Evaluating and visualizing perceptual impressions of daylighting in immersive virtual environments

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ABSTRACT
This paper proposes a gamified approach to collect and visualize human perception of daylighting in large-scale indoor environments using immersive virtual environments (IVEs). The developed system was tested by 20 participants, where their daylighting preferences for the virtual environment were collected at two daytimes through snapshotting and evaluating their points of interest in terms of brightness, as well as their evaluation of the system and daylight quality. Afterward, participants’ feedback was visualized into a perceptive lighting map (PLM) and compared to an image-based quantitative metric. The results of this experimental study found a tendency among participants to report more feedback in areas with large daylight portals rather than other areas with similar light intensity. Additionally, results from both subjective and simulation-based metrics showed consistency in defining daylight intensity, as well as explained the occurrence of contradicting user evaluations of some identical areas in IVE as a result of high contrast in brightness. The findings showed the adequacy of the proposed system as a visual source of user-centered feedback to daylighting in the early stages of design, as well as a supplement tool for building performance simulations (BPS).

1. Introduction

For architectural daylighting design, computer simulations can have three major benefits: Visualization, building performance simulation (BPS), and daylight optimization. BPS provides a quantitative approach to evaluate the quantity and distribution of daylight in a given space while considering design components such as building form, openings, and material physical properties (de Wilde 2018).

Unlike BPS, measuring user perception and preferences is mainly qualitative as it is based on feelings and sensations (Rockcastle and Andersen 2015), which is challenging to be validated as a mere source of design decision-making. For buildings in operation, user perception of daylighting can be measured using survey studies or performance indicators for certain tasks (reading, for example). Nonetheless, it is more challenging to collect such feedback in unbuilt spaces through virtual media, due to the absence of real-life experiences (Tahran et al. 2005).

Immersive Virtual Environments (IVEs) have gained huge momentum as a valid medium to investigate the human perception of unbuilt spaces, including daylight perception (Chamilothori, Wienold, and Andersen 2018). Enormous studies have applied IVEs to investigate subjective qualities of daylighting within a user-friendly immersive interface (Chamilothori, Wienold, and Andersen 2016, 2018; Natephra et al. 2017; Rockcastle, Chamilothori, and Andersen 2017). However, limitations can be found in many of these studies in terms of environment scale, feedback methodology, and the extent of user–environment interaction, as analyzed in more detail in section 2.3. Many of these limitations can be solved using Gamification, which involves the enrichment of serious tasks with game design principles to motivate and increase the overall user experience (Korn et al. 2019).

This paper proposes a methodology for a gamified approach to measure daylight perception for large-scale indoor environments in IVEs. The proposed system utilizes Unreal Game Engine and HTC Vive Pro to visualize daylight effects for an architectural space. Twenty participants were asked to walk freely inside a VR model of a museum, control daytime, and report their bright/dark scene preferences. Also, their responses to a questionnaire on both system usability and daylighting qualities were collected. Finally, based on the participants’ preferences, a heat map of bright and dark areas was generated and compared to a simulation-based map of mean and Standard Deviation (SD) values of brightness, where the consistency among both resources was examined.

The expected outcomes of this study contribute to the improvement of IVEs effectiveness as a tool to assess the human perception of daylighting in large-scale spaces before being built, as well as giving a better understanding to user preferences and limitations related to light design in virtual environments, and whether these...
preferences agree with the widely used daylight empirical measurement indicators.

2. Related work

2.1. Evaluating lighting perception in immersive virtual environments

Numerous studies have addressed IVEs as an evaluative tool for daylighting, including visual comfort, glare perception, and interest in the scene. Chamilothori et al. (2018) validated if immersive virtual reality is adequate to measure the human perception of daylight spaces in five aspects: perceived pleasantness, interest, excitement, complexity, and satisfaction. The experiment compared users’ perception of a real daylight room and its virtual replica through a Head Mounted Display (HMD). The study showed promising results of VR where no significant differences in perception were found between the real and the virtual environment. In a similar experiment, Rockcastle, Chamilothori, and Andersen (2017) employed VR and HMD, along with head-tracking from a fixed view, to collect visual interest ratings of 8 different spaces in different sky conditions, and compared it to results predicted by an image-based algorithm where the study showed consistency between both results. In another study by Rockcastle and Andersen (2013), they compared subjective ratings for 9 virtual architectural spaces in different sky conditions to local and global contrast metrics, whereas one of the interesting findings was 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.

While the discussed studies investigate daylight perception in IVE from an evaluative approach, other researches extend their utilization of IVE by offering interactive systems where users can customize lighting settings, which reflects an important insight on user preferences and behaviors. For example, Natephra et al. (2017) used Unreal engine (UE) to design an interactive lighting design system in VR, offering a simulation for both daylight and artificial light. A wide variety of interactive options were offered, including moving and rotating fixtures, and changing lighting conditions. Another study by Heydarian et al. (2017) investigated user lighting preferences in IVE while offering the choice to open or close window shutters as well as customizing artificial lighting intensity while performing a reading task. The study found that participants not only preferred to have maximum possible daylighting but perform better in that condition.

