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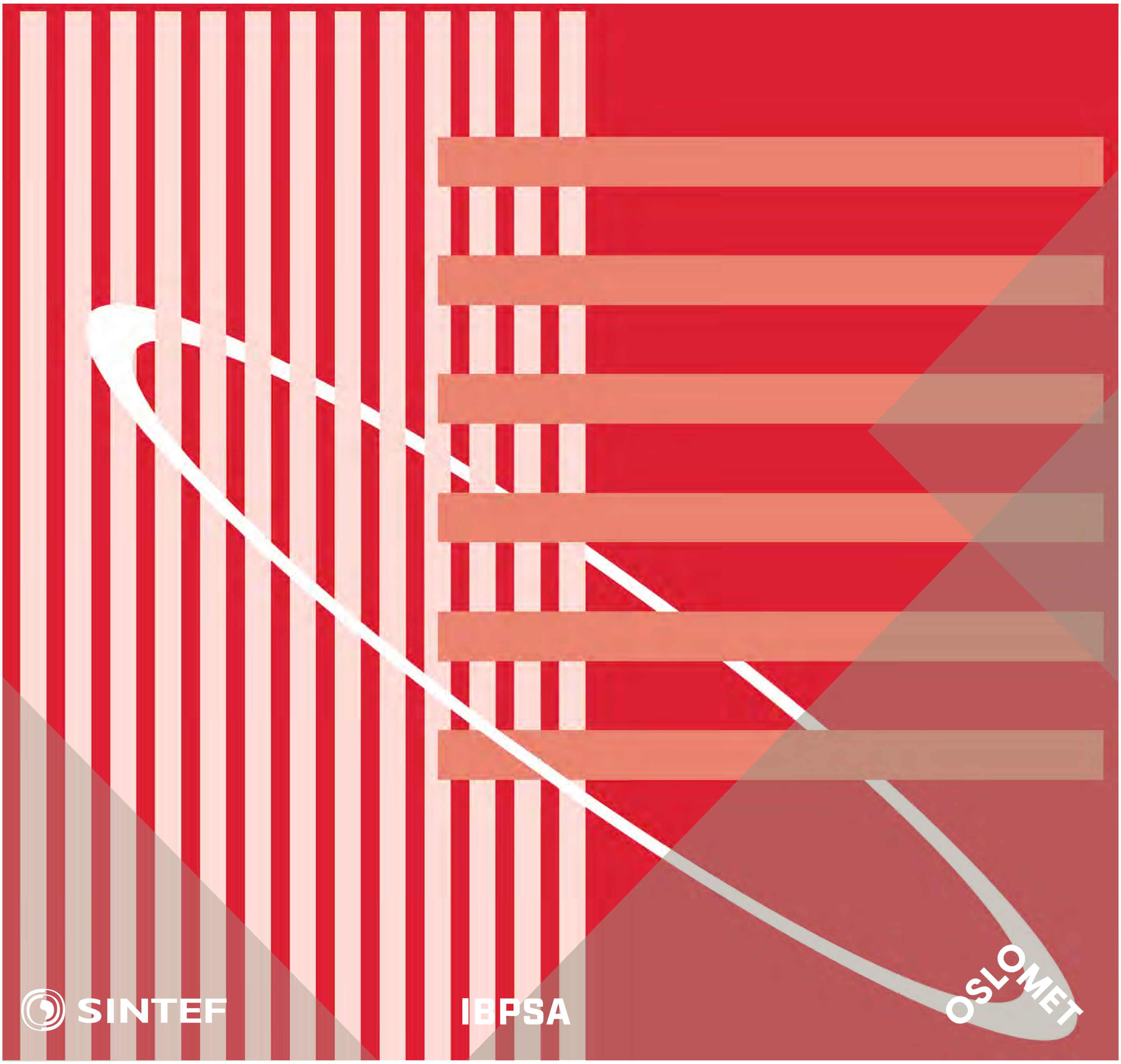

SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

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Visualizing user perception of daylighting: a comparison between VR and reality

