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Doctoral Dissertation

A Study on Visual Perception of Daylighting in Architectural Space Using Immersive Virtual Reality

(没入型仮想現実感を用いた建築空間における昼光に対する視知覚に関する研究)

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Abstract

Immersive Virtual Reality technology has gained momentum in architectural design and research applications, mainly through creating Immersive Virtual Environments (IVEs). Several studies have employed IVEs as an alternative medium of real environments to assess the visual perception of daylighting in architectural spaces. However, limitations can be found in the current literature concerning interactivity and feedback methods. The aims of this study are to propose a novel method to extend the capability of IVE in evaluating daylighting in architectural spaces using a game engine, to validate the proposed method in terms of perceptions and quantitative measurements, and to validate the applicability of the method to architectural design by a case study on a specific building. This dissertation is composed of seven chapters:

In Chapter 1, a brief background of the study highlighting daylight significance in the built environment was described. Furthermore, it comprised the problem statement, objectives, and thesis framework.

In Chapter 2, a narration of the state-of-art was provided, focusing on daylight performance in quantitative measures and user-oriented indicators. Previous studies utilizing IVEs in lighting research were surveyed and discussed. Finally, the effectiveness of game engines in daylight simulation was conferred.

In Chapter 3, an overview of the proposed methods in this study was provided. The construction method of the IVE using a game engine was described. It also introduced the methodology of developing Perceptual Light Maps (PLMs) as a visualization approach of daylighting perceptions in architectural space.

In Chapter 4, the photometric accuracy of real-time rendering in game engines was investigated. Two daylit test models were simulated. Illuminance measurements at several points were compared across a validated lighting simulation and lux meter measurements in reality. Two real-time rendering techniques in the game engine were tested: a conventional technique and real-time raytracing (RTX). Generally, RTX notably outperformed the conventional technique. Compared to real sensor measurements, the average error percentage of RTX outputs was 15.8%, while 15% in the validated renderer. It was found that daylight illuminance in IVE was as accurate as the validated lighting simulation, even with the adoption of real-time rendering.

In Chapter 5, daylighting perceptual accuracy in the proposed method was validated from the viewpoint of users. Thirty-six subjects were recruited in two groups to evaluate daylight perception in a real space and its virtual replica. In a 5-point Likert questionnaire, subjects in the IVE majorly reported a high sense of "being there" and high accuracy of scale representation. The spatial distribution of subjects' perceptions in reality and IVE were generated and compared using PLMs, where a significant positive correlation was found. In addition, the aggregated brightness perceptions in reality and IVE were compared, where a higher significant positive correlation was found. Thus, it was found that the proposed method enabled the evaluation of daylighting perception in the same manner as in real space.

In Chapter 6, the proposed method was applied to Kimbell Art Museum, where 24 subjects explored a virtual replica of the museum, reported their brightness perceptions. The proposed method showed a unique output of the generated PLMs that cannot be identified by physical metrics, which was the detection of "mixed perception" areas, where subjects perceived the brightness of the same view differently. In addition, the cycloid vaults with indirect daylighting, a characteristic of the museum, were investigated as a source of mixed perception. 83% of mixed perception scenes included the vaults. It was found that the higher the luminance ratio between the vault and other scene compositions, the higher the occurrence of mixed perception. It was indicated that the indirect daylighting of the Kimbell Art Museum brought ambiguous brightness perception to the subjects, and it was clarified that the proposed method could detect areas that should be considered for various user evaluations in architectural design utilizing daylight.

In Chapter 7, findings and conclusions obtained from the whole study were summarized, and the possibilities of the proposed method in architectural planning research were discussed.

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Table of Contents

List of Figures

List of Tables

list of Acronyms and Abbreviations

6DoF	Six degrees of freedom
ACES	Academy Color Encoding System
ASE	Annual Solar Exposure
BGI	British Glare Index
BPS	Building Performance Simulation
CG	Computer Graphics
CGI	CIE Glare Index
CIE	International Commission on Illumination
CPU	Central Processing Unit
CRT	Cathode-Ray Tube
CSV	Comma-Separated Values
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
EML	Equivalent Melanopic Lux
FBX	FilmBoX (3D data interchange file format)
FOV	Field of View
GI	Global Illumination
GPU	Graphics Processing Unit
HDR	High Dynamic Range
HMD	Head-Mounted Display
IESNA	Illuminating Engineering Society of North America
IVE	Immersive Virtual Environment
IVR	Immersive Virtual Reality
LDR	Low Dynamic Range
PBL	Points, Badges, and Leaderboards
PBR	Physically-Based Rendering
PLM	Perceptual Light Map
RGB	Red Green Blue
RTX	Real Time Ray Tracing
SD	Standard Deviation
sDA	Spatial Daylight Autonomy
SDK	Software Development Kit
TIFF	Tagged Image File Format (image file format)
TMO	Tone Mapping Operator

UDI	Useful Daylight Illuminance
UE	Unreal Engine
UE4	Unreal Engine Version 4
UI	User Interface
VDV	Velux Daylight Visualizer
VR	Virtual Reality

Chapter 1. **Introduction**

1.1. Background

People spend more than 90% of their time inside architectural spaces (Klepeis et al. 2001; Leech et al. 2002; Schweizer et al. 2007). Thus, attention to the factors influencing the quality of such spaces is essential. One crucial factor is daylighting, of which a significant benefit in architecture is to improve building performance, whether it is represented in energy savings or user comfort, productivity, and satisfaction (Boyce, Hunter, and Howlett 2003:2). On the one hand, many studies have shown that the utilization of daylighting in a building can contribute to reducing the need for artificial lighting during occupied hours, thus reducing total energy consumption (Chi, Moreno, and Navarro 2018; Franzetti, Fraisse, and Achard 2004; Gago et al. 2015). On the other hand, daylight availability in architectural spaces has shown positive impacts on their occupants. For example, various studies showed that good daylighting could improve classroom learning conditions (Mirrahimi, Ibrahim, and Surat 2013; Shishegar and Boubekri 2016). In another study, office workers with more daylight exposure reportedly had higher sleep quality and physical activity than those with less daylight exposure (Boubekri et al. 2014).

When it comes to daylight impact on users, many studies focus on a few types of spaces, primarily office and learning environments, where human performance and productivity are prioritized. However, daylight is also a critical factor in designing public indoor spaces, including museums, exhibitions, and libraries. One example is art museums, where daylighting is emphasized by the role museums have in enhancing human perception and visual qualities (Anthierens et al. 2008). Daylight design in museums can be challenging for architects for several reasons: first, the sensitive nature of the exhibited pieces (paintings, sculptures) towards excessive light (Kaya and Afacan 2018); second, the uncontrolled nature of sunlight which can vary during the day and thus affects the intended visual image (Rockcastle and Andersen 2013), and third, the variety of user types in terms of age, preferences, or visiting reasons (Najbrt and Kapounová 2014).

As one application of Immersive Virtual Reality (IVR), Immersive Virtual Environments (IVEs) have gained momentum as a potential medium to investigate the human perception of unbuilt spaces, including daylight perception (Chamilothori, Wienold, and Andersen 2018). Several studies have utilized IVE to investigate subjective qualities of daylighting within an immersive setting. Some of these studies examined the influence of perceived spatial ambiance of daylight patterns(Chamilothori, Wienold, and Andersen 2016), other developed user-friendly lighting design systems(Natephra et al. 2017), or measured visual perception of daylighting (Chamilothori et al. 2018; Rockcastle, Chamilothori, and Andersen 2017a). However, such studies are often limited in applying interaction and immersion principles, despite being two major aspects for a convincing human experience of the virtual environment (Bishop and Rohrmann 2003; Slater et al. 1996).

This limitation can be associated with the reliance on static daylight simulation tools that lack the ability to render images in real-time, and the small scale of the investigated virtual models that limit user ability to explore various scenarios (Chamilothori et al. 2018; Rockcastle et al. 2017a). These limitations can be a barrier to the validation of IVEs as adequate media for daylight perception studies. In this context, gamification has been one of the newly introduced concepts that can offer real-time user interaction and engagement with the virtual environments (Alsawaier 2018). Gamification involves the enrichment of serious tasks with game design principles to motivate and increase the overall user experience (Korn et al. 2019). Thus, gamification concepts are often applied through the utilization of game engines. In definition, game engines are a set of tools for rendering, scripting, Physics, and artificial intelligence systems intended to create video games (Eike Falk Anderson et al. 2008). While gamification and game engines have been widely used for enhancing participatory design process in architecture (Lo, Schnabel, and Moleta 2017; Schnabel, Lo, and Aydin 2014), there is still a lack of studies that utilized game engines as a daylight simulation and rendering tool in related perceptual studies. Part of this research gap is due to the lack of validation of their accuracy compared to well-established tools such as Radiance (Ward and Shakespeare 1998).

This exploratory study investigates and highlights the potential of game engines as a daylight simulation tool for improved immersion and interaction to assess daylighting experience and brightness perception in virtual environments. First, the methodology of the developed IVE framework is discussed in terms of model creation, lighting and interaction control set up, and evaluation and visualization method of the outputs. To validate the perceptual output of daylight brightness in the VR environment, participants' brightness perceptions for different areas of an accessible space were compared to those in an identical virtual replica simulated in the developed system. Afterward, an application of the system is showcased to assess the perception and experience of daylighting in a large-scale museum building. In this case study, the game engine-based immersive virtual model offered a set of interaction controls, including moving freely through the virtual environment, changing the time of the day (inside VR), and snapshotting what they see. Several participants were recruited to report their brightness perception of different areas inside the virtual model through freely exploring and snapshotting scenes where they perceive as one of the following (very dark/dark/bright/very bright), with the ability to switch IVE daytime between 9 am and 6 pm. Furthermore, the collective perceived brightness in the virtual environment is visualized as a heatmap and is compared to corresponding daylight quantitative metrics. The novelty of this study resides in the following aspects: investigating the potentials of game engines as a light simulation tool for the perception of daylit spaces in VR; applying principles of immersion and interaction to propose a self-expressive approach to collect daylight perceptions in VR; proposing a cognition-based visualization approach to the daylighting environment through perceptual light maps; investigating the correlation between subjective responses in interactive IVE and illuminance and luminance based metrics.

1.2. Problem statement

As for the experience of light in VR, an adequate portrayal of the luminous environment is vital for accurate user input (Murdoch, Stokkermans, and Lambooij 2015). The principles of immersion and interaction have been reported by various studies as the basis for a credible virtual environment in terms of user perception and feel of presence (Alshaer, Regenbrecht, and O'Hare 2017; Bishop and Rohrmann 2003; Slater et al. 1996). The opportunities immersion and interaction can offer to user experience in virtual environments have been illustrated in several studies, addressing their positive impact on user engagement (Wilson and Soranzo 2015) and satisfaction (Hudson et al. 2019), as well as improving the realism and subsequently the potential of user experience studies (Chamilothori et al. 2018).

In this aspect, it may be argued that the current studies on daylight perception in virtual environments have several structural and methodological limitations in applying those two principles and the diversity of case studies. First, the majority of the studies portray a limited variety of building functions and scales, often employing small office spaces with minimal furniture and a simple daylighting approach (e.g., single south-oriented window) (Chamilothori et al. 2018; Heydarian et al. 2017; Natephra et al. 2017). Although this approach could be necessary to reduce the variables in the virtual space, it can lead to an oversimplification of the architectural space depicted and ignore the complicated effects of daylighting, such as ambiance. A second limitation is shown in several studies, where user experiences with the simulated world are restricted to navigating the scene only by head gestures (Chamilothori et al. 2018; Chen, Cui, and Hao 2019). This constraint can limit the implementation of the principles of immersion and interaction, where users cannot move inside the environment or interact with objects within, and therefore may contribute to an unpersuasive user experience in the virtual environment, affecting the perceived presence and perception. This approach also leads to the evaluated view being predefined by the researcher, which contradicts real-life scenarios where occupants -to an extent- can settle within the view that matches their preferences.

One of the major factors driving the discussed limitations is the methodology of simulating the luminous environment in question. Due to the cruciality of having an accurate representation of luminance and illuminance levels in the simulated models, current research relies on established physically-based rendering tools, specifically Radiance-based ones (Ward and Shakespeare 1998). While these tools have shown accurate results compared to sensor measurements (Reinhart and Walkenhorst 2001), they still comprise a time-consuming process to render a single view at a given spatiotemporal setting, and thus their ability to render multiple views in real-time is very limited (Jones and Reinhart 2017). In addition, they do not offer further interaction between users and the simulated environments. Given these limitations, game engines as light simulation tools show potential to overcome time and interaction barriers, due to their ability to offer lighting simulations in real-time, as well as their native integration to gaming techniques with rich interaction and immersion capabilities. However, the lack of validation studies addressing game engines' photometric and perceptual accuracy are a significant barrier against a wider adoption of them in lighting research.

1.3. Research Objectives

This thesis comprises an exploratory study that employs game engines as daylight simulation tools for subjective daylight evaluation in buildings. The objectives of this study are three-fold:

1) Highlight the potentials and implications of employing game engines to improve interactivity and immersion for the subjective evaluation and experience of virtual daylit environments.
2) Introduce a novel approach to subjectively evaluate and visualize daylight brightness based on collective multi-occupant perceptions.
3) Investigate the correlation between brightness perception in interactive IVEs and simple quantitative metrics of daylighting (illuminance and luminance-based). Thus, the contribution of this study lies in its trial to bridge the gap between the competing objectives of maintaining photometric and perceptual accuracy of simulated environments and improving interaction and immersion in occupant-oriented daylighting evaluative research through introducing and investigating real-time lighting simulation in game engines.

1.4. Thesis organization

This dissertation consists of seven chapters as follows:

Chapter 1 Introduction:

This chapter demonstrates the background and motivation of the study, research gap, and objectives that establish the main aim of this research. In addition, it elaborates the organizational structure of the research frameworks and experiments.

Chapter 2 Literature review:

This chapter presents an overview of the state-of-art in daylight performance research and the dilemma between describing such performance in quantitative measures or occupant-oriented indicators. Furthermore, the chapter illustrates several occupant-centric daylight metrics predominant in related research and highlights their attributes related to human comfort. In addition, the principles of immersion and interaction in virtual environments are discussed concerning their influence on user engagement and perception. In this context, Immersive Virtual Environments (IVE's) are surveyed as an effective tool in the subjective assessment of daylighting in the current studies. In addition, game engine potentials as a real-time daylight simulator are discussed in terms of accuracy in comparison to the well-established physically-based renderers.