2.2. Gamification as an engaging design tool

Gamification became one of the most utilized approaches for encouraging individuals to actively participate in various types of activities (Hassan and Hamari 2019). In the last few years, it has become a trending buzzword in many fields as a medium of improving user engagement and enhancing user activity, social interaction, and productivity (Hamari, Koivisto, and Sarsa 2014). Several researchers have addressed the definition of gamification. For instance, Nick Pelling coined the term gamification as a fast and enjoyable transfer of electronic transactions through the game (Pelling 2011). Deterding (2019) defines gamification as a process to translate the engaging aspects of games into other non-gaming aspects in order to generate positive user experience and motivate desired attitudes. Similarly, Karl Kapp identifies gamification as a means for game-oriented thinking, encouraging participatory learning and problem-solving (Aşkın 2019). Gamification is mainly oriented around applying game mechanics (Raymer 2011) into non-gaming contexts, one major example is the use of points, badges, and leaderboards (PBL) (Chou 2019). In this context, gamification can be seen as an approach to invoke the same psychological experiences that actual games bring, to improve users’ focus, motivation and enjoyment in the action they do (Huotari and Hamari 2012).

Gamification has been employed in many fields, including education (Dicheva et al. 2015; Nah et al. 2014), product design, marketing (Hofacker et al. 2016), and co-design (Dodero et al. 2014). In architectural design, many studies have utilized gamification to enhance participatory design and occupants’ feedback on the design process. For example, Haworth et al. (2020) developed an approach to replace the traditional designer-as-user concept by a gamified crowdsourced design methodology, where it showed evidence as an interesting approach to collaborative environment design. In another study by Schnabel, Lo, and Aydin (2014), a gamified design platform was introduced, focusing on urban mass housing projects. The platform aimed to engage architects, landlords, developers, and residents to generate participatory design solutions in a gamified online platform. This enabled the development of novel design outcomes that consider the needs of different parties in the design process. In a similar context, Aşkın (2019) integrated gamification in interior design education, where a post-experiment survey showed that it increased the students’ motivation and provided multiple alternatives through the design process.

2.3. Motivation and research gap

As discussed in Section 2.1, a number of studies have employed IVEs as a medium for perceptual evaluation of daylighting conditions (Rockcastle and Andersen 2015; Chamilothori, Wienold, and Andersen 2018; Rockcastle, Chamilothori, and Andersen 2017; Heydarian et al. 2017), benefiting from the immersive nature of such approach. However, in terms of gamification (as defined in section
2.2), it is evident that there is a gap between applying gamification principles (which involves high interactivity) and utilizing IVEs for daylight evaluation, despite the benefits gamification can add to users’ experience and thus to their feedback reliability. One of the major factors of this gap is the wide reliance on validated light simulation tools (e.g. Radiance) due to its photometric accuracy in representing lighting environment. On the other hand, these tools show notable limitations in rendering speed (Jones and Reinhart 2017) and user interface customization, which are two crucial factors for effective interaction between the user and the virtual environment.

A number of limitations within the current literature employing IVE can be argued as follows: Firstly, lack of diversity in terms of case study scales and types. In many of the studies, the model used for evaluation is often a small room with a simple floor plan and minimal furnishing and surface textures (Chamilothori, Wienold, and Andersen 2018; Heydarian et al. 2017). Also, while studies tend to focus on office spaces, other user-oriented types of spaces such as libraries and museums are very little represented, despite the major role daylight plays within their design process (Kaya and Afacan 2018; Othman and Mazli 2012).

Secondly, it is noted that only a limited number of experiments allow users to walk into the virtual environment (Natephra et al. 2017; Heydarian et al. 2017), where others rely on head movement and looking around as a mere approach of exploration. Finally, while some systems let users interact with the environment (pick objects, switch on lights), the environments tend to be static (inability to change daytime/sun position) and have no built-in tools to export user feedback into analyzable data (images, maps) rather than relying on verbal questionnaires. These limitations can be overcome by delivering gamified content inside IVE, which offers users a wide variety of choices while having tools to express personal preferences.

This paper aims to bridge those gaps by proposing an interactive gamified system where users can move around freely, control daytime and artificial lighting, and snapshot what they see. The system offers a novel approach for collecting user daylighting preferences in virtual spaces and provides a comparative analysis between such feedback and quantitative lighting metrics of the same space. Through this approach, user daylight preferences can be collected during the early stages of the design phase, enabling architects to effectively make more user-centered decisions when it comes to daylighting.