Muhammad Hegazy[1*], Ken Ichiriyama[1], Kensuke Yasufuku[2], Hirokazu Abe[2]
[1]Graduate School of Engineering, Osaka University, Suita, Japan
[2]Cybermedia Center, Osaka University, Suita, Japan
* *Corresponding author: hegazy_muhammad@arch.eng.osaka-u.ac.jp*

Abstract

This study introduces a novel method to investigate human perception of daylight in an interactive and immersive way, using game-engine and virtual reality (VR). The proposed method produces highly realistic renderings in real time of which users can explore freely and report daylight brightness perception using rated snapshots. Perceptions on daylighting in the virtual environment were found consistent with that in the physical one. The proposed approach can overcome some of the challenges facing current light simulation tools, regarding rendering speed and interactivity. It also encourages more validation studies to light simulation in game-engines.

Introduction

Evaluation of the qualitative attributes of daylight is challenging in different aspects, whether the assessed is a real or a virtual environment. The dynamic and variable essence of daylight, on the one hand, borders an obstacle to a completely manageable test environment (Gherri, 2014; Rockcastle & Andersen, 2013). In addition, as daylight efficiency is related to key design features (e.g., building orientation, opening sizes and walls), improving daylight after construction is typically an asset-intensive solution(Ma et al., 2012). On the other hand, simulating daylight correctly in a virtual environment (VE) needs consideration of various parameters to generate persuasive conditions for users to deliver relevant feedback (Bhavani & Khan, 2011).

In virtual reality, immersion and interaction principles are described as two key aspects of a credible user experience of the simulated space (Alshaer et al., 2017; Bishop & Rohrmann, 2003; Slater et al., 1996). Through applying these two aspects more rigorously, interactive virtual environments (IVEs) can offer an alternative to real environments in light-perception research (Kynthia Chamilothori et al., 2018). Various studies have employed IVEs to investigate subjective aspects of daylighting within a human-centric approach. For example, (Kynthia Chamilothori et al., 2016) investigated the impact of the perceived spatial ambiance of daylight patterns through the use of physically based renderings in VR. Using a similar method, (Rockcastle et al., 2017) assessed the visual perception of daylighting in virtual environments. While the previous studies provided basic immersion and interaction in their proposed frameworks, they have also shown limitations with respect to the environment customizability and interactive feedback.

The objectives of this study are twofold; firstly, to introduce a novel, real time approach for subjective evaluation of daylighting in virtual reality. Secondly, to investigate the perceptual validity of the introduced system through comparing perceptions in virtual and physical environments. The proposed approach offers a highly interactive daylight experience that allows users to explore in real time and collect their perception of brightness through 4-point ranked snapshots. Using the developed system at similar spatial and temporal contexts, this approach is validated by an experiment comparing input from subjects in a real daylit environment and its simulated mock-up. The proposed method has the potential to address some of the difficulties confronting traditional light simulation platforms with respect to speed and user engagement. It also accentuates further verification research on game-engines as light simulation tools. The novelty of this study lies in its employment of game engine as a light simulator rather than the benchmark tools (e.g. Radiance), to overcome some of the limitations in previous research regarding the immersiveness (by including head and body movement) and interactivity (using questionnaire-free evaluation system) in the virtual environment. Moreover, to the authors' knowledge, this is the first study to evaluate perceptual accuracy of light simulation in game engines through comparing perceptions in physical and virtual environments.

Background

Persky and McBride (Persky & McBride, 2009) define immersive virtual environments as a collection of hardware and software intended to immerse users in an artificially created virtual environment so that they can perceive their inclusion and interaction into the environment in real-time. Numerous studies have addressed virtual environments as a representative and evaluative tool for daylighting in built-environment, and as an architect-user communication tool. Chamilothori et al. (Kynthia Chamilothori et al., 2018) investigated the reliability of immersive virtual reality in measuring the perception of daylit spaces. The study examined five perceptual aspects: perceived pleasantness, interest, excitement, complexity, and satisfaction. Users' perception in respect with these aspects were collected in a daylit room and compared to that in a virtual replica through a Head Mounted Display (HMD). The study showed consistency between perceptions in real or virtual environments. Similarly, Rockcastle et al. (Rockcastle et al., 2017) employed VR and HMD, along with head-tracking, to collect visual interest ratings of 8 different spaces under different sky conditions, and compared it to results predicted by an image-based algorithm. The study showed consistency between results of users' feedback and predictive algorithms.