Chapter 3 Overview of the research methods:

This chapter illustrates the main frameworks and methodologies adopted in the study. First, it describes the interactive virtual environment development framework. Further, it illustrates the exploratory, self-expressive evaluative criteria followed to assess the brightness of daylit spaces subjectively. Finally, it introduces the methodology of developing Perceptual Light Maps (PLMs) as a visualization tool for the collective user perceptions and interpreting different values of these maps.

Chapter 4 Validating real-time rendering in game engines as a photometric daylight simulation tool:

This chapter sets a validation study to investigate the photometric accuracy of game engines in simulating daylighting. Unreal Engine is selected as a case study in which two-daylit test models were simulated, and illuminance measurements at several points were compared across the game engine, a validated physically-based renderer, and sensor measurements in reality.

Chapter 5 Validating game engines and Immersive Virtual Reality as perceptual daylight simulators:

Building upon the findings of the previous chapter, this chapter extends the validation study of game engine daylight simulation to cover the perceptual accuracy of the virtual experience of the daylit experience in terms of user perception of scene brightness. An accessible architectural space is modeled and replicated in the developed virtual system. Participants' reported scenes of interest and their brightness ratings are compared across real and virtual environments using several aggregation methods for the collected feedback.

Chapter 6 Comparing perceptions in IVE to quantitative daylight metrics:

This chapter employs the findings of the previous two chapters to apply the developed virtual reality system, subjective evaluation, and visualization methods in a distinctive daylit space. Kimbell Art Museum of Louis Kahn is selected as a case study, where several participants explore a virtual replica of the museum in the developed system on two virtual daytimes and report their brightness perceptions of different scenes of interest within the museum. Subjective evaluations of the collected scenes are then compared against quantitative metrics (mean illuminance, mean luminance, vertical eye illuminance, and luminance ratio) to investigate the consistency between physically-based indicators of daylight performance and occupant-oriented assessment of the daylight environment.

Chapter 7 Conclusions and future research:

This chapter presents a summary of the introduced methodologies and frameworks. It also elaborates the findings of the study and their implications on architecture, lighting engineering, and occupant-oriented design. Finally, the limitations of the study and recommendations for future research are discussed.

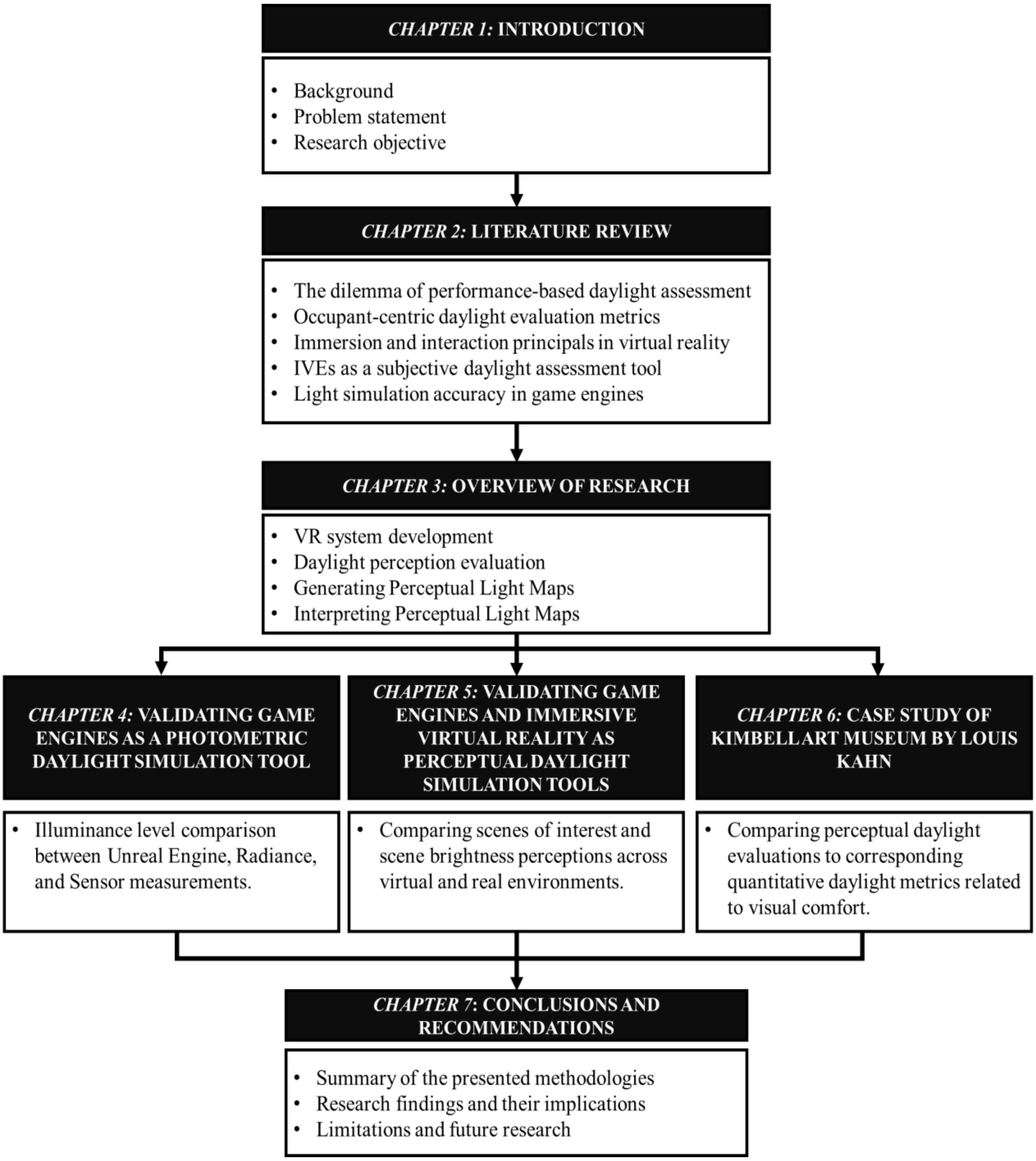


Figure 1: The structural organization of the thesis.

Chapter 2. **Literature review**

2.1. Introduction

This chapter will discuss the major literature regarding daylighting assessment approaches in the built environments and virtual reality as a medium for its subjective assessment. Also, we will discuss the emerging trend of gamification and game-engines in creating virtual environments that achieve immersion and interaction. Limitations of the current research will be highlighted, and the subsequent knowledge gap will be identified.

2.2. The dilemma of performance-based daylight assessment

Daylight quality can be perceived as one indicator of the building's overall performance. In this aspect, climate-based simulation tools are widely accepted for the quantitative assessment of daylight based on illumination values (Mardaljevic et al. 2012). However, the complicated qualities of daylight extend its impact on the wellbeing and comfort of buildings' occupants, and thus several studies have argued that measuring occupants' feedback in terms of daylighting quality is yet essential for an effective performative daylight design (Allan et al. 2019; Andersen 2015; Bian and Luo 2017; Van Den Wymelenberg, Inanici, and Johnson 2010a).

Reinhart and Mardaljevic have contributed to the introduction of validated annual metrics of daylighting, including spatial daylight autonomy (sDA) (Illuminating Engineering Society 2012; Reinhart and Walkenhorst 2001) and useful daylight illuminance (UDI) (Nabil and Mardaljevic 2005). In both metrics, the illuminance range that reflects the occupant's comfort thresholds is considered. However, a thorough look into the range adopted as "comfortable" suggests more investigation of their adequacy as occupant-oriented metrics. The surveys on which these values are based were limited to office workers. Several of these studies were conducted at the time of cathode-ray tube (CRT) monitors, which are more prone to daylight glare than modern screens (Nabil and Mardaljevic 2005; Reinhart, Mardaljevic, and Rogers 2006). Therefore, this arises uncertainty concerning adopting a "generic occupant" preference to daylight, especially for non-office spaces.

Several studies have addressed the subjective aspects of daylight. For example, Painter et al. studied user perception of daylight glare in an office environment through an automatic evaluation system (Painter, Fan, and Mardaljevic 2010). The devised system combined quantitative and subjective assessment approaches by utilizing an HDR camera to capture scene luminance. In addition, a computer-based survey on experiencing glare with the following verbal anchors (imperceptible, noticeable, disturbing, and intolerable) was introduced. In a later study, Shafavi et al. (Shafavi, Tahsildoost, and Zomorodian 2020) surveyed students' perception of daylight in twenty studio rooms daylit by different strategies at different months and compared the results to dynamic and static daylight and glare metrics of the same rooms using simulation tools. The evaluated perceptual feedback included the amount and uniformity of daylight distribution and disturbance of direct sunlight, surface brightness, and light contrast. The study found a correlation between UDI, sDA, and students' perceptions, while a similar correlation could not be established with glare metrics.

Building Performance Simulation (BPS) (Loonen, Klijn-Chevalerias, and Hensen 2019) is a well-known evaluative approach for daylighting. BPS can offer realistic visuals and provide a quantitative approach to evaluate the magnitude of daylight in a given space while considering design aspects such as building form, openings, and material properties (VELUX 2019). Through this approach, the amount of daylight, solar gain, and estimated building energy consumption can be predicted and thus provide the architects with insights to improve their designs at an early conceptual stage. While these simulations can accurately predict and furtherly optimize daylight performance in a building, they have limitations in predicting occupants' behaviors, preferences, and perceptions when using the proposed space (Yan et al. 2015).

User-centered attributes can affect the subsequent performance of the architectural space while in operation in terms of artificial lighting usage, energy consumption, and user comfort (Gaetani, Hoes, and Hensen 2016). One result of ignoring this important factor can be limiting the building's post-occupancy performance. Numerous studies have shown that following recommended guidelines for dynamic daylight metrics, such as Annual Sunlight Exposure (ASE) and spatial daylight autonomy (sDA) neither necessarily lead to satisfactory perceptions among occupants nor match their visual preferences (Bian and Luo 2017; Newsham et al. 2012; Nezamdoost and Van Den Wymelenberg 2017). Therefore, aside from using BPS, investigating daylight performance in the light of occupants' perception has potential as a straightforward way of approaching a satisfactory daylit environment (Parpairi et al. 2002).

However, unlike BPS, which adopts a deterministic approach, measuring user perception and preferences is mainly subjective due to its sensual nature (Rockcastle and Andersen 2015), of which validity can be arguable as a mere source of the design decision making. For buildings in operation, user perception of daylighting can be measured using post-occupancy evaluations (Roberts et al. 2019) or performance indicators for specific tasks (e.g., reading tests (Heydarian et al. 2017)). However, it is more challenging to collect such feedback in unbuilt spaces through virtual media. One reason can be the intricacy of depicting real-life ambiances, such as thermal ambiance and surrounding sonic effects (Tahrani et al. 2005), and hardware limitations in replicating accurate luminous values of real environments (Hvass et al. 2017; Yu et al. 2009).

2.3. Occupant-centric daylight evaluation metrics

Assessing daylight quality regarding visual comfort is increasingly important in building design (Bian and Luo 2017). Jakubiec and Reinhart state that visual discomfort is likely caused by insufficient contrast, direct sunlight visible to the naked eye, or extreme brightness (Jakubiec and Reinhart 2016). Thus, visual comfort can be achieved through a reliable amount of daylight that can offer uniform distribution of light and good visibility to prevent visual stress and help building occupants to accomplish tasks (Shafavi et al. 2020). Many quantitative metrics have been introduced to assess the luminous quality in architectural spaces, with differences in physical quantities measures, measurement period, and recommended thresholds (Carlucci et al. 2015).

Among those metrics is horizontal illuminance, which is the most commonly used metric for measuring daylight performance in building design (Van Den Wymelenberg and Inanici 2016) mainly due to its ease of use and low cost (Van Den Wymelenberg and Inanici 2014). Several studies have aimed to set a recommended threshold for horizontal illuminance concerning human visual comfort. For example, Nabil and Mardaljevic (Nabil and Mardaljevic 2005) have introduced Useful Daylight Illuminance (UDI) as the range of work plane illuminances that match occupants comfort thresholds, and was stated to be between 100 lux and 3000 lux based on occupants preferences in daylit office environments with manually operated shading devices (Bian and Luo 2017). Similarly, spatial daylight autonomy (sDA) sets a target illuminance of at least 300 lux for 50% of occupied hours as the threshold for nominally acceptable daylighting conditions (Chi et al. 2018). Annual sunlight exposure (ASE), which measures the fraction of floor area receiving at least 1000 lux of direct sunlight penetration for at least 250 annual occupied hours, sets a threshold of 10% as the limit of which beyond can cause visual discomfort (LM 2013).

Despite these proposed guidelines, there is still no clear threshold for illumination that can clearly distinct visual comfort and occupants' preferences (Bian and Luo 2017), where some studies have shown a wide variance in human preferences of horizontal illuminance under both daylighting (Van Den Wymelenberg, Inanici, and Johnson 2010b) and electric counterparts (Boyce et al. 2006). Thus, a number of studies have argued that horizontal-illuminance-based metrics, whether point-in-time or annual, perform poorly as representative to occupant's preferences (Bian and Luo 2017; Van Den Wymelenberg 2012, 2014). In part, this is because horizontal illuminance is only a reliable metric for environments where the working plane is horizontal and its absolute quantitative nature regardless of how the human eye perceives light (Kruisselbrink, Dangol, and Rosemann 2018). Alternatively, several studies have used vertical eye illuminance as a threshold of visual comfort (Suk 2019). For example, Bian and Luo (Bian and Luo 2017) have stated a vertical eye illuminance threshold of 3000 lux at which visual discomfort occurs, while studies by Wymelenberg and Inanici (Van Den Wymelenberg and Inanici 2014), and Karlsen et al. (Karlsen et al. 2015) stated a lower threshold around 1250 lux.

On the other hand, luminance-based metrics can be more reliable than illuminance-based ones as an indicator of visual comfort (Marty et al. 2003), as luminance is closely related to how humans perceive brightness (Intergovernmental Panel on Climate Change 2014). Among those metrics is luminance distribution (luminance ratio), which defines the ratio between the average luminance of the window and that of the immediately adjacent surface (Steffy 2011), where the maximum luminance ratio is recommended at 20:1 between daylight media and their adjacent surfaces (Rea 2000). Similarly, Suk (Suk 2019) states that a luminance contrast ratio between task area and surroundings can be considered an indicator of visual discomfort, where IESNA (Illuminating Engineering Society of North America) recommends a contrast ratio of 3:1(Rea 2000). In addition, discomfort glare indices, which predict the occurrence of glare and thus visual discomfort, have been widely used as an indicator of occupant-oriented daylight assessment (Osterhaus 2005; Van Den Wymelenberg and Inanici 2014).