3. Methodology

This study aims to present a novel approach of implementing IVE for measuring subjective characteristics of daylighting in indoor environments through a gamified system, where users are offered more flexibility and choices while giving their daylight preferences in real-time in IVE; then, their preferences are compared to quantitative metrics to check consistency between user perception and such measurements. To validate the proposed system, a case study on a large-scale art museum was conducted, where 20 participants were recruited to collect their daylighting preferences as well as their evaluation of the system usability and daylight qualities of the museum.

3.1. Case study

A virtual model based on the Kimbell Art Museum in Fort Worth Texas (by Louis Kahn) was designed and modeled as the case study of the proposed system (Figure 1). This building was chosen as the case study for its unconventional daylight utilization (Kacel and Lau 2013) and secondly, being a public building expands the pool of its potential users to virtually anyone, unlike the limited usability of office environments. Thirdly, it extends over a large area and contains multiple spaces with variable daylight effects throughout the day, and each space has enough complexity to enrich the immersive experience and make users more curious to explore.

While various studies have investigated the luminous environment in Kimbell Art Museum both quantitatively and subjectively (Kacel and Lau 2013; Pierce 1998; Varzgani 2015; Roginska-Niesluchowska 2016), there is a lack of studies employing interactive systems and real-time rendering for a user-based daylighting evaluation of the museum, which is covered in this paper.

3.2. Experiment setting

The designed virtual model comprised 6 cycloid vaults with a total width of 56 m and a total length of 96 m over three bays. The floor plan covered an area of 3380 m² and consisted of 6 main areas (main lobby, three galleries, cafeteria, and library) (Figure 2).

For daylighting, each vault had a longitudinal roof opening along its center equipped with reflectors to maximize light gain on the ceiling (Figure 3). Also, walls and arched walls contained narrow light slits. The model had one main courtyard in the north gallery, and two small courtyards in the south galleries.

The experiments were conducted in a dedicated office space at Osaka University in Suita, Japan. This space had three windows facing North-east and North-west, shutters were fully retracted during experiments in order not to distract participants’ perception with ambient sunlight from the outside. The experiments took place from March to May 2019 between 12:00 pm and 6:00 pm.

A Desktop PC equipped with NVidia Quadro RTX 6000 graphics card and 64 GB of RAM was used to operate the system. The designed model location and
Figure 1. Axonometric of the designed model, showing roof structure and spaces.

Figure 2. Floor plan of the virtual model showing main areas as follows; 1) Lobby 2) Library 3) Café 4) North gallery 5) South gallery A 6) South gallery B.

Figure 3. Daylighting strategy in Kimbell museum through light reflector devices (Louis I. Kahn Building | Kimbell Art Museum).
lighting were based on the original site in Fort Worth, Texas. The date was set to 23 June with a clear sky and the default time was 9 am. However, the system enabled participants to change time freely up to 6 pm.

3.3. Model setup

The workflow for creating the proposed IVE system was as follows: First, detailed plans and elevations of the building were modeled in AutoCAD. Then, the blueprints were imported into 3ds Max as splines, where all the meshes and surfaces were created to realize the full digital model of the museum (Figure 4). Daylight-related geometries such as reflectors were modeled separately to guarantee accurate daylight simulation. Furthermore, furniture and art pieces (sculptures, paintings) were created and positioned in 3ds Max.

Using Vray, physical materials were added to all the surfaces to resemble the appearance of the real museum, where reflection and refraction values were set up accordingly. Textures were scanned and stitched using a library of photos for the interior of the museum, whereas their scales were adjusted using 3ds Max UV mapping tools (Figure 4(b)).

3.4. Daylighting setup

After finishing the full-textured model in 3ds Max and V-ray, it was imported into Unreal Engine (UE) 4.22 using the Datasmith Plugin. Through this approach, the model materials and textures were preserved. Materials with refractive and/or reflective values were recreated from scratch in the UE material editor to ensure accurate light simulation.

For the daylighting setup, a single directional light source was used to simulate the sun, which was linked to a sun position plugin to automatically control intensity, tone, and position of the directional light and sky sphere according to real location data (Figure 4(c)). Coordinates were set to 32.755501 and −97.330803 (Fort Worth, Texas) and the date was set to 23 June and Time zone to −6. Sky lighting was simulated through a Preetham sky model (Preetham, Shirley, and Smits 1999) with a sunny sky condition. Daylight simulation was built separately at two day times (9 and 18) at the highest lighting quality, and each timing was stored as a separate game level (Figure 5).