In another study by Rockcastle and Andersen (Rockcastle & Andersen, 2015), they compared subjective ratings of (contrast, uniformity, complexity, variation, stimulation, and excitement) for nine virtual architectural spaces in different sky conditions to local and global contrast metrics. The study found that ratings of (excitement and stimulation) were consistent with quantitative contrast measurements more than that of (contrast) itself, of which those quantitative measurements were developed for, suggesting more investigation on user comprehension of the term 'contrast'. Furthermore, other studies integrated both subjective and physiological responses to daylighting in IVE; In a study by Chamilothori et al. (K. Chamilothori et al., 2019), the impact of sunlight pattern geometry on occupants was investigated through measuring skin conductivity and heart rate while in IVE, along with a verbal questionnaire. The experiment showed that spaces with irregular sunlight patterns were perceived as more exciting and more interesting on the subjective side and caused cardiac deceleration on the physiological side.

Other experiments expanded IVE's application in lighting study by creating digital tools for daylight modelling and visualization. For example, Heydarian et al. (Heydarian et al., 2017) analysed consumer lighting habits in IVE by configuring the settings of window shutters and artificial light intensity while executing a reading function. The study showed that the participants favoured full daylighting and in this situation performed better. Similarly, Carneiro et al. (Carneiro et al., 2019) proposed an IVE-based input system to direct the lighting needs of the occupants as to light intensity and energy usage. The system showed efficiency in guiding subjects to rethink their lighting preferences, especially those relating to energy. In a different application, (Kreutzberg, 2019) captured 360° panoramas from scale model interiors to enable a 1:1 experience of daylighting effects virtual reality. The introduced approach aimed to guide students through the conceptual design phase with scale models, by offering a more engaging experience to the space and its different lighting scenarios.

In lighting evaluation research, consistency of photometric values between simulation and reality (i.e. illuminance and luminance) is necessary (Merghani & Bahloul, 2016). In this regard, one of the main benchmark tools in daylight simulation is Radiance, which uses sky model data and backwards ray tracing to simulate light behaviour accurately, offering an acceptable error range compared to reality (Ward, 1994). However, producing high quality renders in Radiance and similar applications is often a time consuming process, which limits the ability of users to explore wide range of scenarios in short time (Jones, 2019). As a result, various ongoing studies have explored methods to speed up the rendering process in Radiance (Jones & Reinhart, 2017a, 2019, 2017b). In this regard, game engines are known for their ability to render lighting in real-time through several techniques, one of which is light mass, which "bake" direct and indirect light effects on the model surfaces and thus enable to move inside the environment without the need to re-render each scene (Sheng et al., 2013). Recently, the introduction of real-time ray tracing in game engines enabled even faster, physically-based results (Liu et al., 2019). However, one of the significant barriers of adopting such tools in light evaluation research is the lack of validation studies regarding photometric accuracy. A few researchers have explored the suitability of various game engines for non-gaming applications, such as lighting simulation (Christopoulou & Xinogalos, 2017; Petridis et al., 2012, 2010). Moreover, Natephra et al. (Natephra et al., 2017) have used Unreal Engine to develop an immersive VR light modelling framework to provide realistic simulation of daylight as well as artificial illumination. The system offered a range of interactive tools including shifting and revolving fixtures and adjusting lighting levels.