Among various related indices, daylight glare index (DGI) and daylight glare probability (DGP) have been two well-established metrics concerning daylight-induced glare assessment. DGI is an early glare metric introduced by Hopkinson (Hopkinson 1972) -based on the British Glare Index (BGI)- that takes into account occupant's view direction, background luminance as well as size, location, and luminance of the light source (Bian and Luo 2017). In an extensive cross-validation study (Wienold et al. 2019), the performance and robustness of 22 established and newly introduced glare metrics were evaluated based on a variety of experimental setups and spatiotemporal settings. The study found that glare metrics based on saturation effect performed better than those based on contrast effects. Specifically, Daylight Glare Probability (DGP) metric, which considers both contrast and saturation in an additive manner, had the highest performance and the highest robustness. For contrast-based metrics, CIE glare index (CGI) performed the best. In a literature review study by Wasilewski et al. (Wasilewski et al. 2019), different glare simulation techniques were reviewed regarding their spatiotemporal resolution limitations. One common direction among the reviewed simulation methodologies was the focus on efficiency -thus simplification- of calculation, which may subsequently generate results inconsistent with user assessment findings. The study emphasized the importance of combining human subject glare assessment and current glare predictive simulations as a future research direction.

2.4. Gamification as an engaging architectural design tool

Gamification became one of the most utilized approaches for encouraging individuals to actively participate in various activities (Hassan and Hamari 2019). In the last few years, it has become a trending approach 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 (Deterding 2019) defines gamification as a process to translate the engagement aspects of games into other non-gaming aspects to generate a 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 prominent 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). Many studies have utilized gamification in architectural design to enhance participatory design and occupants' feedback on the design process. For example, Haworth et al. (Haworth et al. 2020) developed an approach to replace the traditional designer-as-user concept with a gamified crowdsourced design methodology, where it showed evidence as an interesting approach to collaborative environment design. In another study by Schnabel et al. (Schnabel et al. 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 approach enabled the development of novel design outcomes that consider different parties' needs in the design process. In a similar context, Askin (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.

2.5. Immersion and interaction principles in Virtual Reality

While virtual reality (VR) is widely perceived in connection with head-mounted displays and 360º media (Garnham 2019), its history and applications can be traced far beyond those trends (Myeung-Sook Yoh 2001). Architectural research has adopted this technology at an early stage, as seen in the 1995 study by Schmitt et al. (Schmitt et al. 1995) about the role and applications of VR in architecture, as well as later studies by Frost and Warren (Frost and Warren 2000) and Shiratuddin (Shiratuddin and Thabet 2002) that utilized VR tools for participatory design and virtual office walkthroughs, respectively.

However, as for light perception in VR, an accurate representation of the luminous environment is crucial for valid user feedback (Murdoch et al. 2015). Several studies have claimed the principles of immersion and interaction as the foundation of a convincing virtual environment concerning user feedback (Alshaer et al. 2017; Bishop and Rohrmann 2003; Slater et al. 1996). Slater (Slater 2018) defines 'immersion' as an objective property of a VR system, stating its ability to support the response to a perceptual action where technical merits such as wide field-of-view, high-resolution, head-tracked display with full real-time motion capture, and auditory/haptic feedback would essentially put a VR system at a higher level of immersion. On the other hand, Li et al. (Li et al. 2019) describe 'interaction' as a replication of the sensory experience between the user and the virtual scene, offering the same feeling as the real world through feedback. Thereby, two steps of interaction are essential for the user to interact with objects in VR; selection (e.g., grabbing) and manipulation (e.g., changing position, orientation, color, etc.) (Bowman and Hodges 1997; Streppel, Pantförder, and Vogel-Heuser 2018).

As would be discussed in the next section, the two principles of immersion and interaction have been considered by several studies on daylight perception, mainly through using immersive headsets and physically-based lighting renderings (Chamilothori et al. 2018; Heydarian, J. P. Carneiro, et al. 2014).

However, the lack of a more inclusive application of those concepts, concerning freedom of movement, interaction with objects, and haptic feedback, can be a barrier towards rigorous VR systems providing accurate user feedback. In this context, game engines can offer an adequate platform to design a more engaging user experience in VR, where users can freely explore a scene, interact with and change its contents, and give feedback while in the virtual environment. In definition, a game engine is a set of tools of rendering, scripting, Physics simulations, and artificial intelligence systems intended to create video games (Eike F. Anderson et al. 2008). Game engines have been previously utilized in lighting research. However, this utilization was often limited to connecting the 3D scene (rendered in other tools) to VR tools (headsets), rather than conducting a full light simulation (Chamilothori et al. 2019; Rockcastle, Chamilothori, and Andersen 2017b).

2.6. IVEs as a subjective daylight assessment tool

As an application of the broader field of Immersive Virtual Reality (IVR) (van Dam, Laidlaw, and Simpson 2002), Immersive Virtual Environments (IVEs) have gained momentum as an alternative media to reality in architectural studies. Persky and McBride (Persky and McBride 2009) define IVEs 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 the built environment and as an architect-user communication tool.

Numerous studies have addressed IVEs as a representative and evaluative tool for daylighting in the built environment, nevertheless as an architect-user communication media. Several studies have been conducted in architectural spaces to investigate daylight-related perception-based evaluations, including visual comfort, glare perception, and interest in the scene. Chamilothori et al.(Chamilothori et al. 2018) validated IVE adequacy to measure the perception of daylit spaces in five aspects: perceived pleasantness, interest, excitement, complexity, and satisfaction. The experiment compared users' perception of an actual daylit room to its 360° rendered replica, shown to participants 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 virtual environments. In another study by (Heydarian, Carneiro, et al. 2015), a similar VR headset was used to compare task performance (object identification, reading speed, comprehension) in an office environment and a similar physical environment, where no significant differences were found in performance between virtual and real spaces. A third study addresses artificially lit environments (Chen et al. 2019), human subjective feelings towards a physical lighting environment, and an identical reproduction in VR, 2D videos, and photos. The study illustrated that VR was rated the closest to the physical environments in terms of subjective rating, concluding that VR can present lighting attributes of diffuse/glaring and bright/dim qualities of lighting consistent with the physical environment.

In a similar experiment, Rockcastle et al.(Rockcastle et al. 2017a) employed VR and HMD with head-tracking to collect visual interest ratings of 8 different spaces in different sky conditions. Furtherly, the subjective results were compared to those predicted by an image-based algorithm. While the study showed consistency between both results, the authors suggested that considering eye-tracking data could lead to a more refined analysis of users' view behaviors. In another study by Rockcastle and Andersen(Rockcastle and Andersen 2015), they compared subjective ratings of (contrast, uniformity, complexity, variation, stimulation, and excitement) to local and global contrast metrics for nine virtual architectural spaces in different sky conditions. One of the findings was that ratings of (excitement and stimulation) were consistent with quantitative contrast measurements more than that of (contrast) itself, for which those quantitative measurements were developed. This finding raises an open question about 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.(Chamilothori et al. 2019), the impact of sunlight pattern geometry on users was investigated by measuring skin conductivity and heart rate while in IVE, and a verbal questionnaire. The study showed that spaces with irregular distribution sunlight patterns were evaluated as more 'exciting' and 'interesting' on the subjective side and led to cardiac deceleration on the physiological side.

While the discussed studies investigated daylight perception in IVE from an evaluative standpoint, other studies extended their utilization of IVE through developing interactive systems through which users can customize lighting settings. This extension can reflect a vital insight into user preferences and behaviors. For example, Natephra et al.(Natephra et al. 2017) used Unreal Engine (UE) to design an interactive lighting design system in VR, offering a precise simulation for daylight and artificial light. Using UE's BluePrints script, a wide variety of interactive options were offered, including moving, rotating fixtures, and changing lighting conditions. Another study by Heydarian et al.(Heydarian et al. 2017) investigated user lighting preferences in IVE by offering the choice to customize window shutter state and artificial lighting intensity while performing a reading task. The study found that the majority of participants not only preferred maximum possible daylighting but also performed better in this condition. Similarly, Carneiro et al. (Carneiro, Aryal, and Becerik-Gerber 2019) developed a feedback system in IVE to influence occupants' lighting preferences (natural and artificial light) regarding light distribution and energy consumption. The system feedback was found effective in helping participants reconsider their choices, especially energy-related feedback.

2.7. Light simulation accuracy in game engines

Game Engines can achieve photorealistic renderings in real-time(Sheng et al. 2015), mainly through simulating light behavior based on the inverse square law (Zafar and Adapa 2014), which states that light intensity is inversely proportional to the square of the distance between the light emitter and surface receiving light (Ryer 1997; Voudoukis and Oikonomidis 2017). Recently, several advancements to game engine technology have been achieved (Maggiorini, Ripamonti, and Cappellini 2015; Yuexiang SU 2018), including the realization of accurate, unbiased lighting simulation, through the emergent applications of real-time ray tracing (Burke et al. 2019; Liu et al. 2019) and physically-based rendering (PBR) techniques (Karis 2013; Unity Technologies 2019).

By nature, game engines are majorly based on real-time rendering to allow seamless communication between players and the game environment. Therefore, game engines often use several techniques to optimize an adequate representation of lighting environments without sacrificing performance. One of those techniques is "baking" lightmaps, where light rays are traced, and the resultant effects of light and shade are projected over surfaces as textures (Geig 2013). While this technique can generate visually appealing results, it is limited when the light source or surfaces are movable in real-time. In recent years, advancements in Computer Graphics (CG) hardware have enabled more accurate techniques to simulate lighting in game engines, mainly Real-Time Ray Tracing (RTX) (Nvidia 2020), where physically correct renderings can be computed dynamically for a variety of global lighting effects, including reflections, refractions, and shadows (Gersthofer 2020). As RTX simulates the behavior of light rays bouncing from the light source to different surfaces, a higher number of calculated bounces per ray can significantly improve the final output's quality and accuracy. However, it can heavily affect the performance of the system (e.g., framerate).

Architecture has been one of the early fields to use game engines' flexibility as a design and visualization tool. In an early study (Shiratuddin and Thabet 2002), Unreal Tournament-the predecessor engine of Unreal Engine- was used to create a virtual walkthrough for an office space, highlighting the primary advantages of game engines over traditional renderers in terms of walkthrough capabilities and lighting effects. Similarly, another study (Moloney and Harvey 2004) employed "Torque 3D" game engine to develop a collaborative virtual environment in the context of architectural education, making use of the participatory nature of the environments offered in game engines.

In the aspect of daylight perception, game engines are often coupled with Virtual Reality (VR) hardware to offer an enhanced feeling of immersion and interactivity, which are two essential principles needed for a convincing virtual experience (Alshaer et al. 2017; Slater et al. 1996). In one study to measure perceptual impressions of daylit spaces in VR (Chamilothori et al. 2018), physically-based renders of an office space were projected in Unity 3D Game Engine as a textured cube map to produce an immersive environment mapping. In another study, a hybrid system that synergizes advanced features of game engines with validated raytracer was developed (Subramaniam, Reis, and Hoffmann 2020). The developed tool offered an immersive virtual medium to assess visual comfort in indoor spaces by enabling the user to evaluate various lighting scenarios in real-time. In a third study, an immersive light visualization tool for design support was developed by integrating light simulation data from DIALux software with the Unity Engine (Wong et al. 2019).

In these discussed studies, game engines were not used as the simulation tool of daylighting but as a supplementary interaction tool to the physically-based images produced by validated renderers. While this can show the importance of representing accurate luminous effects of daylit environments in virtual settings, it also highlights the limitations this approach brings to user experience and assessment. These limitations include using static images rather than walkable 3D meshes, limiting locomotion to head movement or teleport, and predefining the lighting scenarios users can explore or evaluate. In this context, the limitations of Radiance software -which was widely used for daylight simulation in the discussed studies- have been addressed by Jones (Jones and Reinhart 2019), aiming to explore the potentials of using Graphical Processing Unit (GPU) rather than Central Processing Unit (CPU) in Radiance to minimize the time required to render views.

As daylighting performance metrics are often based on accurate calculations of illuminance levels, such as spatial daylight autonomy (sDA) and Useful Daylight Illuminance (UDI), it is essential to conduct further validation studies to the accuracy of different game engine simulation techniques in order to employ them in daylighting research and make use of their advantages over traditional physically based renderers. Several studies have investigated the adequacy of different game engines for non-game applications, including lighting simulation (Christopoulou and Xinogalos 2017; Petridis et al. 2010, 2012). One game engine that highly considers realism in lighting simulation is Unreal Engine 4 (UE4), of which daylighting simulation physical accuracy can be verified in different aspects. First, lighting algorithms in UE4 are based on physically-based shading, where the physical interaction between light and surfaces is replicated accurately according to the inverse square law (Walker 2014), and material properties follow its real-world behavior (Epic Games 2018d; Karis 2013). Moreover, different light types in UE4 are defined by physically-based lighting units; for example, directional lights are expressed in Lux and skylights in Candela per meter squared (Epic Games 2018c). UE4 is based on the Bruneton sky model for daylighting, which is proven for its accuracy in real-time skylight simulation (Bruneton 2016). Also, the dynamics of daylight are represented in the inclusion of Rayleigh and Mie multiple light scattering (Bruneton and Neyret 2008). In addition, other accurate sky models are supported in UE4, including a fully-featured Preetham sky model and a partly supported CIE/Perez sky model (Jakica 2018).

The accuracy of daylight simulation in UE4 against both sensor measurements and physically-based simulation tools was validated in a comprehensive study by Natephra et al. (Natephra et al. 2017). In their study, an office room was modeled and imported into UE4 for lighting setup. Lighting illumination levels (in lux) provided by UE4 simulation was compared against actual illuminance values measured in reality using a light meter, as well as to simulation results in Radiance (Ward and Shakespeare 1998) and 3DS Max Lighting Analysis (Autodesk 2017), both are physically-based renderers (Reinhart and Walkenhorst 2001; Tsountani and Jabi 2014). Illuminance values were collected at six testing points at four different scenarios. In all of them, the most significant absolute error in daylight simulation for UE4 did not exceed 11.08%, which fits the recommended acceptable error range stated by Fisher (Fisher 1992) of 10% for average illuminance and 20% for each test point between reality and simulation. Thus, UE4 illustrated a potential to generate light illuminance values consistent with other physically-based simulation tools and with an acceptable error range compared to measurements in real settings.