3.5. Verification of scene luminance in game engine

As the consistency between the simulation effect and the photometric characteristics of the actual view needs to be validated, a comparison was set at one scene of the virtual museum, between illuminance values produced by UE4 simulation and those calculated by a validated light simulation tool. Velux Daylight Visualizer V 3.0 was selected for quantitative daylight simulation, where luminance values were calculated for the investigated scene. This tool was selected in particular due to its sophisticated interface (compared to the command-line-based Radiance (Ward and Shakespeare 1998)) and its thoroughly validated results (Labayrade, Jensen, and Jensen 2009; Iversen et al. 2013). The 3D model was imported from 3DS Max, and surface properties and daylighting settings in UE4 were replicated in Daylight Visualizer. Then, a luminance simulation was run at a fixed scene in the north gallery of the museum, where luminance values at 9 points were collected. The simulation ran at 9 am and 6 pm time settings. In UE4, the luminance values at the given points were extracted using the built-in HDR Histogram viewer, which can render the scene in false color that represents luminance levels simulated by UE4 lighting (Figure 6). Table 1 shows a comparison between the luminance values calculated by Velux daylight visualizer and corresponding values in UE4 simulation at the two scene times (9:00 am and 6:00 pm). Across the nine investigated points, it was noticed that UE4 calculations overestimated that of Daylight Visualizer at some points (e.g. point H), while underestimated the calculations at other (e.g. point A). Thus, to unify the positive and negative discrepancies between the two tools, the error percentage of UE4 compared to Daylight

Figure 4. A diagram showing the experiment workflow and outputs.
3.6. Interactive IVE setup

Various controls were developed and programmed using Blueprints, which is a visual scripting tool for UE. Through this approach, participants had the option to (move freely in the virtual space, jump, show/hide daytime label text, switch on/off artificial lighting, change daytime, snapshot what he/she sees). An HTC Vive Pro HMD with 2880 × 1600 pixels combined screen resolution and 90 Hz refresh rate, Vive motion controllers, and two tracking stations were connected to the system.

Participants’ daylighting preferences were collected at two days times (9 am and 6 pm) through walking around different areas within the museum and snapshotting the spots they felt brighter/darker than average (Figure 4(f)). These snapshots were stored in the system and converted to identical cameras in 3ds Max to generate a collective overlook of user-based daylight heat map comparable with various quantitative daylight (Figure 4(e)). Also, a post-experience questionnaire was provided to collect participants’ evaluation of the usability of the system as well as simulated daylight properties (Figure 4(d)).

Through this approach, the output of this study aims to introduce a methodology to tackle both subjective and quantitative daylight measurements side by side as one unified metric (Figure 4(g)) to evaluate (and later optimize) daylight performance of indoor environments in early stages of design, considering both human-related factors and energy/sustainability recommendations.

4. Experimental procedures

A pilot study was conducted to validate the IVE system performance and collect preliminary feedback for future
improvements. For this pilot study, only three participants were recruited. However, they offered extensive feedback which helped us bypass the limitations of the system and improve the overall performance. For example, the time needed for the transition between daytimes was minimized. World scale settings were recalibrated to be more accurate. Finally, lighting simulation was rebuilt separately for each daytime for better variation in position, intensity, and tone of simulated sunlight.

4.1. Participants

For the main experiment, 20 participants (12 males, and 8 females) were recruited in this study. The participants were 60% Masters students and 40% Bachelors students at Osaka University and were aged from 18 to 24 years (80%) and from 25 to 39 years (20%). While the participants were majorly architecture students, they had limited knowledge of daylight metrics and evaluation, which was important to ensure unbiased feedback towards the system. VR experience among participants seemed to be limited, where 40% have never tried an HMD and 45% tried it only once.

4.2. Experiment protocol

Firstly, participants were introduced to a computer-based introduction form and read a brief about the research topic and the experimental procedures. Then, they proceeded to an introduction about the Kimbell Art Museum, including a video walkthrough in different parts of the building. Finally, an explanation of the tasks they should fulfill during the experiment was provided. Secondly, participants were asked to put on the HMD and try a sample scene to get familiar with the IVE system and controls (Figure 7).

After participants felt familiar with the HMD and controllers, the full virtual museum was loaded at the default position at the lobby at 9 am. Participants were asked to use the snapshot button to report the spots (scenes) where they feel one of the following cases existed regarding daylighting: very dark, dark, bright, or very bright scene. Participants were free to take as many snapshots as they wanted and freely manage to switch between 9 am and 6 pm (Figure 8). Each time a participant took a snapshot, he/she was asked to verbally report their evaluation of what they snappedhotted.

Once participants finished their tasks, they were asked to take off the HMD and then were introduced to a 5-point scale questionnaire with the following verbal anchors on the extremes: strongly disagree matches 1 point and strongly agree matches 5 points. For scale interpretation, responses ranging from 1 to 3 points were addressed as negative (disagreed), while 4 to 5 points were considered positive (agreed). The questionnaire collected users’ preferences during the experiment, as well as evaluation of the system usability (quality and immersion, interaction, comfort) and daylight properties (uniformity, intensity, functionality, aesthetics) (Table 2).