In this study, Unreal Engine 4 (UE4) was used to create the immersive framework to simulate daylight. UE4 was preferred over other engines because of different factors; firstly, UE4 uses a range of physically dependent lighting units (Epic Games, 2018a). Secondly, Lighting algorithms in UE4 are based on real light physics, in which the actual relationship between light and surfaces is correctly represented as per the inverse square law (Walker, 2014) and Material attributes imitate the behavior in the physical world (Epic Games, 2018b; Karis, 2013). For daylight, UE4 is based on the Bruneton sky model (Bruneton, 2016), which can simulate the dynamics of daylight, including Rayleigh and Mie multiple light scattering (Bruneton & Neyret, 2008). Furthermore, the photometric accuracy of UE4 compared to field measurements and Radiance was verified in a study by Natephra et al. (Natephra et al., 2017). The error percentage of UE4 regarding illuminance estimation was found below 10% as recommended by Fisher (Fisher, 1992).

Methodology

This section describes the methodology of creating the virtual reality system, perceptual evaluation, and analysis of the subjects' feedback in reality and VR. Firstly, the selected indoor environment is modelled in detail and exported to the game engine software, where physically based materials are added to the surfaces, and the interaction controls in VR are setup. Daylighting simulation is ran in the game engine using a physical sun object for direct sun light and a physical sky model for ambient daylighting. The spatiotemporal settings are set in accordance to experimental settings in the real environment. In both VR and the physical environments, subjects are given a tour to the accessible areas of the building, then verbally instructed to explore these areas freely and report daylight intensity in their scenes of choice on a 4-point nominal scale, using VR controllers or smart phone camera. To analyse daylight perception in both environments, snapshots reported by the subjects are recreated as camera objects in the 3D modelling software to replicate position, target scene and daylight rating. In each area, the number and rating distribution of snapshots in VR and reality are compared.

Test Environment

A multipurpose office hall was selected as the test environment in this investigation (**Error! Reference source not found.**). It features an open floor plan space daylit by a courtyard of 7.0m x7.0m dimensions. The investigated space hosts open areas, meeting rooms, canteen corner, and an open meeting hall (Figure 2). A 3D model of the test area was created in 3Ds Max software, based on the building's blueprints and field work scans. Furthermore, in Unreal Game-Engine 4 (UE4), the 3D model was imported to build physical materials, light rendering and Virtual reality interface functions.

Figure 1: Main area in the investigated environment

The developed IVE system aimed to enable more immersion and interaction of users while collecting daylight-related feedback. To offer 6 degrees of freedom in exploring the virtual environment, the head-mounted display was used to track the user's head movement (looking around), while two tracking stations were used to track body movements (physical movement). Furtherly, several interaction controls were programmed to dual motion controllers using the Blueprint scripting tool in UE4. Users could use the controller's buttons to move in all directions horizontally, jump, and take a snapshot of what they see. The later control was added as a self-expressive approach to enable users to report their brightness perception of various scenes in VR without the need for questionnaires. Moreover, the IVE system was equipped with environment customization controls such as changing daytime in VR. Finally, a similar keyboard and mouse controls were added in case researchers needed to intervene.

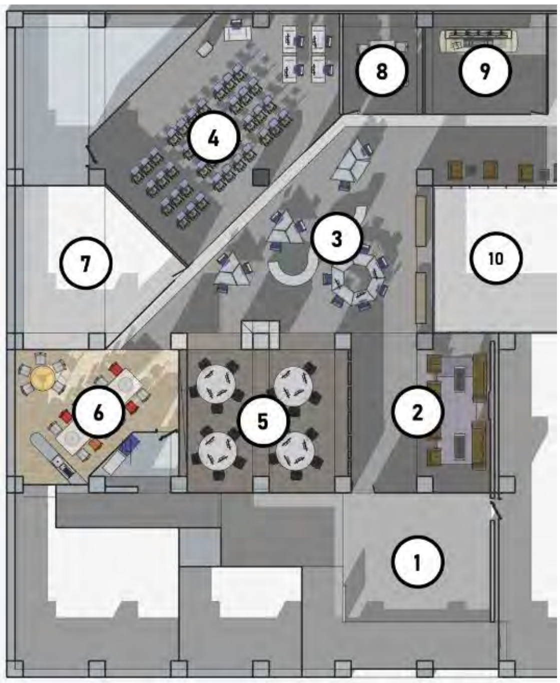

Figure 2: Accessible areas in the investigated space: 1) entrance lobby, 2) court corner, 3) open office, 4) open meeting hall, 5) computer room, 6) canteen, 7) lab room, 8) meeting room 1, 9) meeting room 2, 10) courtyard.