While aligning to an acceptable error threshold to evaluate the accuracy of a lighting simulation tool can represent a useful baseline, it is essential not to accept an error range without discretion, especially in perceptual-based studies. In other words, the reliability of an error range depends on the scenarios under which daylighting is simulated. While a scenario of an obviously very bright or very dark environment may not arise the range of acceptable error as an issue, it is the fuzzy condition where the differences in illuminance levels are mild that an error range can make a difference.

Tone mapping is another crucial challenge for game engines when used to collect subjective daylight perception in real-time. Tone mapping is responsible for converting high dynamic range (HDR) scenes produced in the game engine to a lower range compatible with the end-result display screen -HMD in our study- (Salih et al. 2012); thus, it controls how bright or dark user can perceive a scene compared to real-life (Ledda, Santos, and Chalmers 2004; Salters et al. 2012; Yoshida et al. 2007), necessitating this procedure as a vital factor in the accuracy of perceptual feedback on brightness (Devlin 2003). As addressed in Section 2.6, several studies have shown that visual impressions of daylit environments in IVEs have no significant difference to those in real ones, despite the limited dynamic range of the employed displays. For meaningful brightness evaluation in immersive environments, tone mapping should dynamically simulate the eye adaptation effect. In other words, it imitates how the human eye adapts with very dark or very bright scenes (Kalloniatis and Luu 2007). While dynamic tone mapping is a known ongoing issue in lighting research using IVEs (Chamilothori et al. 2018; Melo et al. 2018), several game engines use tone mapping algorithms that consider this issue. For example, the tone mapper operator used in UE4 is consistent with standard algorithms set by the Academy Color Encoding System (ACES), which ensures accurate transition of color and luminous qualities (Epic Games 2018a; Maltz 2016). Furthermore, UE4 provides a dynamic on-the-fly tone mapping algorithm that can automatically adjust the exposure values of the scene as the luminous environment changes (Epic Games 2018b; Mittring 2012).

2.8. Conclusions

The review and analysis of the current studies on daylighting and IVEs have revealed the following:

1) Daylighting plays a significant role in the performance of the building on both energetic and occupant-centric levels.
2) As an IVR application, IVEs can be an effective tool in the subjective assessment of architectural spaces, where users can experience the space in an immersive and interactive way.

3) Several studies have employed IVEs to assess a wide range of subjective qualities of daylighting, including visual impressions, satisfaction, brightness perception, and productivity.
4) Most of the current studies have adopted conventional rendering tools to simulate daylighting of architectural spaces in IVEs. While this approach offers high photometric accuracy, it limits the user experience and experimental methodology in various ways, including lack of interactivity between the user and the environment, pre-definition of the evaluated views (single scenario), and reliance on verbal questionnaires.
5) The previously discussed limitations also lead to the lack of spatial visualization outputs (e.g., heatmaps) to the collective perception and impressions of daylighting in the architectural space.
6) Game engines provide a feasible solution to the limitations of conventional simulation tools regarding evaluating daylighting of architectural spaces in IVE. However, there is a lack of verification studies on their simulation outputs' photometric and perceptual validity.

Given the limitations and gaps identified in this chapter, the next chapter will outline the research objectives to bridge these limitations and the methodology followed to achieve the objectives.

Chapter 3. **Overview of the research methods**

3.1. Introduction

In the previous chapter, the analysis of the current literature revealed a number of limitations in the virtual systems and methods used in the evaluation of subjective daylighting qualities of architectural spaces in immersive virtual reality. In light of the revealed limitations, in this chapter, the methodology and workflow of the study are illustrated. The following methodological approaches are discussed further: First, the development of a game-engine-based IVE system is illustrated, including model creation, daylighting setup, and interaction controls. Second, perception evaluation criteria in IVE are discussed. Third, the methodology of generating the perceptual lightmaps as a spatial visualization of the collective feedback of participants is explained.

3.2. Research workflow and phases

Based on the literature review conducted in Chapter 1, various limitations of the current systems and methodologies are identified concerning daylighting research in Virtual Reality. Several research gaps could be detected through these limitations, including lack of experimentation on interactive or walkable environments, reliance on verbal questionnaires, and lack of collective visualization method for the collected user feedback regarding subjective response to daylighting. A significant factor contributing to these limitations is the reliance on validated daylighting simulation tools, which are limited in rendering speed and interactivity with the rendered environment. Thus, the main research objective of this research is bridging the research gap in the current studies by introducing a novel method of rendering and evaluating daylighting in architectural spaces by replacing conventional rendering tools with real-time rendering in game engines. The research methodology comprises four phases (Figure 2):

1) VR system development: based on the survey on emerging real-time rendering tools, the selection of game engines as light simulation tools is justified based on their potential in creating interactive environments and seamless integration with VR tools. After selecting the most relevant game engine to this study, the cruciality of accuracy in lighting research necessitates verifying that illuminance calculations are comparable to those in reality and validated renderers. To integrate game engine outputs to VR, selecting relevant VR hardware (Head Mounted Display) is justified based on feasibility, display quality, and previous studies.
2) User-evaluation method: the interactivity controls (e.g., walking, looking around, changing temporal settings) are coded into the VR system. The methodology of perception evaluation is designed through a task-based verbal order, which aims to offer freedom in selecting scenes and their brightness evaluation. Added questionnaires are developed to collect further data on the perception of presence in VR and general impressions on daylight environment.

3) Visualization method: using the crowd-based data collected using the previously discussed evaluation criteria, a spatial representation of the collective perception ranges of brightness is generated. Introduced in this study as "Perceptual Light Maps", these maps output heatmaps of participants' perceptions and scenes of interest on a subjective scale (darker, brighter). The maps can also pinpoint areas of contraction in brightness perception among participants. Another visualization method based on the focal point of each evaluated scene is also generated, which shows a 3D spatial distribution of evaluated scene centers color-coded by perceived brightness level. This method also shows occupancy patterns and trends in scenes of interest among participants.

4) Method applications and analysis: this phase verifies the perceptual accuracy of the developed system and evaluation criteria. Regression analysis is conducted between brightness perceptions in a real architectural space and its virtual replica in the developed system. After validation, the method is re-applied on a larger, more sophisticated case study. Consistency between the perception of its scene and quantitative indicators is analyzed using regression analysis.

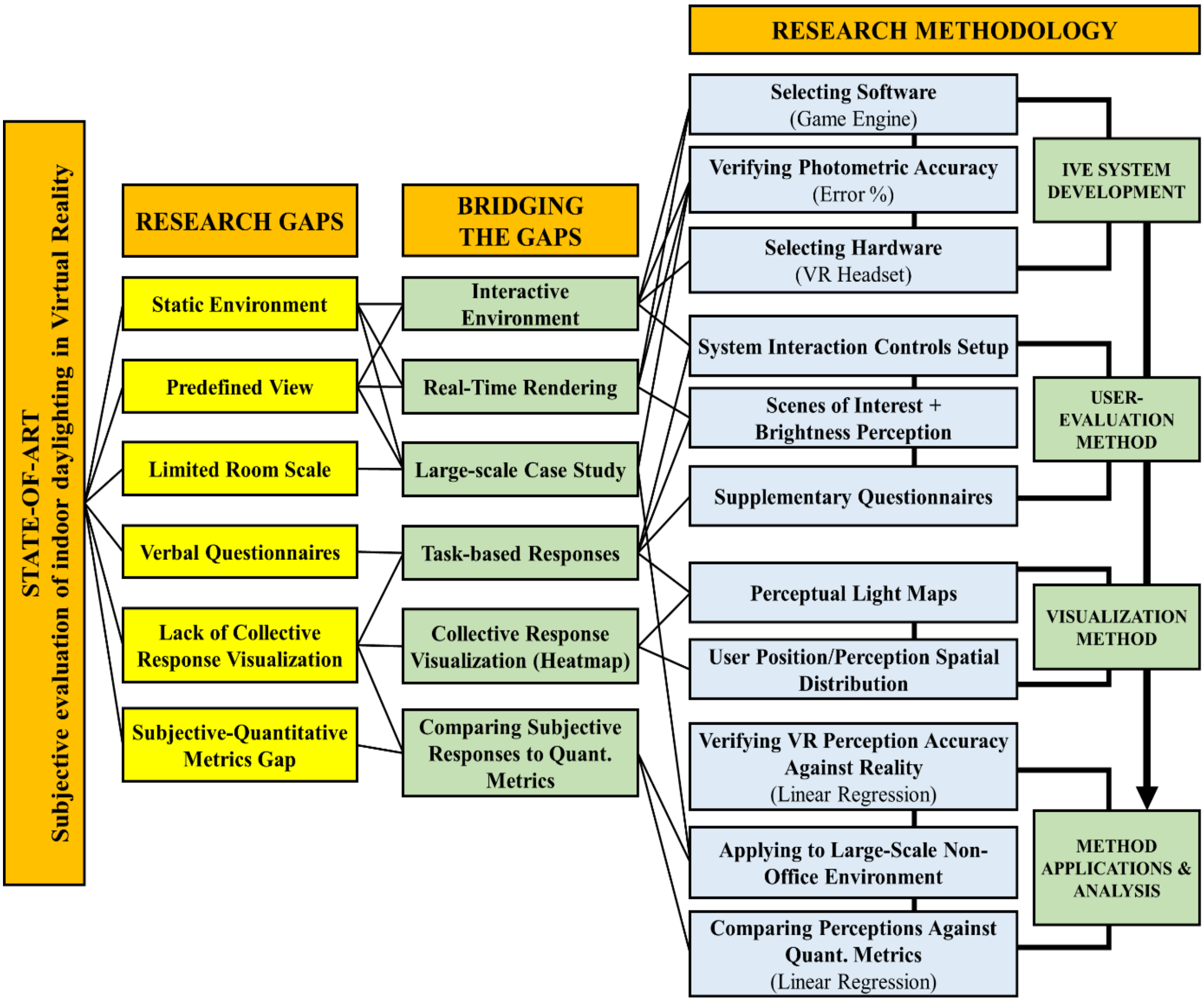


Figure 2: Research methodology workflow.

3.3. IVE system development

The workflow for creating the proposed IVE system is discussed as follows (Figure 3): the 2D drawing of a target building is imported into 3D modeling software as splines, where all the meshes and surfaces are created to realize a digital model of the building. After finishing the full textured model, it is imported into game engine software. For daylighting setup, a single directional light source is used to simulate the sun, linked to a sun position plugin to auto-control intensity, tone, and position of the directional light and sky sphere according to spatiotemporal data. Geographical coordinates can be set to the desired location and the date and time of the simulation. Daylight simulation is built at the highest lighting quality to enable realistic global illumination and indirect sunlight effects.

Various controls are developed using scripting language built in the game engine to provide the participants with a user interface (UI) to interact with the system. Through this approach, participants have the option to (move freely in the virtual space, jump, show/hide daytime information text, take snapshots of what they see). In addition, rigid body physics simulations are applied to walls and furniture to block participants' movement through them. A head-mounted display (HMD) with controllers and two tracking stations is used in the system to track participants' movements within the virtual environment. Thus, participants' interactions with the system are mainly conducted through motion controllers, with similar keyboard and mouse buttons included in case the researchers need to intervene while participants are experiencing the virtual environment.

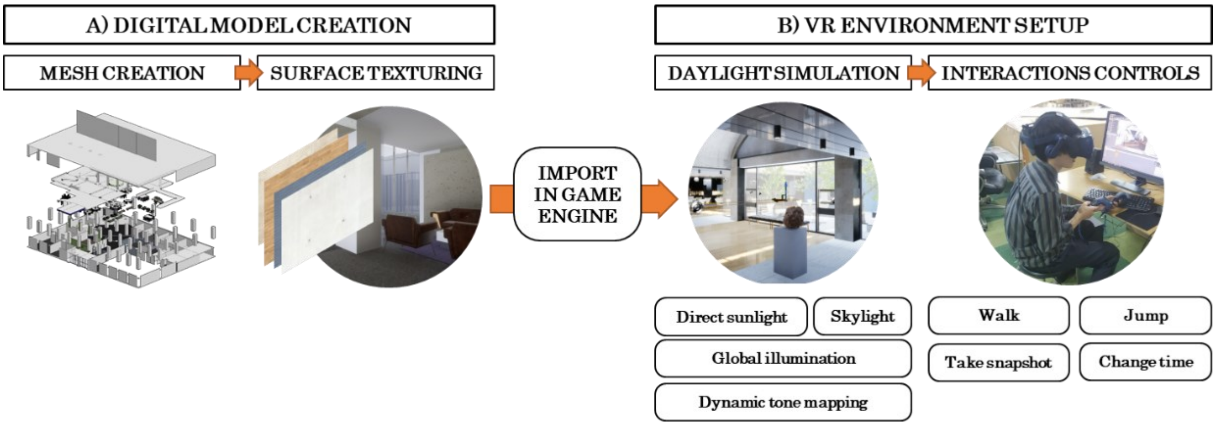


Figure 3: Methodology of creating the virtual environment system.

3.4. Daylight perception evaluation criteria

In order to collect human perception of daylighting brightness in the virtual environment, participants go through several procedures (Figure 4). First, participants are introduced to a computer-based form, where they are asked to read a brief about the experiment procedures and check a submission checkbox as consent. Then, they are given a simple questionnaire on demographics, the experience of VR and daylight aspects, and physical symptoms to be sure of their physical eligibility. Furthermore, they proceed to an introduction about the investigated building, including a video walkthrough in different parts of it. Afterward, they put on the HMD and experience a sample VR model to get familiar with the controls within the virtual system. After participants feel familiar with the HMD and controllers, the investigated VR model is loaded. The participants are asked to use the controllers to walk around and explore different areas within the building for 30 seconds. Then, the participants are verbally instructed to explore different areas freely with daylighting in mind and take snapshots of the areas/scenes of which they perceive their brightness as one of the following: very dark, dark, bright, or very bright. Participants are free to take as many snapshots as they wanted and freely manage to change virtual daytimes when they take snapshots.

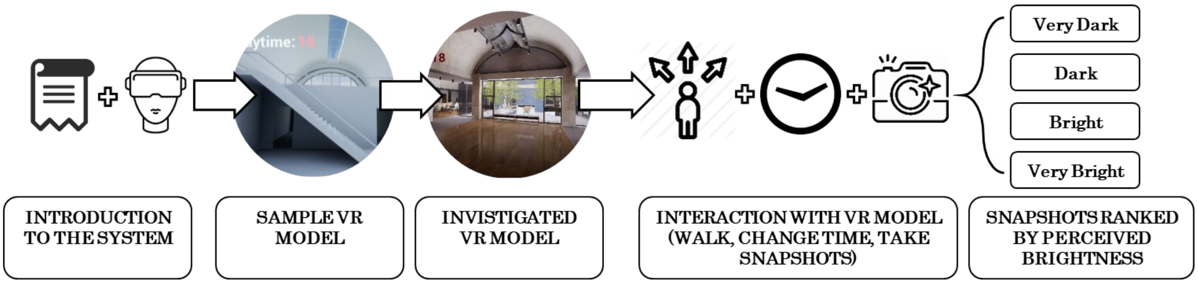


Figure 4: Methodology of collecting participants' perception of daylighting in the virtual environment.

