Max©. In order to ensure that the lighting conditions' setting in the iVE were similar to those in the physical office space, the related information was set as the same properties of luminaires in the laboratory experiment. Subsequently, the immersive virtual environment was exported with a photo-realistic quality and participants' lighting preferences were collected to evaluate the impact of wall luminance and uniformity on preferred task illuminance within the physical environment and the iVE.

In [9], differences in visual perception were assessed, both from a subjective and an objective point of view. A comparison between a typical office room under electric lighting conditions and its virtual representation was developed using a physics-based imaging technique. Participants were asked to perform two tasks: the character contrast test presented on an achromatic chart, and the Stroop test with a chromatic chart. In order to reproduce the luminous environment of the test-room, a high dynamic range image (HDRI) was obtained from seven low dynamic range images (LDRIs) with different exposure values by varying the camera shutter speed. The seven LDRIs were combined into an HDRI using Photosphere software. Photosphere generates a camera response curve based on the LDRI series that shows the relationship between the pixel and its related luminance value, calibrated using a single point luminance measurement within the visual scene. The resultant calibrated HDR images cannot be directly displayed to users because of the limited luminance range of head-mounted displays, which is a common issue with available VR HDM. To account for this, a tone mapping process was used to compress large ranges of luminance values of the actual scene contained in the HDRI into a lower dynamic range.The resultant tone-mapped images were combined into a 360° panorama using PTguiPro software. The illuminance received at the eye in the HMD was measured using a chroma-meter (Konika Minolta CL-200) in a completely dark environment. This was to verify that the illuminance from the VR display was similar to vertical illuminance value measured in the real luminous environment, from the same viewing position.

2.2. Daylighting

Differently from previous research, in [10]–[12] the game engines were used as a tool to show 360° environment images through HMDs. Rockcastle and Chamilothori, in [10], used the simulation software Radiance to build 360° HDR images for 8 architectural scenes lit by daylight. The obtained images were presented, through a HMD, to the participants, with the aim of analysing their visual interest within the scene and acquiring objective measurements of the data through a head-tracker. The image-based algorithm, Modified Spatial Contrast (mSC), which is able to calculate local differences in brightness between neighboring pixels within an image, was used for sampling the image from a high resolution down to a mid-level resolution. The angular fisheye renderings of the architectural scenes were tone-mapped using the "pcond" algorithm, allowing a projection-based compression of luminance, and a gamma correction of 2.2 based on the measured luminance range of the display. The authors collected subjective perceptual ratings from the architectural physically based renderings and compared them to image-based measures related to impressions of visual interest.

In [11], an experiment with 29 participants was conducted to compare the user's perception of a real daylit environment and its equivalent representation in VR as well as testing the effect of the display method on the participants' perceptual evaluations. A series of perspective view HDR renderings were generated using "rpict" in Radiance, dividing the 360-degree field of view into 6 sections with 90 degrees horizontal and vertical field of view. By keeping the viewpoint fixed and varying the view direction, the produced set of renderings form an expanded cube. The exposure of the HDR renderings was adjusted intuitively to match the appearance of the real space by using "pfilt" to apply a uniform exposure multiplier. The images were then converted to low dynamic range BMP files using "ra_bmp" with a gamma correction factor of 2.2 and ensuring the application of identical settings for all six view directions. In order to provide a measure of the luminance discrepancy between the real environment and its virtual representation projected in the HMD, authors compared the luminance in 7 reference points between the two environments. The luminance in the real was directly measured from the HDR photograph, while for the projected images of the virtual space it was derived using the response curve of the HMD. Although the resulting luminance measurements did not directly correspond to those from the subject's point of view, they allowed for comparable assessment of the luminance deviation between the real and virtual scenes.