Experiment procedures

Thirty six subjects were enrolled (20 males, 16 females) to provide their opinions on daylighting in the test room. The number of subjects needed were identified as illustrated by several related studies (Abd-Alhamid et al., 2019; Cauwerts & Bodart, 2011; Cha et al., 2019; Kynthia Chamilothori et al., 2018; Franz et al., 2005; Heydarian et al., 2014). To alleviate the presentation-order bias that can arise while viewing physical and VR environments (Kynthia Chamilothori et al., 2018; Charness et al., 2012) subjects were randomly separated into two groups, each exposed to either actual or virtual environment. Furthermore, to estimate the effect size that can be acquired with this number of participants, we conducted a priori power analysis using G*Power software (Faul et al., 2007). At a statistical power of 0.8, our sample size was found adequate to detect large effects (Cohen, 1992), with an effect size (Cohen's d) of 0.97.

The experiment was carried out under a condition of overcast sky. The researchers instructed subjects about the purpose of the study and a description of the necessary tasks. To start the experiment, subjects were advised to wander freely around various locations within the test area, and to use their smartphones to snapshot places that they consider as bright or dark on a 4-point scale. The verbal order used was as follows: “please explore different areas freely with daylighting in mind, snapshot the areas/scenes of which you perceive brightness as one of the following: very dark, dark, bright, or very bright”. At each snapshot, subjects were asked to explain what they meant to look at, as well as their snapshot brightness rating. Experiment time was limited to 20 minutes, during which researchers didn’t interact with subjects (Figure 3 upper). Afterwards, subjects were told to upload their snapshots to a specific web-based database, along with ranking for each shot.

In the virtual model, time and sky conditions were configured as to that during the experiment in the real environment. Subjects were provided with a computer-based overview on the intent and procedures of the study. They were then introduced to a motion controls demonstration to know what and how they should control inside the IVE. Eventually, an explanation was given about the tasks to be performed during the experiment. Prior to wearing the VR headset, subjects spent a total adaptation period of 10 minutes in the testing room.

After the subject got comfortable with the IVE system, the simulated model was loaded starting at the entrance lobby. The subjects were asked to assess their experience of brightness in freely chosen scenes utilizing the same verbal order as demonstrated in physical environments. Subjects were able to take as many screenshots as they liked and move between various areas of the virtual model (Figure 3 lower). Any time a subject took a snapshot, he / she was asked to verbally disclose what they intended to look at, as well as their perceived brightness of that snapshot the 4-point scale.

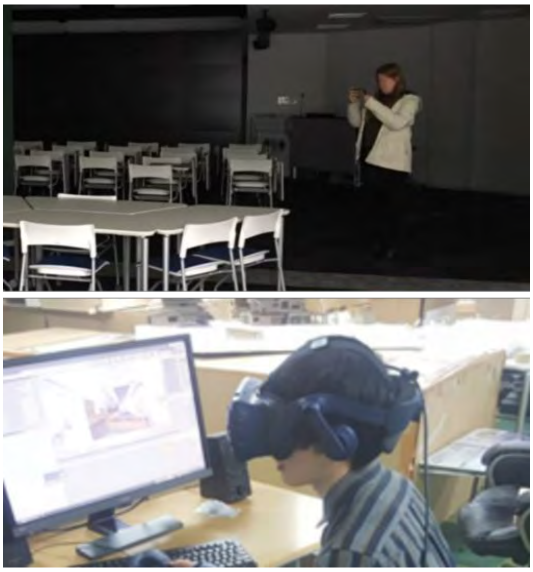

Figure 3 Subjects in real (upper) and virtual spaces (lower).