While several studies have adopted the magnitude estimation approach (Ware 2021) to assess subjective brightness perception, using the discrete 4-point scale with the anchors (ver dark-very bright) was found more relevant for this study for various factors:

1) The contribution of this study lies in extending the interaction and immersion applications for evaluating the subjective impressions of daylit environments in virtual reality, including scene brightness perception. Therefore, it builds upon the current body of research regarding building simulation and occupant-centric metrics, of which most adopt discrete scales to capture user perceptions and preferences on different attributes of the architectural space. For instance, (Chen et al. 2019) used a 7-point discrete scale to measure user perception of a room's brightness in virtual reality, with dim/bright as verbal anchors. A similar scale is also used for evaluating daylight glare among occupants, where the degree of discomfort glare is reported using a "glare sensation vote" of 4-point scale ranging from "Just Perceptible" to "Just intolerable"(Mochizuki and Maehara 2019).
2) The magnitude estimation scale requires two factors to be present in the experiment; first, a reference scene with a given brightness value is provided to the participants. Second, the participants are exposed to the same target stimuli. In this particular study, none of these two factors are present. The experimental protocol is based on the following verbal instruction "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". In other

words, participants have the freedom to interact with a large-scale environment, exploring different views and areas and thus reporting brightness perception only for their scenes of interest. Also, providing the participants with a reference scene of a given brightness value would contradict the experiment's aim to capture impressions on the daylit environment based on individual unbiased preferences.

3) One of the goals of this study is to provide an occupant-oriented evaluation of daylighting in complement to simulation-based quantitative metrics. Therefore, the 4-point discrete scale was designed to highlight only the areas of interest to the users, where glare-inducing (bright-very bright) or underperforming (dark-very dark) daylighting scenarios may occur. Hence, median scale points were skipped as no participant would report a scene that is "neither bright nor dark". It is also worth mentioning that brightness studies that adopted the magnitude estimation approach primarily measured the brightness of a light source, not a complicated architectural environment. For instance, Barlow and Verrillo (Barlow and Verrillo 1976) measured the perceived brightness sensation of brief flashes in a uniform visual field, while Zele et al. (Zele et al. 2018) generated the stimuli using a custom-built 5-primary photo-stimulator.

3.5. Generating perceptual lightmaps

In this context, a perceptual lightmap (PLM) is an approach introduced to visualize daylight intensity based on human perception rather than simulation to provide a subjective luminance map over all the surfaces of the investigated VR model. (Figure 5) shows the methodology of creating PLMs using participants' snapshot data. First, the resultant snapshots are collected, tagged by scene time (at which the subject took the snapshot) and the 4-point brightness ranking (very dark to very bright). Snapshots are recreated in a 3D modeling software as physical camera objects, where a crowd visualization of all snapshots is acquired, categorized by subject's position, target scene, and brightness ranking. Each camera object is imported as a 2D spline into an image processing software, where ambient color grading is generated for each camera target based on its corresponding ranking, graded from blue (dark) to red (bright), where denser color saturation in a given area means a higher number of snapshots with similar perception. Each snapshot ranked by participants as very dark or very bright is imported as two identical cameras to double the magnitude of its color within the generated heat map.

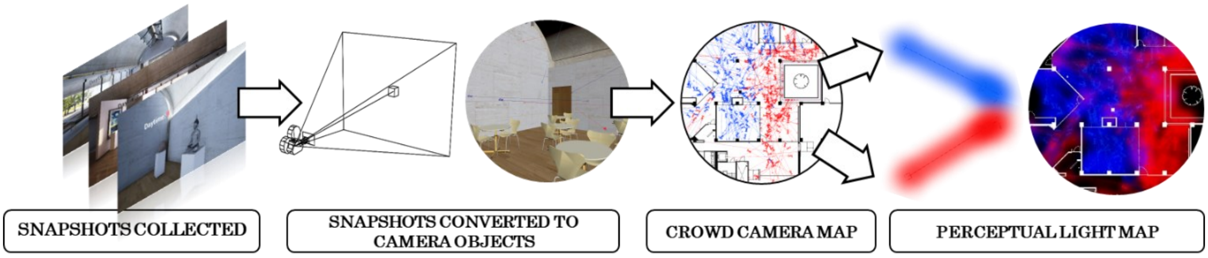


Figure 5: Methodology of generating perceptual lightmaps (PLMs) from participants' perceptions.

3.6. Interpreting perceptual lightmaps

Perceptual lightmaps can provide valuable insights for building architects and lighting designers regarding occupants' perceptions of brightness in various areas of the proposed space. These insights can be helpful to ensure that areas with light-sensitive functions would not trigger visual discomfort or negatively affect occupants' performance. However, as PLM data is non-absolute, it is essential to use PLMs in supplement with quantitative daylight metrics, such as illuminance and luminance maps, as well as with yearly-based metrics such as spatial daylight autonomy (sDA) and useful daylight illuminance (UDI), which can give absolute illuminance thresholds for predictive daylight performance in the proposed design. Moreover, PLM's predictive potential improves with a higher number of snapshots, and thus including a larger number of participants in PLM experiments is recommended as the floor area examined increases.

Architects and designers can interpret visualization data in PLMs according to four-color codes:

- **Black**: these areas are not covered by the snapshots provided by participants, where they did not focus on, or it was not easily accessible. These areas can have average daylighting conditions that participants may see unworthy of reporting. However, further investigation of these areas is recommended by increasing the number of participants in the experiment or analyzing perceptual brightness in the areas surrounding these spots.
- **Red**: These areas are where participants perceived high (above average) intensity of daylight. Areas with highly saturated red means either a higher number of participants reported them as "bright" or "very bright". In these areas, daylighting-related functions (reading, computer work) might be adequately conducted without the need for electric lighting. However, visual discomfort may occur in these areas due to glare, which can be investigated using quantitative metrics.
- **Blue**: These areas are where participants perceived noticeably low intensity of daylight. Areas with highly saturated blue are where a higher number of participants reported as "dark" or "very dark". Therefore, depending on space function in these areas, increasing daylight intensity or using electric lighting may be recommended.
- **Violet**: In these areas, participants perceive daylight intensity in a contradictive manner, where some participants report the area as "bright" while others report as "dark". In this research, these areas are defined as "mixed perception" areas. It is recommended that the architect examine these areas individually with the support of quantitative metrics.

3.7. Conclusions

In this chapter, the research design and methodologies were illustrated. The research methodology comprised four main phases. The introduced framework for creating the immersive virtual environment uses the immersion and interaction capabilities of game engines. Second, a new subjective evaluation method is proposed, using the added interactivity of the introduced IVE. In this method, users do not need to answer verbal questionnaires or evaluate a given view/location within the architecture space. Instead, they can freely explore the space while reporting perception of their scenes of interest on a 4-point scale that focuses on highlighting areas with below/above average daylighting. Third, the method for creating a perceptual light map is discussed, representing the collective perception of users to the brightness of the architectural space. Finally, the three discussed phases would be applied to a case study to analyze the proposed method's implication further. Before using this methodology, it is essential to ensure that the photometric accuracy of daylighting rendering in the game engine is acceptable. Thus, in the next chapter, a validation study to the accuracy of illuminance measurements in the game engine is conducted, compared to sensor measurements in real life and measurements in other validated simulation tools.

Chapter 4. **Validating real-time rendering in game engines as a photometric daylight simulation tool**

4.1. Introduction

In the previous chapter, the workflow and methods of this research were discussed. The discussion showed that creating the IVE system and the evaluation criteria used the benefits of real-time rendering in game engines. However, it is essential to verify the accuracy of such rendering regarding daylighting to validate the acquired data compared to real-life scenarios. Therefore, this chapter investigates the luminous accuracy of game engine renderings against validated physically-based renderers and sensor measurements in reality. Illuminance values (in lux) in two case studies with different spatiotemporal and sky settings were compared across a validated simulation tool (Radiance) and a game engine (Unreal Engine 4) with different render settings. The findings of this chapter will push towards a more comprehensive validation of game engines as a simulation tool to represent luminous qualities of daylit environments in a more immersive and interactive virtual setting.

4.2. Real-time rendering techniques in game engines

In Section 2.7, a brief description of rendering approaches in-game engines was introduced. The investigated game engine in this chapter is Unreal Engine 4 (UE4), which was selected due to its wide application in architectural visualization (Unreal Engine 2018) and its advanced integration to sophisticated real-time rendering techniques compared to other available engines. This section will shed more light on the approaches used in UE4 to achieve real-time rendering of daylighting.

4.2.1. Baked lightmaps

In UE4, the conventional method of rendering light and shades is based on generating a “lightmass”, which is better known in game engine terminology as “baked lightmap”. To generate a baked lightmap, the effects of light on static objects in the scene are calculated, and the results are written to textures that are overlaid on top of scene geometry to create the effect of lighting (Unity Technologies 2021). the produced lightmaps can include both the direct light that hits a surface and the ‘indirect’ light that bounces from other objects or surfaces within the scene, also known as “global illumination”.

Because lightmaps are precalculated, they represent an efficient solution to create interactive environments where users can explore (walkthrough) in real-time. However, this approach has limitations in terms of daylighting due to the following factors: 1) the dynamic nature of daylighting makes it necessary to simulate various scenarios (e.g., daytimes, sun angles) in real-time. Several lighting scenarios require multiple pre-calculations of the lightmaps, and thus can be an obstacle against real-time exploration of the space. 2) To optimize the time needed for the pre-calculation, this approach often replaces physically-based light tracing algorithms with biased approximation techniques. This approach can produce visually realistic results. However, the photometric accuracy of such results in terms of illuminance and luminance calculations may not be validated. Therefore, a case-by-case calibration of light settings and magnitudes (compared to reference values) is needed to improve the photometric accuracy of lighting simulation using baked lightmaps.

4.2.2. Real-time ray tracing (RTX)

Ray tracing is a rendering technique that can produce highly realistic lighting effects. Generally, it is an algorithm that traces the path of light rays based on Physics laws and then simulates how the light interacts with the virtual objects it ultimately hits in the computer-generated world. Compared to lightmaps, this approach follows a physically accurate, non-biased approach of simulating the complicated behavior of light rays as they bounce infinitely between surfaces, regardless of the light source. Due to this fact, ray tracing is known to be a highly time-consuming process, depending on the complexity of the scene simulated and the quality settings (number of rays/bounces traced) for the ray tracing algorithm used.

Recently, significant advancements in rendering hardware facilitated conducting ray tracing in real-time, opening the door to a wide range of applications. In UE4, real-time ray tracing can simulate various lighting effects: 1) Global illumination, which generates indirect lighting by tracing bounces of light rays over all surfaces in the scene. 2) Reflections: only light rays bouncing over reflective surfaces (e.g., metals) are simulated. 3) Refractions: only light rays bouncing through refractive surfaces (e.g., glass) are simulated. While simulating all three effects in a given scene leads to the most photometrically accurate results, it can also dramatically increase the processing time needed to generate the results, affecting the feasibility of interacting with the scene in real-time.

4.3. Methodology

The methodological approach followed in this study consists of five phases as follows (Figure 6); First, two case studies were selected as the test environments for the comparative analysis, reflecting a variety of complexities and daylighting qualities. Second and third, spatiotemporal and sky condition settings under which daylighting is measured are set, respectively. Fourth, metrics involved in the comparison are selected. In this study, horizontal and vertical illuminance levels at selected sensor points were compared. Finally, the simulation platforms in which daylight is simulated are selected and set. The simplified case study was simulated using Radiance software as the validated benchmark tool, while real-life measurements were taken as the reference in the case of the complicated space. Three rendering techniques in UE4 were examined for the two case studies. The first technique is the traditional baked lightmap, in which the engine calculates lighting in non-real-time and projects the effects of light and shade on static surfaces. The second and third techniques were represented in real-time ray tracing, with the number of bounces calculated varied between 3 and 7 to reflect different scenarios of balancing accuracy against performance. Ray tracing simulation was conducted for global illumination, reflection, and refraction effects. The simulations were conducted on a PC workstation equipped with a GeForce RTX 2080 GPU and an Intel i7-9750H CPU.

The following sections discuss the methodology of selecting, modeling, and measuring illuminance values in the two case studies.

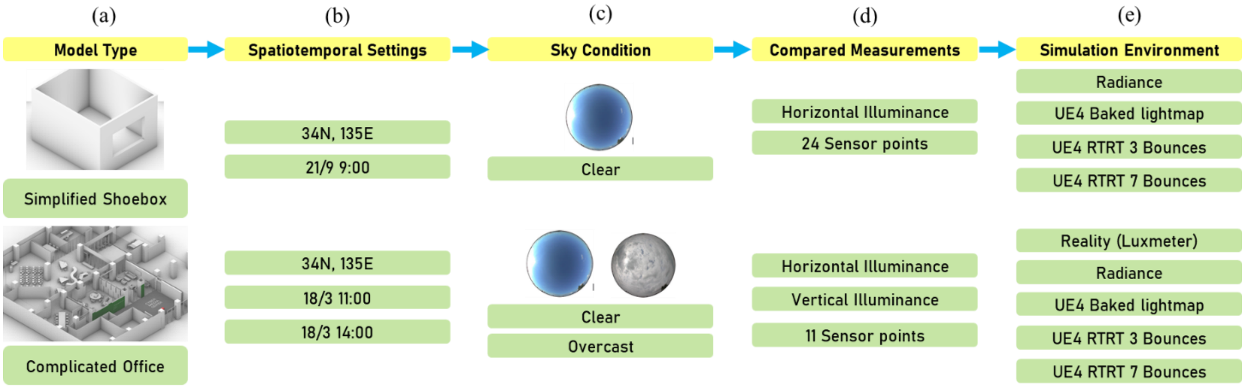


Figure 6: Illustration of the methodological approach of the study

4.3.1. Simplified Shoebox Model

In daylighting simulation, numerous parameters within the simulated model can affect the accuracy of the final results and the simulation time. These parameters include the colors, textures, reflectivity, and translucency of surfaces, the complexity of the model, and how sunlight enters the space (direct, ambient). Therefore, a simplified shoebox model (Figure 7) was selected as an initial case study that eliminates the potential interference of these parameters on simulation results and focuses on the accuracy of game engine rendering in a basic scenario. The simplified model is a 6x7x4 meters box with one rectangular opening (3x2 meters) oriented towards the South, with no glass window or furniture. As the selected model was generic and not based on an actual experimental room, illuminance measurements in Radiance were adopted as the reference values compared to the outputs in UE4.