4.3. Perception-oriented luminance maps

To properly visualize the daylight preferences collected into an output that is comparable to other relevant quantitative daylight metrics, more analysis was needed. Therefore, we introduced a methodology to generate perceptive lighting map (PLM), which is

![Figure 7](image-url) A participant trying the sample scene at different daytimes.
4.4. Comparing perceptive lighting maps against daylight metrics

This section presents a case study of comparing perceptive-based daylight evaluation to relevant simulation-based metrics, in order to have an insight on the consistency of simulation-based daylight performance indicators with actual user needs, and thus achieve performative daylight solutions through a more user-centered approach. There are various types of quantitative daylight metrics, some of which are limited to fixed date and time (illuminance and luminance), while others are annual (Spatial Daylight Autonomy (sDA) ((Chair) Heschong et al. 2012), Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic 2005)).

(Figure 9) shows an Illuminance map (in Lux) for the virtual model, side by side to the generated PLM. The illuminance map was simulated in VELUX Daylight Visualizer with the same location and time settings as in the developed system. While the two maps agree on some data results, for example, the highest light illuminance around the main courtyard, such comparison can still be questionable. On one hand, as seen in other quantitative lighting metrics, the illuminance map measures the quantity of luminous flux falling on a 2D surface, in other words, light intensity falling on horizontal surfaces (e.g. floors, desks). On the other hand, perceptual-based measurements like PLMs are based on the user’s impression of the ambient environment in 3D space, not to a specific surface. A similar limitation also applies to consolidated annual metrics such as sDA and UDI. Moreover, the methodology of generating the perceptual maps is based on point-in-time measurements; thus, it cannot directly be compared to over-the-year metrics.

In the context of visual comfort and occupant perception of daylighting. Luminance-based metrics, vertical illuminance, and cylindrical illuminance have shown better results than horizontal illuminance in predicting discomfort glare and occupant light preferences (Marty et al. 2003; Van Den Wymelenberg and Inanici 2014; Torres and Verso 2015). While the reported snapshots did not cover every corner of the virtual environment, the generated PLMs could qualitatively predict perceptual daylight intensity at any point of the investigated model. Thus, a similar simulation-based light map, extending over the whole floor plan was needed for a robust spatiotemporal comparison between perceptual and actual luminances in the virtual model.

4.4.1. Image-based brightness

In order to realize an accurate comparative analysis between PLM outputs and daylight quantitative measurements, a metric that indicates average daylight brightness in 3D space, similar to PLM, should be used. Therefore, we developed a novel image-based metric of daylighting in a virtual environment based on luminosity histogram analysis. In photography, a luminosity histogram is a graphical representation of pixel brightness within a digital image expressed by the tonal range of each pixel in units from 0 (darkest) to 255 (brightest) based on RGB (red, green, blue).
Table 2. The post-experience questionnaire aspects and questions.

| Aspect                               | Sub-aspect       | Question                                                                 |
|--------------------------------------|------------------|--------------------------------------------------------------------------|
| System usability                     | Quality and      | Q1: I felt the virtual environment was consistently similar to the images of the real building. |
|                                      | immersion        | Q2: The overall feel of the environment was realistic.                    |
|                                      |                  | Q3: My height relative to the world felt accurate and natural.            |
|                                      |                  | Q4: Objects’ sizes (tables, chairs, etc.) felt accurate and natural.     |
| Interaction quality                  |                  | Q5: I did not need much time to get familiar and move freely inside the virtual space. |
|                                      |                  | Q6: I got the feeling that I was fully immersed (present) inside the virtual space. |
| Light penetration                    | Uniformity       | Q7: The sample virtual space at the beginning was helpful to get used to the controls and motion further. |
|                                      |                  | Q8: The controller buttons were responsive and easy to access while wearing the headset. |
|                                      |                  | Q9: Sense of movement felt realistic and natural.                         |
|                                      | Intensity        | Q10: I didn’t feel much motion sickness while moving inside the virtual space. |
|                                      |                  | Q11: The headset screen resolution was convincing (pixels were not noticeable). |
|                                      |                  | Q12: The brightness of headset screens was not tiring to my eyes.         |
|                                      | Variability      | Q13: Position of the “Daytime” label was convenient.                      |
|                                      |                  | Q14: Most areas inside the virtual space got the same amount of sunlight. |
|                                      |                  | Q15: I liked the fast brightness change effect while moving inside the virtual space. |
|                                      |                  | Q16: Sunlight intensity was sufficient during the two days.               |
|                                      |                  | Q17: I didn’t experience any glare effect (excessive light) inside the virtual space. |
|                                      |                  | Q18: Changing the daytime effectively changed sunlight intensity inside the virtual space. |
|                                      |                  | Q19: Changing the daytime effectively changed sunlight color (tone) inside the virtual space. |
|                                      |                  | Q20: Changing the daytime effectively changed shadow and shade patterns inside the virtual space. |
|                                      | Functionality    | Q21: Sunlight is solely sufficient to illuminate the virtual space (floors, walls, etc.) |
|                                      |                  | Q22: Sunlight is solely sufficient to illuminate the art pieces (paintings, statues, etc.) |
|                                      |                  | Q23: Overall, I preferred to switch on artificial lights throughout the virtual space. |
|                                      |                  | Q24: Overall, I felt the art pieces are better illuminated using artificial lighting rather than sunlight. |
|                                      | Esthetics and    | Q25: I had a pleasant feeling while being in the virtual space.           |
|                                      | perception       | Q26: Shadows and shades generated by sunlight gave beautiful patterns on walls and floors. |