Results and analysis

During the tests in actual and simulated environments, subjects were expected to travel freely around various areas and record their experience of brightness by taking a screenshot of the scenes they interpret as one of the following: very dark, dark, bright or very bright (Figure 4). Table 1 illustrates subjects’ feedback in actual and simulated environments and their respective ratings. With 345 and 330 snapshots respectively, subjects marginally submitted more scenes in real environment than in VR. Likewise, the average ratings of all shots in both reality and VR were fairly similar, with an average of 2.26 and 2.47 respectively, reflecting an average ranking varying from dark to bright in both environments. In real-environment snapshots, though, a consistent distribution of snapshot ratings could be observed compared to a significant difference in snapshot rankings in simulated environments, at an SD value of 3.40 and 15.26 respectively.

Table 1 Overview of reported snapshot rankings in real and virtual environments

Responses	**Reality**	**VR**
Total snapshots	345	330
“very dark” shots	89	65
“dark” shots	89	87
“bright” shots	85	101
“very bright” shots	82	77
Mean value of all shots (1=very dark, 4= very bright)	2.26	2.47
SD value	3.40	15.26

Figure 5 shows a description of the region and related classification of the recorded snapshots. Observational assessment shows a general consistency in the total snapshots recorded in both reality and VR in separate locations, with the exception of the canteen area, where a higher rate of snapshots was captured in reality than in VR (29, 17 snapshots respectively). In both, subjects largely recorded in the open office area, while the least recorded was in the lab room.

Distributed by brightness ratings, the snapshotted “very bright” scenes were shown mostly in the open office area, suggesting a shared perception of it among subjects as the brightest in both real and VR environments. Though, significantly more snapshots were submitted in the open area in reality than in VR (54, 38 snapshots respectively). In addition, a steady outcome in both environments could be shown in case of “bright” scenes, where the open office area had the most reported bright shots in both cases (40, 49 snapshots in reality and VR respectively).

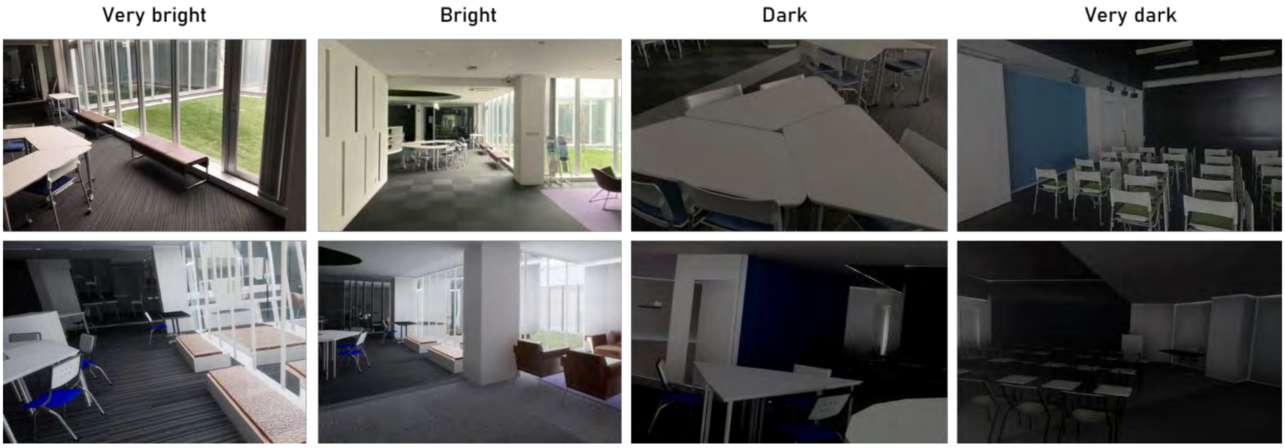

Figure 4: Subjects' snapshots in reality (upper row) and VR (lower row) showing different brightness ratings.