In [12], a total of 72 participants were exposed to immersive VR scenes of a daylit interior space, rendered in Radiance, with three façade variations of an equal aperture ratio, to investigate the joint impact of façade geometry and associated sunlight pattern on occupants. The renderings, that were obtained from Radiance, were used to generate a fully immersive 360° environment seen from a static viewpoint, following a workflow for creating immersive VR scenes from physically-based renderings, developed by the authors which is described in detail in Ref. [11]. The average RGB values of the cubemap projection, as well as the vertical illuminance at the center of each VR lens from the viewpoint of a participant were measured for each façade variation to provide a measure of similarity between the scenes. The scenes differ in vertical illuminance with a maximum factor of 1.14, below the threshold of 1.5 which represents the smallest significant difference for a just noticeable change in illuminance.

2.3. Daylighting and electric lighting

In [13], the iVR was used to reproduce an office equipped with 3 windows with shading systems and luminaires. By combining the number of active luminaires and the shading systems position, different luminous scenarios were defined. During the tests carried out by wearing the HMD, the participants had to read a text placed on a desk in the virtual environment and choose the light condition best suited for the visual task. The illuminance level inside the virtual environment was calculated, simultaneously, by authors through Honeybee and Ladybug plugins in Grasshopper. Three environmental and lighting analyses were performed: (1) daylight factor analysis (DFA), in which simulations were based on annual and daily solar radiation at a given location and orientation; (2) continuous daylight autonomy (CDA), which was used to measure daylight autonomy values, and (3) useful daylight luminance (UDI). Participant lighting preferences were collected in a static lighting environment. The authors evaluated the participants' "preferred lux level" based on the Honeybee and Ladybug simulations.

Heydarian and Carneiro, in [14], used the iVR to reproduce the virtual model of a single office and to compare manual and semi-automatic control systems for the integration between electric and natural light. In the virtual environment, the participants had to read a text placed on a desk and adjust the preferred light condition by using the two control systems. The model, designed in Revit©, was then taken to 3ds Max© to optimize the geometry and add materials, lighting, reflection, shadows, and texture in order to make it look as similar to the physical office space as possible. In order to ensure that the lighting settings in the 3D models were similar to those in the physical environment, the illuminance levels in the physical environment for different lighting conditions (dark, electric light only, natural light only, both electric and natural light) were measured several times on different days using an illuminance meter (Konica Minolta T-10). The averaged values were used to set-up the lighting levels for the 3D models. Then the participants' "preferred lighting level", obtained by combining natural and electric light, were collected. Following, an overview of the papers analysed (Table 1) and a description of the headsets mentioned (Table 2).

Table 1. Overview of the papers analysed.

Bibl. Ref.	Electric Lighting	Daylighting	Feedback	iVR Hardware	Measurements	Interactivity of the environment
[8]	Yes	No	Task illuminance	Oculus Rift DK2	Not specified	No
[9]	Yes	No	Comparison between the real and virtual environment	HTCVive	Vertical illuminance Real environment-HMD	No
[10]	No	Yes	Visual interest	Oculus Rift CV1	Not specified	No
[11]	No	Yes	Comparison between the real and virtual environment	Oculus Rift DK2	Luminance discrepancy HDR (of the Real environment) -HMD	No
[12]	No	Yes	Preferences about different shading typology	Oculus Rift CV1	Vertical illuminance Real environment-HMD	No
[13]	Yes	Yes	Illuminance level	Oculus Rift DK2	Not specified	Yes
[14]	Yes	Yes	Illuminance level	Oculus Rift DK1	Not specified	Yes

Table 2. Description of the headsets mentioned.