channel brightness scale units (Nikon 2019). In the same context, luminosity can be hereby considered a lighting metric that qualitatively represents the brightness of a given scene. In such a case, the brightness mean value of an image would express its average relative luminance based on the average tonal value for all pixels in the image. Similarly, the standard deviation of brightness values expresses the discrepancies between pixel brightnesses and the mean value. Thus, a low standard deviation can suggest a low contrast in the image exposure (i.e. lighting) and vice versa. Research work by Inanici et al. has investigated luminance-based design metrics based on HDR images as a tool for predicting human visual comfort of lighting (Kumaragurubaran and Inanici 2013; Van Den Wymelenberg, Inanici, and Johnson 2010).

(Figure 10) shows the workflow of mapping scene brightness data for the virtual model. Firstly, the floor plan of the virtual model was divided into 162 square grids as measuring points, each of 3.9 x 3.9 m dimensions. Then, the grid is overlaid on the virtual model in Unreal Engine, and using Nvidia Ansel Plug-in (NVIDIA Ansel 2017), a High Dynamic Range (HDR) 360° Panoramic image is snapped at the center of each measuring point at 9 am. The generated HDR images’ luminances were calibrated and tone mapped using the Ward method (Larson, Rushmeier, and Patko 1997) in Hdrscape software (Kumaragurubaran and Inanici 2013). In Photoshop Histogram analyzer, the brightness data of each image could be extracted. In this case, two values were of importance to this study, the first is “mean brightness”, which expresses the average brightness of all the pixels in the image (intensity), and the second is “brightness Standard Deviation (SD)”, which indicates the extent of extreme brightness values (very dark, very bright) within the image (brightness contrast). With these two values recorded for each given measuring point, they were mapped on the model floor plan as text values and color gradients ranging from blue (lowest) to green (highest).

5. Results and analysis

As discussed in section 4.2, after participants finished their VR experience, they were given a post-experiment questionnaire to assess various aspects of the virtual system usability and perceived realism level. In response to Q1 (Table 2), the majority of participants agreed on the consistency between the virtual environment and the real museum, where 40% agreed (4-points) and 25% strongly agreed (5-points) to the statement (Figure 11Q1). For Q2 regarding the overall realistic feel of the virtual environment, 83.4% of participants responded positively (4 to 5 scale points). The system also got a positive impression of scale perception, whereas 55% strongly agreed that they felt the scale of the surrounding objects to be natural, while 25% agreed (4 points) (Figure 11Q4).

Regarding system controls, 83.3% of participants found the controllers to be responsive (Q8), while 50% found the system easy to get familiar within a short time (Q5). However, the locomotion technique
used was reported by some users as “too fast” or has a “sliding effect”. In the questionnaire, 35% of participants did not feel the sense of movement was realistic (Q9) (1 to 3 scale points).

Regarding simulated daylighting evaluation, 55% of participants showed fair to strong agreement (4 to 5 scale points) that the intensity of simulated sunlight was generally sufficient in the two reviewed daytime (9 am and 6 pm) (Figure 11Q16) and adequate to lit walls and floors (70%) (Q21). Also, the majority of participants positively evaluated the variability of simulated sunlight in terms of intensity (Q18), tone (Q19), and generated shadows (Q20) at different times (75%, 79.2%, and 54.1%, respectively). However, for exhibited items (paintings and sculptures), 41.7% of participants preferred if artificial lighting lit them along with daylighting.

5.1. Daylight perception in IVE

Participants were asked to report their daylighting preferences in IVE by snapshotting the scene which they perceive as very dark, dark, bright, or very bright within the six areas of the virtual museum during two daytimes in virtual reality (Figure 13). Participants were also able to compare the brightness of a given scene in VR at 9 am and 6 pm immediately by standing at the same scene and change time settings using the motion controllers. (Figure 12) shows the distribution of reported scenes at two daytimes spread among the main 6 areas of the museum (defined in Figure 2), ranked from very dark to very bright. Participants produced 326 snapshots, with a nearly equal distribution between bright (53%) and dark rankings. Participants reported dark scenes at 9 am at a nearly equal rate to the bright ones (42%). Another finding is that while the north gallery, where the main courtyard can be found, had most of the reported bright scenes during 9 am, the south gallery A had a higher number of bright snapshots at 6 pm; however, the fact that its courtyard is much smaller.