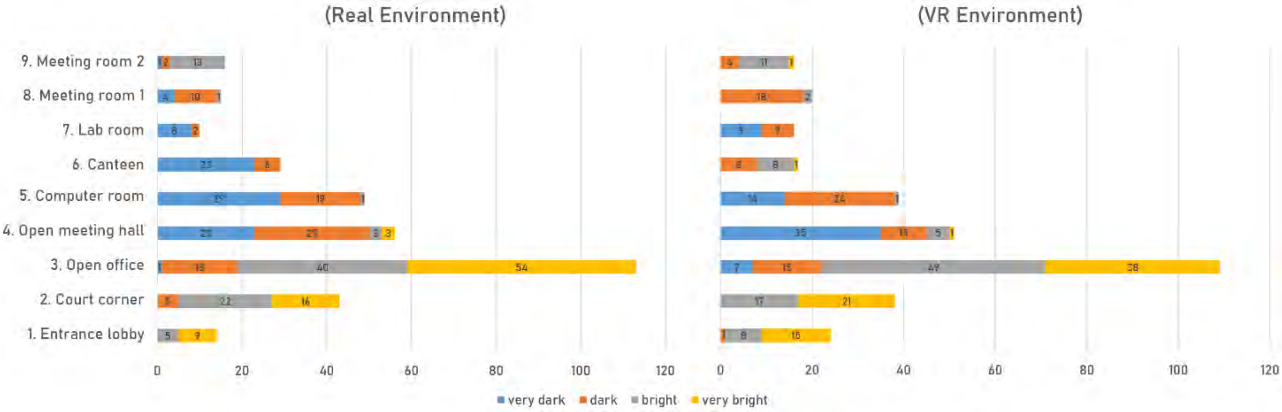

Figure 5: Snapshot distribution by area and ranking in real (left) and virtual environments (right).

In case of "dark" snapshots, similarly, the open meeting hall (27 shots) and computer room (24 shots) produced the highest number of snapshots in reality and VR respectively. In case of "very dark" scenes, subjects reported the most at the open meeting hall (23 shots) and the computer room (35 shots) in VR and reality respectively.

Discussion

The VR system introduced in this article suggested a strategy for incorporating game engines into IVEs used in subjective light evaluations. Within this regard, a game engine was used as a rendering element to simulate daylight and create an interactive method of feedback. Although the introduced method requires additional research about its potentialities and limitations, it enables a broad variety of applications to address existing drawbacks of current IVE strategies. This potential is demonstrated through the enhancement the proposed system brought in the interactivity and simulation speed in the virtual environment. Furthermore, the interactive method of ranked snapshots has provided a more personalized output and consequently a higher variety of responses from a small number of subjects. It also gave empirical insights on subjects' contextual settings when they provided their perceptual feedback (e.g. standing point and target scene). Comparative analysis between the subjective responses in reality and VR reveals a sensible agreement between the numbers of reported scenes in the two environments. This consistent allocation was also noticeable among the majority of the investigated areas, where subjects in VR perceived brightness in a similar way to those in the physical environment.

While the representation accuracy of the developed IVE was validated by comparing brightness perception in VR and physical environment, including quantitative human comfort indicators (e.g. glare, and productivity) could shed more light on the limitations of the proposed system. Moreover, in this study, daylight intensity was subjectively identified through the subjects' perceptions. In a further ongoing study, a quantification methodology will be developed in order to validate the photometric accuracy of the game engine renderings in terms of physical lighting measurements, mainly illuminance (in lux) and luminance (in Cd/m^2).

Conclusions

In this study, a game engine was employed as light simulation tool in an immersive real-time daylighting environment using a self-expressive assessment approach. The developed system provided a real time simulation of daylighting as well as facilitated an interactive method to report light perception within the virtual environment. To investigate the adequacy of the proposed method, thirty-six subjects distributed across two groups explored a daylit physical environment and its virtual replica in the developed system. In the two environments, subjects snapshotted and rated brightness of various areas within the test environment on a 4-point scale (very dark, dark, bright, and very bright). Subjects reported a fairly similar number of scenes in the two environments, where the most reported bright scenes were found around the courtyard and entrance lobby, and the most reported dark scenes inside semi-closed areas with a high volume of furniture. In both physical environment and VR, there were no significant discrepancies were found between subjects' brightness perceptions. The findings of this study illustrate the potentials of game engines as tools to simulate daylight accurately and improve user interactivity with VR systems in light perception studies. It also encourages further research to validate the photometric and luminous accuracy of such engines against the well-established physically based rendering tools.

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