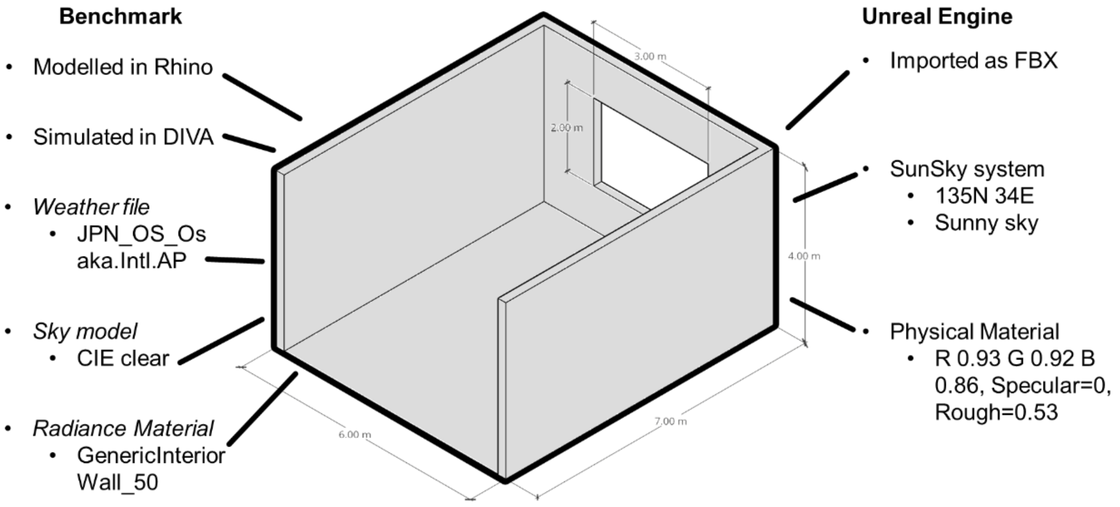


Figure 7: Simplified model attributes in the benchmark renderer and game engine

The model was created in Rhino 3D; lighting analysis was conducted on the model using DIVA for Rhino tool (Jakubiec and Reinhart 2011), which includes a fully-featured version of Radiance for physically accurate renderings. The spatial settings of the model were set based on the weather file for Osaka (JPN_OS_Osaka.Intl.AP) with a CIE clear sky. Temporal settings were set to September 21st at 9:00 am. One generic material (GenericInteriorWall_50) was applied on all surfaces of the model. As measurements were based on horizontal illuminance, an analysis grid of 0.6-meter spacing and 0.8-meter height above the floor was created using DIVA, generating 110 analysis nodes. However, to avoid redundant measurements, data included in the comparison was limited to 24 distinctive, uniformly distributed nodes (Figure 8 left).

In UE4, the model was imported in FBX format. A spatiotemporal scenario for daylighting was realized using the SunSky system equipped with the Engine, which can be considered the equivalent of weather files in Radiance. This system can automatically adjust sun brightness and position and sky conditions based on real spatiotemporal settings. In that aspect, geographical coordinates were set to 135 and 34 (Osaka, Japan), with identical temporal settings as in Radiance. Furthermore, a physically-based material matching diffuse color and reflectivity of Radiance material was created in UE4 and applied to the model. Illuminance levels at selected nodes were measured in UE4 using the HDR Histogram tool, which is integrated into the engine and can show absolute illuminance and luminance levels at any given point on the viewport, in a similar manner to the “Falsecolor viewer” tool in Radiance (Figure 8 middle and right).

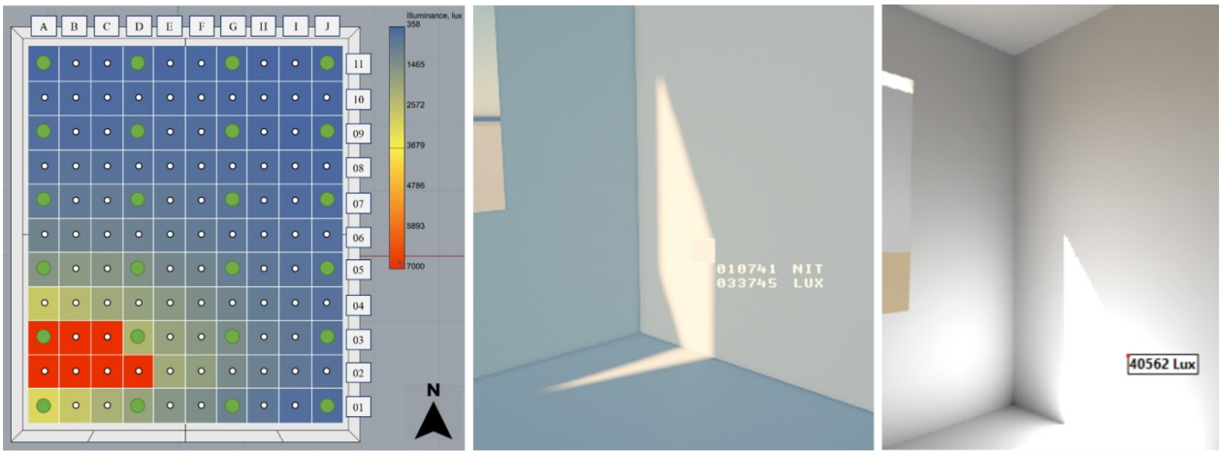


Figure 8: (Left) Measurement grid for horizontal illuminance generated in DIVA, nodes in green are included in the comparison. (Middle) measuring illuminance levels in UE4 using the integrated lighting analysis tool (HDR Histogram). (Right) Measuring illuminance at a given point for a Radiance output HDR image.

In UE4, the output illuminance at selected nodes was measured under three rendering scenarios. In the traditional baked lightmap technique, the indirect lighting multiplier was set to 2, the reflection type was “screen space”, and the simulation quality was set to “Highest”. In the second and third scenarios, real-time ray tracing (RTX) was used to calculate Global Illumination (GI), ambient lighting, reflections, and refractions. For GI, RTX was set to “Brute Force”, which is more GPU intensive but generates more accurate results. In RTX, the number of bounces calculated can lead to a more realistic rendering while sacrificing performance. However, it can also affect illuminance levels measured due to more lighting reflected on different surfaces. Therefore, a variation of 3 and 7 bounces was investigated as separate scenarios. (Figure 9) shows a rendering of the simplified model at the selected spatiotemporal settings in Radiance and the three UE4 scenarios.

Figure 9: A point-in-time rendering for the simplified model; (a) Radiance, (b) UE4 with no RTX, (c) UE4 RTX 3 bounces, (d) UE4 RTX 7 bounces.

4.3.2. Complicated Office Model

When it comes to daylighting simulation, one of the significant advancements of game engines over traditional ray tracers is their ability to offer rich interactivity and immersion capabilities to the virtual environments explored. These capabilities can be represented in first-person walkthroughs in real-time, collision physics, and dynamic sky system (full-day cycle). However, these potentials cannot be highly illustrated in simplified models like the previously discussed case study because they are too small to explore and have no objects with which they interact. Therefore, game engines can show more potential for simulating daylighting in large, explorable spaces. Hence, the selection of the second case study was prone to the following criteria:

1) To include a large-scale space.
2) Both direct and indirect daylight effects should be available throughout the day.
3) To host various related functions (i.e., meeting, studying, dining, computer-based work).
4) To be accessible by the researchers for a prolonged period, with the ability to control lighting conditions.

An office building within a university campus was selected to fulfill the stated criteria (Figure 10). The test environment was limited to a common hall area on the 1st floor, daylit by a courtyard of 7.0m x7.0m dimensions (Figure 11).

In this case study, illuminance levels measured in the real environment were taken as a reference to compare to Radiance and UE4. A set of 11 analysis points were selected within the central area of the space, reflecting a variety of directly and indirectly daylit, horizontal and vertical surfaces (Figure 11 right). Illuminance levels at these points were collected on March 18th, using a Konica Minolta T-10A luxmeter at 11:00 am (clear sky), and 2:00 pm (overcast sky), where all artificial lights were switched off and blinds were fully opened to ensure the environment is lit only by sunlight.

A digital replica of the test environment was modeled in 3DS Max software using the original floor plan drawings of the building and reference images of the current situation. Furthermore, surface textures (e.g., carpets, furniture) in reality were scanned and overlaid over respective surfaces in the 3D model. For lighting analysis in Radiance, the model was imported to Rhino 3D in FBX format. Due to the limitations of Radiance with complex scenes, the polygon count of furniture was optimized, and surface textures were abstracted to average diffuse colors and applied as Radiance materials, with the consideration of the physical properties of different materials. In DIVA, the same weather file was used for the simplified model, and the 11 measurement points were created as analysis nodes in the same locations as reality. Simulations were run twice to reflect the two temporal and sky condition settings.

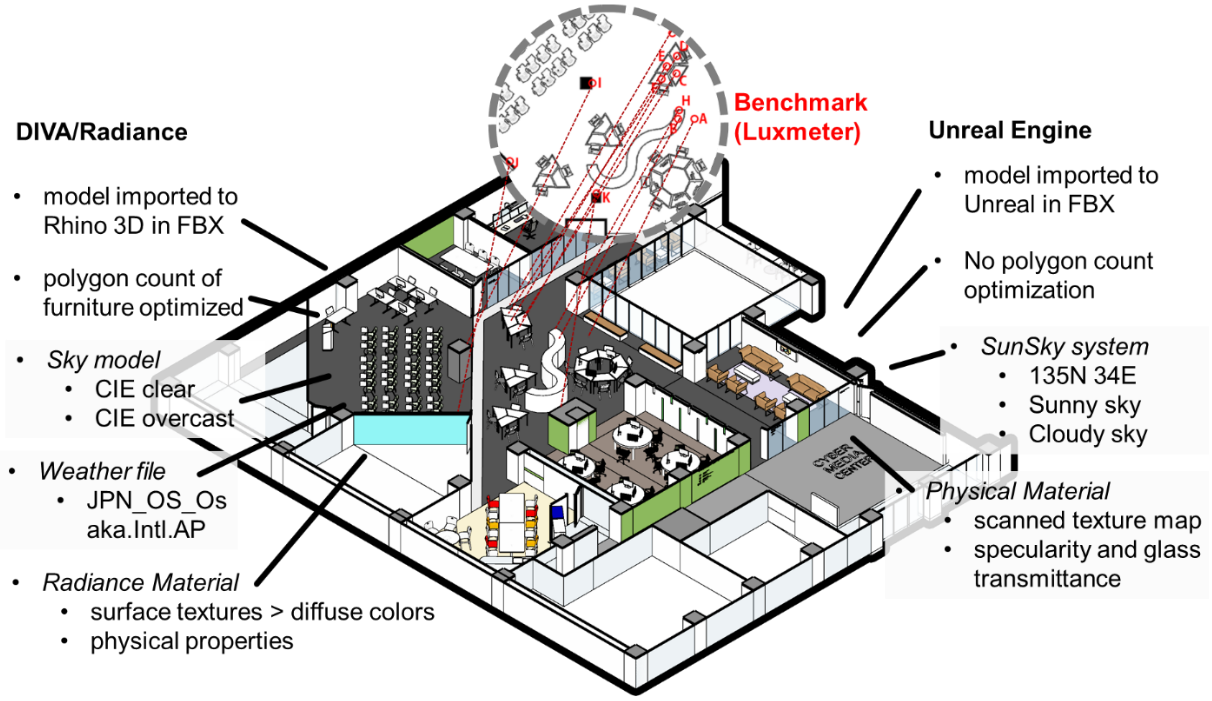


Figure 10: Complicated office model attributes in the benchmark renderer and game engine.

Figure 11: (left) the lounge area in the selected case study. (middle) different functional areas within the selected case study, the measurement points included in the study are in areas C and D, J represents the courtyard. (Right) Sensor points selected for comparison, points H, I, J, and K are on vertical surfaces.

On the other hand, the model was imported from 3DS Max to UE4 using the Datasmith plugin, ensuring seamless conversion of meshes and textures between the two tools. As UE4 can equip a very large polygon count, the original fully detailed objects were maintained without optimization. Lighting analysis and illuminance measurements in UE4 followed the same methodology and render settings followed for the simplified model, generating three sets of scenarios reflecting different rendering techniques in UE4 (Figure 12).

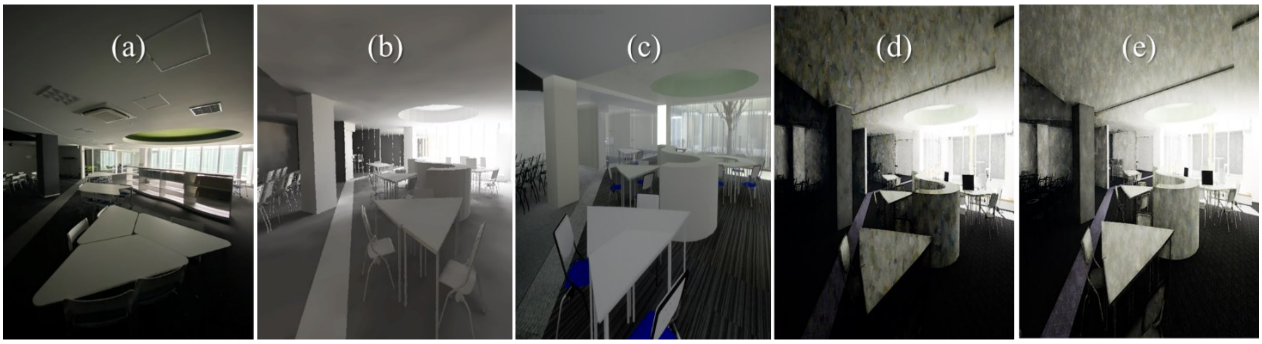


Figure 12: A point-in-time view at 11:00 am for the test environment, and its corresponding simulation outputs in different techniques. (a) real space, (b) Radiance, (c) UE4 with no RTX, (d) UE4 RTX 3 bounces, (e) UE4 RTX 7 bounces.