Based on the methodology discussed in Section 4.3, Figure 14 shows user daylight evaluation maps at 9 am and 6 pm. The results showed that areas surrounding the main courtyard (north gallery and cafeteria) obviously had the highest density of perceived bright scenes at both daytimes. However, in some areas such as south gallery A and parts of the cafeteria, participants tended to report more bright scenes at 6 pm than 9 am. Another finding was the “mixed perception” spots (violet color),
where participant’s perceptions conflicted for the same area, some evaluated as bright while others evaluated as dark. This effect could be found along the exhibition wing in the north gallery A at 9 am, while found in the lobby area at 6 pm. However, map analysis did not show a significant tendency of this effect to occur more at one daytime than the other.

5.1.1. Case study: comparing PLM to scene brightness values

Through the methodology discussed in section 4.4.1, a quantitative daylight metric in the virtual environment, based on the average brightness of a scene 3D space, could be generated and thus compared to the produced PLMs (Figure 15). In this section, a case study of comparing PLM data at a given daytime to a quantitative lighting metric of the virtual environment is illustrated, where both are based on evaluation of average brightness of a given scene in 3D space. This comparison aims to validate the accuracy of participants’ feedback in perceiving daylight intensity in IVE, and whether their results can agree with other daylight metrics at the same settings. To do so, the position of each of the 217 snapshots in PLM (9 am) was matched to the deduced brightness mean value at the same location on the floor plan.

SPSS statistical software was used to conduct a scatter plot graph (Figure 16), as well as a Pearson correlation analysis between user snapshot ranking at a given point and its corresponding mean brightness values. The correlation coefficient \(r\) was 0.424, with a statically significant correlation level \((P < 0.001)\) (Table 3). This analysis proves a moderate positive correlation (Akoglu 2018) between brightness mean values and participants’ perception in IVE, and thus the consistency between results based on PLMs and this quantitative metric.

5.1.2. Mixed perception: contradictions in daylight perception in IVE

In this study, the generated PLM visualized daylight intensity in a virtual environment based on the
6. Discussion

This study introduces an interactive system to collect user feedback and preferences on daylighting in virtual environments and generates Perceptive Lighting Maps (PLMs) that indicate subjective performance in a comparable approach to quantitative, simulation-based daylight metrics. The case study of comparing PLM data to brightness maps shows the benefits this system can offer to architects and lighting designers in improving their design alternative to be more human-oriented and detect potential conflicts between simulation results and future-user perception of the same space at early stages of design.

As regards to workflow speed, the use of game engines as light simulation tools showed noticeable advantages over traditional photometric rendering tools (e.g. Radiance, V-Ray). In this study, the used game engine was fully compatible with the meshes and materials produced in the 3d modeling software, and thus needed no additional time for refining or tweaking the model. Furthermore, the process of setting up the VR controls was simple as it is already embedded in the game engine and only needs minimal customization by the user. Moreover, the built-in daylighting plugin enabled a simple definition of sky conditions and spatiotemporal settings of the model. For daylighting rendering, one of the major advantages of game engines is the ability to render the whole model in real time. Thus, after the initial lighting setup, users can freely explore any part of the model without the need to wait for new renders to be generated. These observations show that even with the added benefits of building the gamified model in VR, the time needed to achieve this result is noticeably less

Table 4 shows the corresponding brightness mean and SD values for each of the 10 scenes. It was found that 9 out of 10 scenes had a higher SD than average. As SD value expresses contrast levels in the captured scene, it may suggest that the more non-uniform lighting in the scene the more participants’ perception is confused. However, many factors can contribute to such a phenomenon, including participant personality, which is not within the scope of this study, and thus it will be investigated thoroughly in a future study.

Figure 14. Heat maps showing the density of users’ evaluated snapshots (T is daytime).
than that in traditional software tools (e.g. 3Ds Max), specifically when many scenes/lighting conditions within the model need to be evaluated.

In this experiment, our proposed VR system had a generally positive evaluation by users in terms of realism, scale perception, and daylight quality, which is consistent with findings of similar studies utilizing IVE for daylight subjective evaluations (Chamilothori, Wienold, and Andersen 2018; Chamilothori, Wienold, and Andersen 2016). These advantages show the potential adequacy of IVE as an alternative to real environments to measure daylight perception, as well as the potential of game engines as an accurate light simulation tool.
Table 3. Pearson correlation analysis between scene brightness values and user snapshot rankings.

| Scene brightness | Pearson correlation | N   | Sig. (2-tailed) |
|------------------|---------------------|-----|-----------------|
| Brightness       | .424***             | 217 | .000            |
| User ranking     | .424**              | 217 | .000            |

**Correlation is significant at the 0.01 level (2-tailed).

A majority of participants reported motion sickness while in IVE. While this is a known limitation of VR (Langbehn, Lubos, and Steinicke 2018), around third of the participants did not feel the locomotion technique was realistic enough, which constructs the finding that the “slide” motion effect used in the system was disorienting to the physical state of participants and thus motivated motion sickness.