HMD	Resolution	Field of View	Display type	Refresh rate	Tracking Type
Oculus Rift DK1	640x800	90° horizontal 90° vertical 127° diagonal	single LCD	60 Hz	3DoF Non-positional
Oculus Rift DK2	960x1080	94° horizontal 99° vertical 137° diagonal	single OLED	75 Hz	6DoF Outside-in
Oculus Rift S	1280×1440	88° horizontal 88° vertical 124° diagonal	single LCD	80 Hz	6DoF Inside-out via 4 integrated cameras
Oculus Rift CV1	1080x1200	93° horizontal 101° vertical 110° diagonal	2 x OLED	90 Hz	6DoF Inside-out through USB connected IR LED sensor
HTC Vive	1080×1200	88° horizontal 88° vertical 124° diagonal	2× OLED	90 Hz	6DoF Inside-out
HTC Vive Pro	1440×1600	88° horizontal 88° vertical 124° diagonal	2x AMOLED	90 Hz	6DoF Inside-out

3. Limitations and discussion

The literature review highlights some indications and/or limitations about the use of Game Engines for lighting design:

- *Virtual head-mounted displays:* Abd-Alhamid et al, in [9], underline that the visual properties were affected due to limitations of the current virtual head-mounted display, as they cannot display HDR images.
- *Glare*: In [9], [11], [12], is underlined that the limited luminance range of the current head-mounted displays strongly affects the investigation on the visual discomfort, because it can be problematic to reproduce conditions inducing discomfort such as glare in the virtual reality environment.
- *Age of participants*: in [11]–[13], the participants to the experiment were generally under the age of 35 years old;
- *Duration of the experiment:* In [8], [12], the different perception time between the virtual and real environments has been emphasized. This is also due to the different exposition time of the participant to the environments;
- *Reproduction of the variability of natural light conditions:* another significant barrier found in this field, [11], [13], is the difficulty of reproducing the daylight variation in the virtual environments;
- *Virtual model quality:* in [8], the importance of a good virtual model is underlined. Moreover, poor reproduction of the virtual model is also related to the screen resolution or the processing power of the hardware;
- *Definition of the objective parameters*: the lack of a standardised nomenclature can be noticed;
- *Photometric reliability:* the literature review highlights that, often, the iVR is used without an objective comparison between the virtual and real environments in terms of the exact distribution of the light.

To make a critical analysis of these studies, the authors believe it is necessary to better investigate the concept of virtual reality.

Burdea et. al, in [1], described the virtual reality as "*a technology that adds the dimensions of immersion and interactivity to three-dimensional computer generated models and offers an exploration that is not viable with the traditional form of representation*".

As this observation highlights, interactivity is one of the major advantages of this technology.

Among the researches analyzed, only Heydarian et al, in [13], [14], investigated immersive virtual reality with human-environment interactivity.

However, these research works did not perform appropriate photometric analysis of the virtual environment. Specifically, in [13], the illuminance level inside the virtual environment was calculated, simultaneously, by authors through Honeybee and Ladybug plugins in Grasshopper. Therefore, neither a photometric analysis was made within the virtual environment realised through the game engine, nor within the HMD. The same goes for [14]: in order to ensure that the lighting settings in the 3D models were similar to those in the physical environment, the illuminance levels in the physical one were measured using an illuminance meter, but there is no reference neither to measurements made within the virtual model, nor in the HMD.

Despite having carried out more detailed photometric analyses, the other works described above, [8]–[12] , did not use an immersive virtual reality that allows the user to interact with the environment. Rather, the game engines were used for viewing 360° photo or 360° rendering; users had the possibility to rotate their head 360 ° but cannot move within the environment.

Therefore, to the knowledge of the authors, the reliability of the game engines in reproducing the correct light distribution, from the photometric point of view, is a crucial aspect for the application of iVR in lighting design, which still has to be thoroughly investigated

4. Conclusion

This paper aims to underline the current state of applications of virtual reality for interior lighting design. The review highlights that, when the environment has the possibility to make the user interact with it, measurements to verify the correct photometric distribution of the light are not carried out. However, in the field of lighting design, photometric accuracy is essential. Overall, the authors agree that virtual reality is a promising methodology for investigating people's visual perception but, to date, few research groups have performed photometric analysis in the field of iVR lighting design. However, while the iVR allows for a very realistic reproduction of the real world, the literature review revealed very little information about the ability of the iVR to replicate the physical distribution of light within the immersive and interactive virtual environments.

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