4.4. Results and Discussion

In both case studies, the rendered images in UE4 showed their ability to generate results that are visually close to those produced in Radiance. Unlike Radiance, which needed about 2 minutes on a high-end workstation to produce one image, UE4 could generate the images in real-time, allowing more freedom to explore virtually infinite views and lighting scenarios. However, this freedom imposes challenges in UE4 to balance quality and performance. In other words, using RTX with a three-bounce count led to highly noticeable artifacts (noise) within the produced scene, but it could be navigated smoothly at 60 frames per second (FPS). While rising bounces to 7 partially eliminated noise and increased the overall quality of the scene, it noticeably decreased the performance down to 24 FPS. This finding was evident in the complicated model, specifically in areas far from direct sunlight.

For the simplified model, illuminance levels at the selected points were compared between Radiance as a reference and the three UE4 rendering scenarios (Figure 13 left). In all four scenarios, illuminance values ranged between 200 and 7000 lux, with most measurements below the 2000 lux threshold. Through observational analysis, it was found that outputs of UE4 with baked lightmap technique (no RTX) were the most varied from those in Radiance. Moreover, it was shown that this technique failed to distinguish between illuminance levels below 2000 lux, where redundant measurements of (1200-1300 lux) were found for most points with indirect daylighting. In contrast, outputs of RTX renderings followed a similar pattern of values to that of Radiance. In the case of RTX with three bounces, measurements were found to be consistently underestimated across all points, compared to Radiance. Increasing the bounces to 7 noticeably improved the results, specifically for points close to direct sunlight, while slightly overestimating the illuminance of the farther points (e.g., points J01-J11).

In the complicated model, all illuminance levels were found to be below 1000 lux. Thanks to the availability of real-life measurements, in this case, it was possible to compare the accuracy of UE4 renderings compared to a validated simulation tool like Radiance, taking luxmeter data as reference for both (Figure 13 right). As expected, Radiance results were very close to those of reality. As for the simplified model, renderings in UE4 baked lightmap (no RTX) obviously varied from reality, with redundant values across points B-H in the two-day times tested. In the case of RTX with 3 bounces, measurements showed a fewer variation from reality and followed the same pattern of high and low values. Moreover, RTX with seven bounces performed noticeably better, with a few values closer to reality than Radiance (points I11 and K11).

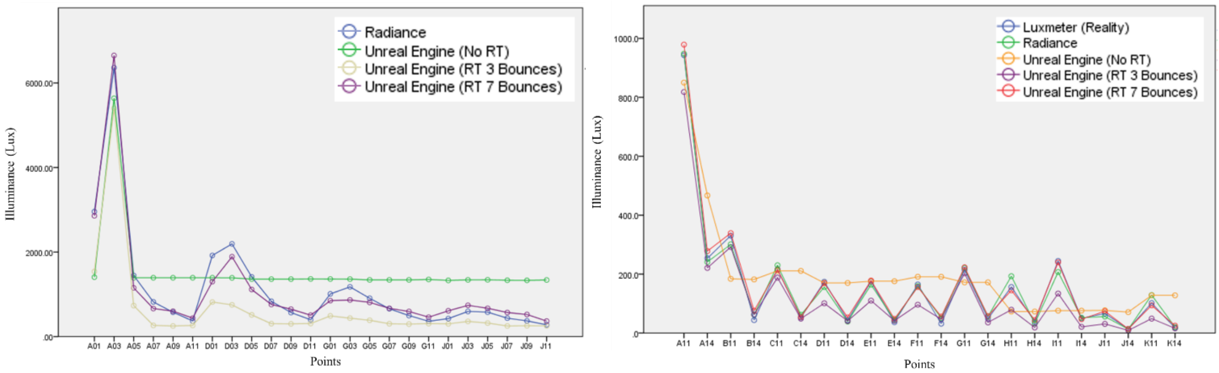


Figure 13: (Left) illuminance measurements in the simplified model using different rendering tools. (Right) luxmeter measurements for the real office space, and respective illuminance measurements of its virtual replica in different rendering tools, point number reflect the time during which was measured (e.g., A14 is Point A at 2:00 pm).

Furthermore, the discrepancies between illuminance outputs of reference benchmarks and UE4 were quantified by calculating the relative error of each measurement compared to the reference, as well as the average error for all points (Table 1) using the following formula:

$$\frac{|investigated\ value - reference\ value|}{reference\ value} \times 100.$$

In the simplified model, the lowest and highest errors in UE4 baked lightmap calculations were 3.7% and 381%, thus for all points, a very high average error of 126% was found for all points measured. This finding illustrated that, on average, this rendering technique estimated illuminance levels as low as half or as high as double of the reference values. Notably, lower error ranges were found in the case of RTX with three bounces, ranging between 8% and 67%, and an average error of 44% for all points. In line with the observations, RTX with seven bounces showed the lowest average error (19.8%), with the lowest error of 1.5% and the highest of 40%. It is worth noticing that the deduced errors were referenced to Radiance, and thus, they reflect how close the measurements are to Radiance calculations rather than absolute values in real life.

Table 1: Average relative errors for all the measured points compared to references.

Case	Reference	Number of points	Average error of all points (%)			
			Radiance	UE4 No RTX	UE4 RTX3	UE4 RTX7
Shoebox	Radiance	24	-	126.1	44.2	19.8
Office	Reality	22	15.0	162.7	30.6	15.8

In the complicated model, error percentages were referenced to the luxmeter data. As expected, Radiance showed the lowest average error (15%) across all points, with the lowest and highest errors as 0.5% and 60%, respectively. UE4 baked lightmap showed an average error even higher than that in the simplified model (162%), illustrating a high discrepancy in estimating illuminance levels in the complicated, textured environment. However, RTX with three bounces showed better results, with an average error of 30%, 5, and 56% as the lowest and highest errors, respectively. Furthermore, the results of RTX with seven bounces showed almost similar average error (15.8%) as that in Radiance. Following the recommendations by Fisher (Fisher 1992), an acceptable error range between measurements and simulation should be 10% for average illuminance calculations and 20% for each measurement point. While the average error for UE4 RTX renderings slightly exceeded this threshold, it is also worth noticing that it was the case for Radiance, meaning that in this specific study, UE4 RTX could quantitatively output results that match the accuracy of a validated ray tracer.

Moreover, as discussed by Reinhart and Anderson (Reinhart and Andersen 2006), it is worth noticing that the ultimate sensor that perceives and assess the appearance and brightness of daylit spaces is the human eye, and thus the difference between 400 lux and 500 lux (20% error) might not be humanly noticeable in the first place. As shown in (Figure 9) and (Figure 12), UE4 could generate images that are more visually similar to Radiance in the simplified model. On the contrary, the quantitative accuracy of the measured points was higher in the case of the complicated model. The reasons for this drop in accuracy for the simplified model renderings despite the lack of interfering parameters are not clear, thus it is important to investigate such aspects in a broader range of cases and spatiotemporal settings.

4.5. Using a hybrid rendering approach

The above validation study showed the advantages and limitations of using lightmaps and real-time ray tracing to simulate daylighting in game engines. On the one hand, real-time ray tracing showed superior results compared to lightmaps concerning photometric accuracy. However, achieving this accuracy was accompanied by low framerates and artifacts, which were not present in lightmaps renderings. The implementation of game engine rendering within immersive virtual reality requires considering several factors to improve user experience and minimize motion sickness. Among these factors is maintaining a high framerate and uniform visual appearance across the explored space in VR.

Therefore, this research will utilize both lightmaps and ray tracing in the creation of IVEs evaluated by participants (Figure 14). In this hybrid approach, ray tracing will be used only for reflections and refractions, while lightmaps will be used for global illumination (indirect lighting). To ensure the photometric accuracy of the results, calibration of lighting settings will be conducted separately on each created model, and the output illuminance and illuminance will be compared to those in a verified light simulation tool.

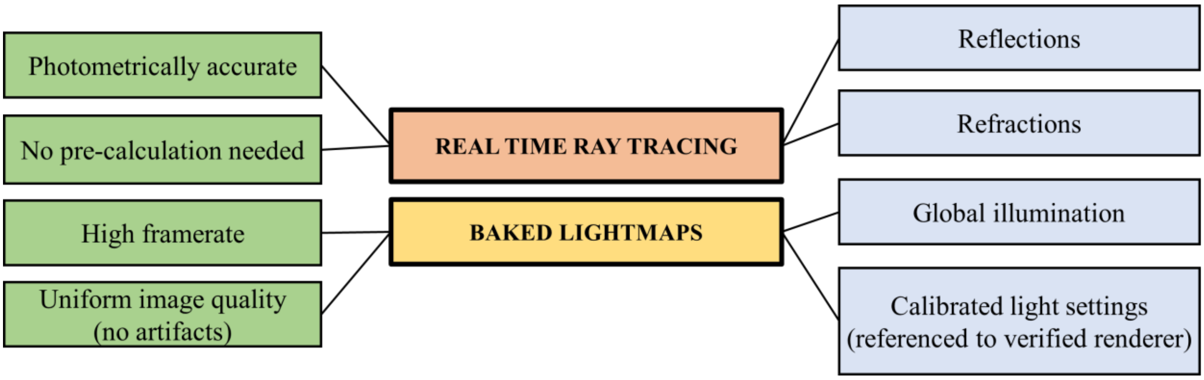


Figure 14: Hybrid method of rendering in game engine, using real-time ray tracing and baked lightmaps.

4.6. Conclusions

This chapter investigated the luminous accuracy of Unreal Engine based on point-in-time illuminance values. Two daylit case studies were selected to reflect different spatial complexity levels, and three rendering techniques (uncalibrated baked lightmap, ray tracing three bounces, and ray tracing seven bounces) were used to generate the scenes. The following findings could be concluded:

1) In general, scenes rendered using ray tracing generated noticeably more accurate results than those rendered using baked lightmaps, in terms of illuminance values compared to simulated and real references.
2) In the simplified model, ray tracing with a higher bounce count showed an average error of 19.8% compared to simulated reference rendering. In the case of baked lightmaps, the average error was higher than 100%.
3) In the complicated model, the average error percentage of ray tracing outputs was 15.8% (higher bounce count) compared to sensor readings, while 15% in the validated physically-based renderer. These very close results showed the possibility of acquiring photometrically accurate renderings in game engines using ray tracing.
4) Despite its accuracy, ray tracing showed two major limitations in terms of low frames and rendering artifacts, which hinders its application to simulating architectural scenes in immersive virtual reality.
5) A hybrid approach is proposed to benefit from the accuracy of raytracing and stability of baked lightmaps, where raytracing is used for rendering reflections and refraction, while global illumination is rendered as a lightmap.

The conclusions in this chapter discuss the validity of outputs in the proposed game-engine-based system in terms of quantitative light metrics. The following chapter will investigate the validity of perceptual responses of the architectural space in simulated the proposed IVE system compared to being in the actual space.

Chapter 5. **Validating game engines and Immersive Virtual Reality as perceptual daylight simulation tools**

5.1. Introduction

The previous chapter investigated the validity of real-time renderings in game engine regarding photometric outputs. The next step towards validating the proposed system in this research is to investigate the consistency between participants' perceptions of the system and reality. Therefore, this chapter discusses the validation of the introduced approach through an experiment comparing participants' feedback in a physical daylit environment and its virtual replica using the developed system at similar spatiotemporal settings.

5.2. Methodology

5.2.1. Experimental hypothesis and variables

The main question of this study is oriented around "how adequate are game engine-based daylight simulations for the perception of daylit spaces in virtual environments?". Therefore, the specific hypothesis tested in this study is that the participants observing the virtual environment in the developed system will have report scenes and their perceptual brightness similarly to those experiencing the real environment. In other words, there will be no significant discrepancy between reported perceptions in the physical environment and its virtual replica. A corollary hypothesis is whether the participants would report a high sense of presence in the developed interactive virtual environment.

Table 2: Overview of variables and questionnaire attributes.

Independent variable (IV)	
IV1	Exposure media: real or virtual environment
Dependent variables	
Reported scenes (RS)	
RS1	Scene position
RS2	Brightness perception [a]
Sense of presence [b]	
Q1	How realistic and natural was your sense of moving around in the virtual environment?
Q2	How much did you feel like "being there" in the virtual space?
Q3	How much did you quickly feel familiar with the VR space?
Q4	How much did you feel objects scale to be natural?
Q5	How much did you feel your scale to be natural?
Q6	How much did the virtual space become the reality for you?
Q7	How much did the virtual space look consistent with reality?
Controlled variables	
Spatiotemporal settings (SS)	
SS1	Indoor space configuration (multipurpose open office space)
SS2	Sky condition (overcast)
SS3	Daytime (noon)

[a] Discrete 4-point scale (very dark, dark, bright, very bright)

[b] A 5-point scale, 1 corresponds to *not so much* and 5 corresponds to *very much.*

(Table 2) describes the experimental design variables in this study. The experiment features a sole independent variable, which is whether the participant experiences the test environment in reality or in the virtual system. Furthermore, as the participants walk inside the architectural space and report scenes of interest and their brightness rating, two dependent variables are set. For participants experiencing the virtual environment, a presence questionnaire is also present, comprised of seven questions with a 5-point scale of verbal anchors “not so much” and “very much” on the extremes. Across the real and virtual media, three factors related to spatiotemporal settings are set as controlled variables set by the researchers (space configuration, sky condition, and daytime).

5.2.2. System tools and specifications

In this study, a set of hardware and software tools were used to develop the proposed IVE system. HTC Vive Pro head-mounted display (HMD) was used, with 2880 x 1600 pixels combined screen resolution and 90 Hz refresh rate; the display had a luminance of 143 cd/m^2 and a 110^o horizontal field of view (FOV). Two Vive motion controllers and two motion tracking stations were used to provide users with 6 degrees of freedom (6DoF) (Batallé 2013). The virtual environment was modeled using SketchUp 18.0 and refined in 3DS Max 21.0. Unreal Engine 4.23 and OpenVR self-developer kit (SDK) were used to set up the daylight simulation and the IVE interactive experience. The system ran on a desktop PC equipped with an i7 7600K processor, NVidia Quadro RTX 6000 graphics card, and 64 GB of RAM.