Unlike previous studies, where user perception evaluation is limited to a fixed scene, our proposed system gave participants the freedom of movement and choice to express their individual experience within IVE and only highlight what they find worth noticing. The produced snapshot maps focused on visualizing user evaluation of daylighting. However, it can be a useful resource to investigate users’ “wandering” behavior inside the virtual space and thus predicting points of interest and high-occupancy areas at an early design stage. The generated PLMs showed that users tended to have higher presence and interest in areas with large daylight portals (as in courtyards) and thus gave more feedback there rather than in other areas with smaller window sizes, even if they have the same brightness. Another finding was that participants gave contradicting evaluations as dark and bright for a number of spots, which is inapplicable in quantitative measurements. The mixed perception phenomenon was visualized as violet spots in PLMs. Using brightness SD map, where it was found that areas of mixed perception often had a higher SD compared to scene with a clear detection of bright or dark zones. In other words, scenes with higher contrast between bright and dark areas affected user perception of concluding whether the scene is dark or bright.

As a lighting metric, PLMs showed consistency with results drawn from quantitative mean brightness values in terms of identifying daylight intensity in different areas. Knowing the underlying information that PLMs offer, this finding shows not only their potential as a supplement to quantitative metrics but also their advantages as a rich indicator of daylight performance of which accuracy is improved as the number of snapshot feedback increases.

7. Limitations and future work

This paper introduces a framework to collect and visualize user daylight preference in virtual environments.

Table 4. Areas of “mixed perception” and their respective SD and mean brightness values.

| Area | SD value (56.47)” | Mean value (90.38)” |
|------|------------------|------------------|
| 1    | 61.51”b          | 65.02            |
| 2    | 73.45”b          | 127.39”b         |
| 3    | 59.81”b          | 81.71            |
| 4    | 63.36”b          | 92.20”b          |
| 5    | 62.88”b          | 90.16            |
| 6    | 31.70            | 50.43            |
| 7    | 63.67”b          | 76.20            |
| 8    | 69.40”b          | 102.32”b         |
| 9    | 61.69”b          | 89.03            |
| 10   | 60.66”b          | 79.30            |

* Average value for all measuring points.

b Values above average.

Figure 17. Scenes where “mixed perception” occurs and their respective snapshots at 9 am.
Despite the overall positive review of the system and its ability to successfully produce results consistent with quantitative metrics, a number of limitations can be found. As future work, we intend to improve the proposed system by adding more gamified tasks and user performance indicators (i.e., reading tests). In addition, we aim to increase the sample size which will help to furtherly validate the findings of this study. Another limitation to the system is the high record of motion sickness reported by users, which makes it difficult to sustain user immersion for long times. We aim to overcome this limitation by developing less motion sickness-inducing locomotion techniques (e.g., teleport (Langbehn, Lubos, and Steinicke 2018)).

While the system’s case study in this experiment was based on a real building (Kimbell Art Museum), the results deduced from the system were not compared with an on-site daylight analysis. Therefore, we aim to assign another case study of a real building that is easily accessible, to compare the resultant perception-based evaluations in both the virtual and real environments. Another potential limitation is that the experiment was limited to one spatial setting and one date and sky condition (clear sky). As a future work, perceptions under an overcast sky conditions would be furtherly investigated for the same building model. While mean and SD brightness values are considered valid indicators of the environment’s brightness and contrast in different areas, in a future study, we aim to validate the introduced methodology through comparing PLM outputs to established quantitative metrics, including vertical and cylindrical illuminances.

8. Conclusions

In this study, we proposed a novel interactive approach to collect and visualize perceptual user daylighting preferences in a museum virtual environment at two days times. Twenty participants submitted 326 evaluated points of interest through snapshotting in IVE, as well as their evaluation of the system and simulated daylight quality. The results showed a positive impression from participants towards the system and the freedom it offered. Additionally, it was found that areas around large sunlight portals had a significantly higher number of reported snapshots. The developed perceptive lighting maps offered a visual insight into users’ behavior and showed various areas in the virtual model that had contradicting evaluations by users (mixed perception). Through comparing such maps to image-based brightness analysis, a potential correlation was found between areas of high brightness SD values and mixed perception effect. The comparison also showed consistency between both maps in identifying daylight intensity.

The system used in this study offers designers a visualized user-centered feedback that is comparable to quantitative daylight simulation outputs, enabling them to review their designs in the light of actual user needs and perception of the space regarding lighting at an early stage of conceptualization. Additionally, the proposed system can be furtherly developed to investigate more user attributes, including occupation rates and façade setting preferences.

Disclosure statement

No potential conflict of interest was reported by the authors.

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