5.2.3. Case study: real environment

In this study, an immersive VR system is developed to investigate the brightness perception of daylighting in virtual environments. To validate the adequacy of the developed system, it is crucial to compare users’ feedback in real and virtual environments. While many related studies focused on simple office spaces (Chamilothori et al. 2018; Heydarian, Pantazis, et al. 2015; Natephra et al. 2017), the authors addressed these characteristics as potential limitations that may obscure the generalization of the findings of these studies. Furthermore, the proposed approach employs the interaction principle by providing users free exploration capabilities to the environment and a self-expressive way to report individualized perceptions on daylighting. Therefore, selecting a large-scale architectural space showed a more robust investigation of the potentials and limitations of the proposed system within the conducted validation case study.

Hence, the investigated case study selection was prone to the same criteria followed in Section 4.3.2. A multipurpose space at Osaka University was selected as it fulfilled the stated criteria (Figure 15). The test environment was limited to a common hall area on the 1st floor, daylit by a courtyard of 7.0m x7.0m dimensions. The investigated space hosts various study areas, meeting rooms with glass walls, a kitchenette corner, and an open conference hall (Figure 16).

Figure 15: Selected case study (lounge area).

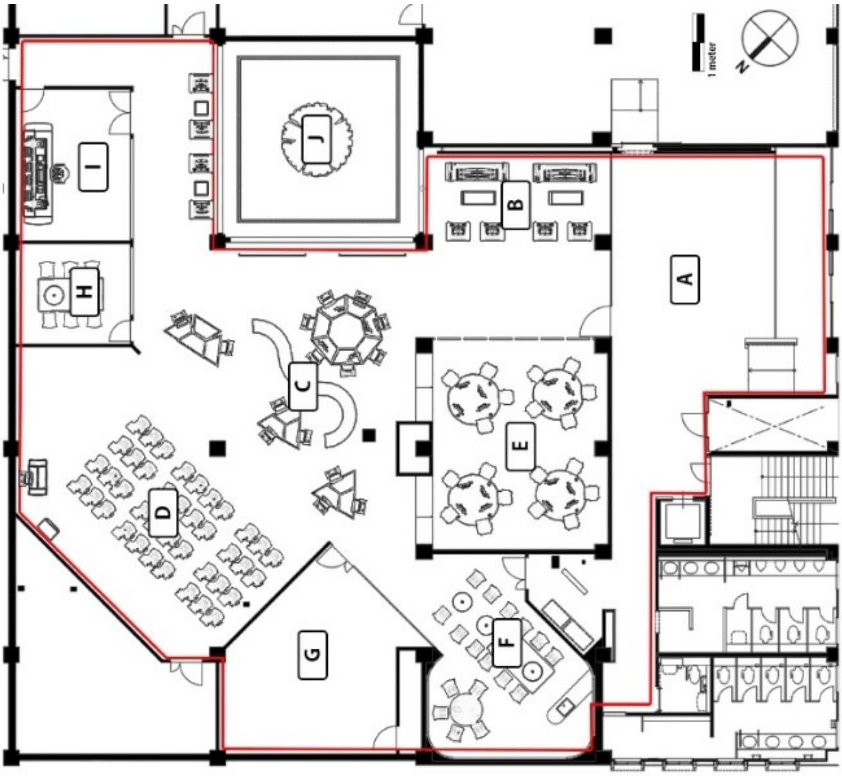


Figure 16: Floor plan of the selected case study illustrating regions accessible by users (red line) and areas as follows: A) entrance hall, B) lounge area, C) co-work area, D) conference hall, E) workshop room, F) kitchen, G) fabrication lab, H) meeting room, I) presentation room, J) courtyard.

5.3. Case study: virtual environment

5.3.1. Creation of the 3D model

A fully detailed 3D model of the test environment was created using the original floor plan drawings of the building and reference images of the current situation. Also, finishing materials and textures used in the real environment were scanned for further usage in the 3D model, and accurate physical properties of each material were considered. A basic model was initially created in SketchUp software to include essential structural elements, furniture, and preliminary materials definitions (Figure 17a). Furthermore, the model was imported into 3DS Max software to refine the model and add textured materials (Figure 17b). Finally, the 3D model was imported into Unreal Game-Engine 4 (UE4) to create physical materials, set up the daylight simulation, and develop the VR interaction controls (Figure 17c).

5.3.2. Materials and lighting settings

In 3DS Max, realistic materials were applied to the model to give an initial impression of the environment composition and scale textures correctly on various surfaces. In UE4, all materials were refined to match the physical properties of the real materials. In UE4's material editor, materials were defined by the following physical properties: translucency, base color (Texture), roughness, metallicness, and specularity.

Daylighting simulation in UE4 was based on a single directional light source to simulate the sun (Intensity: 110 Klux, temperature: 5500K) and a sky model for ambient daylighting. The light source was linked to a "sun position" add-on to automatically set the sun and sky conditions concerning spatiotemporal settings. An overcast Preetham sky model was used to simulate the skylight. Geographical coordinates were set to 135.525 and 34.820 (Suita, Japan) and time zone to +9. Date and time were set in correspondence to when the experiment in the real environment took place. Real-time camera settings were set as (Exposure (Ev_{100}): -10 to +20, indirect light multiplier: 2, reflections type: raytracing). Finally, rendering simulation quality was set at "Production" (highest).

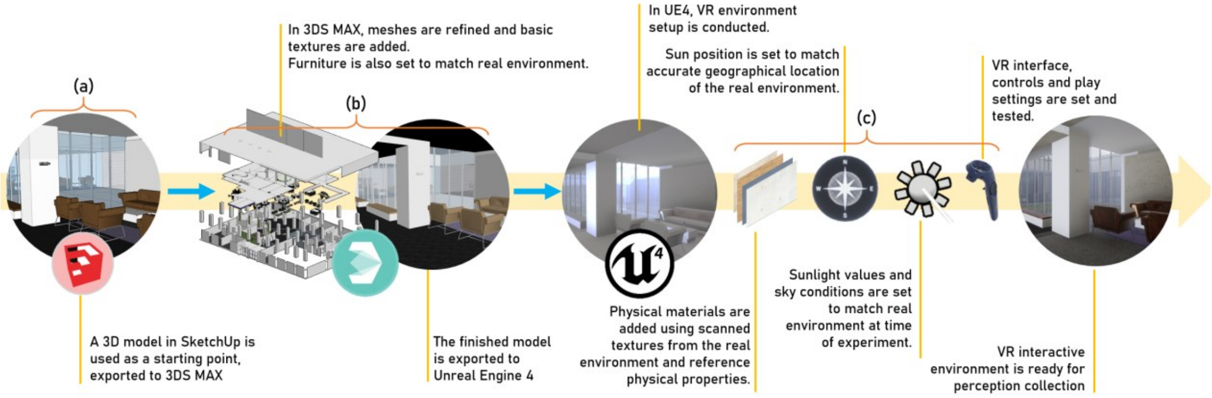


Figure 17: Methodology of creating the IVE system in UE4.

5.3.3. Tone mapping

To convert high dynamic range (HDR) scenes produced by UE4 to low dynamic range (LDR) ones compatible with the VR head-mounted display, a tone mapping operator (TMO) was used. The ACES filmic tone mapping algorithm (Hable 2010) was utilized throughout the system. Studies have emphasized the accuracy of the filmic tone mapper in providing adequate replication of soft transitions in bright areas while maintaining original color saturation in darker areas (Dille, Fuhrmann, and Fischer

2016). Furthermore, it has shown an advantage over several TMO's in color tone reproduction in real-time (Hable 2010; Maltz 2016).

Filmic TMO was defined in the developed system by the following parameters: Slope=0.88, Toe=0.55, Shoulder=0.26, Black clip=0.0, White clip=0.04. Since the virtual environment was experienced in real-time at 90 frames per second, it was necessary to consider dynamic tone mapping to simulate eye adaption when switching between different luminous environments. For that purpose, an auto-exposure algorithm was used to define the range and speed at which exposure changes when the user moves between different areas (Table 3).

Table 3: Parameter settings for on-the-fly tone mapping

Metering Mode (algorithm)	Auto Exposure Histogram
Exposure Compensation	0.0
Min EV_{100}	-10.0
Max EV_{100}	20.0
Speed Up	3.0
Speed Down	1.0

5.3.4. Interaction controls

The developed IVE system offers high levels of immersion and interaction for users while reporting their perception of daylight brightness in VR. 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). Furthermore, several interaction controls were programmed to the VR motion controllers using "Blueprints" scripting tool in UE4. Users could use the controllers' 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 individualized brightness perception of various scenes in VR. Finally, a similar keyboard and mouse controls were added in case researchers needed to intervene.

5.4. Experimental Protocol

5.4.1. Participants

In this study, thirty-six participants (20 males, 16 females) were recruited to give their feedback on daylighting. The recruitment process was performed through email invitations to undergraduate and graduate students at various schools at Osaka University. The participants aged between 21 and 25 (92%) and 26 and 30 (8%) with educational levels ranged from Bachelor (22%) to Masters (72%) and Ph.D. (6%). Through a pre-recruitment interview, the participants were found to have limited knowledge about daylight metrics and evaluation criteria, which was crucial to ensure an unbiased, non-expert perception of daylight conditions.

A “between-subjects” experimental design was selected, where participants were randomly divided into two groups, each experiencing either the real or virtual environment. This design was favored over a “within-subjects” one as participants were expected to give self-expressive feedback on various areas of the tested model, where exposing the same participant to the real and virtual environment may raise a presentation-order bias (Chamilothori et al. 2018; Charness, Gneezy, and Kuhn 2012). Besides, it increases the possibility of fatigue or loss of focus given the large scale of the investigated model and the subsequent work requiring participants to report perceived brightness levels in two similar environments. Besides, a within-subject design would mandate some participants to experience the virtual environment before the real one, which generates difficulty maintaining the controlled variables of temporal and sky condition settings. For instance, a participant who perceives the virtual model at noon under an overcast sky (in virtual settings) would have to perceive the physical environment under the same conditions, which may be unfeasible due to sky conditions' uncertainty in real-life. In this context, using a between-subject method provided a uniform condition where the first group experienced the physical environment at noon under an overcast sky. Then, these conditions were reproduced for the VR group. Also, to minimize the variation within personal preferences, the two groups selected were of a uniform age range, education, culture, and ethnicity.

The selected sample size of thirty-six participants was found to be consistent with several related studies that investigated perceptual aspects of daylighting in virtual environments, of which sample sizes ranged between 16 and 40 (Abd-Alhamid et al. 2019; Cauwerts and Bodart 2011; Cha et al. 2019; Chamilothori et al. 2018; Franz, von der Heyde, and Bülthoff 2005; Heydarian, J. Carneiro, et al. 2014). 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.

5.4.2. Experiment procedures in real environment

The experiment was conducted on December 18, from 11:00 am to 12:30 pm, under an overcast sky condition. To prevent the participants from influencing each other while rating the real environments (herd behavior), they were allowed into the test space in groups of five. As shown in (Figure 18a), participants were allowed into the entrance lobby of the test area. The researchers provided a verbal instruction and an overview of the needed tasks. Each participant was given a quick tour of the nine accessible areas within the building to avoid ambiguity or mid-experiment confusion. Participants were instructed to roam freely around different areas to begin the experiment and use their smartphones to snapshot areas they perceive as overly bright or dark. The task was formulated in the following verbal order: “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”. For each snapshot, participants were asked to clarify what they meant to look at and their brightness ranking for that snapshot on the 4-point scale. Experiment time was limited to 20 minutes, during which researchers did not impose any instructions on the participants (Figure 19 left). Afterward, the participants were asked to upload their snapshotted scenes, along with their rankings, to a dedicated cloud-based directory.

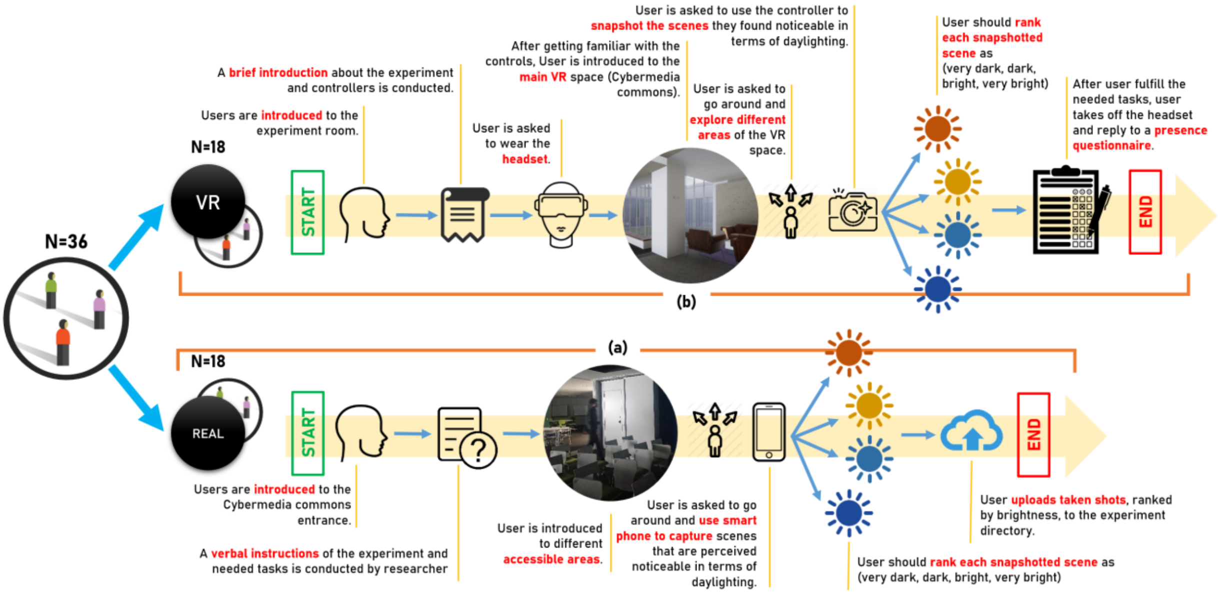


Figure 18: Experiment protocol in real and virtual environments.

Figure 19: Participants experiencing real (left) and virtual environments (right).

As a few participants were allowed into the test space as groups, several measures were taken to mitigate potential interference from multiple users' participation (herd behavior):

1) each group was limited to no more than five participants, synergized with the large footprint (460m^2) and multiple areas within the test space. This approach ensured that the participants could scatter around different areas without close contact.
2) At the beginning of the experiment, the participants were instructed against proximity while reporting scenes and not publicly declaring their brightness perception of each scene.
3) A post-experiment analysis of each participants' wandering path and scene selections was conducted for each group using the reported images' time stamps. As shown in (Figure 20), the observational analysis showed that despite experimenting simultaneously, participants within the

same group followed distinctive paths while exploring the environments, specifically for the first reported scene and the areas not included in their reports.

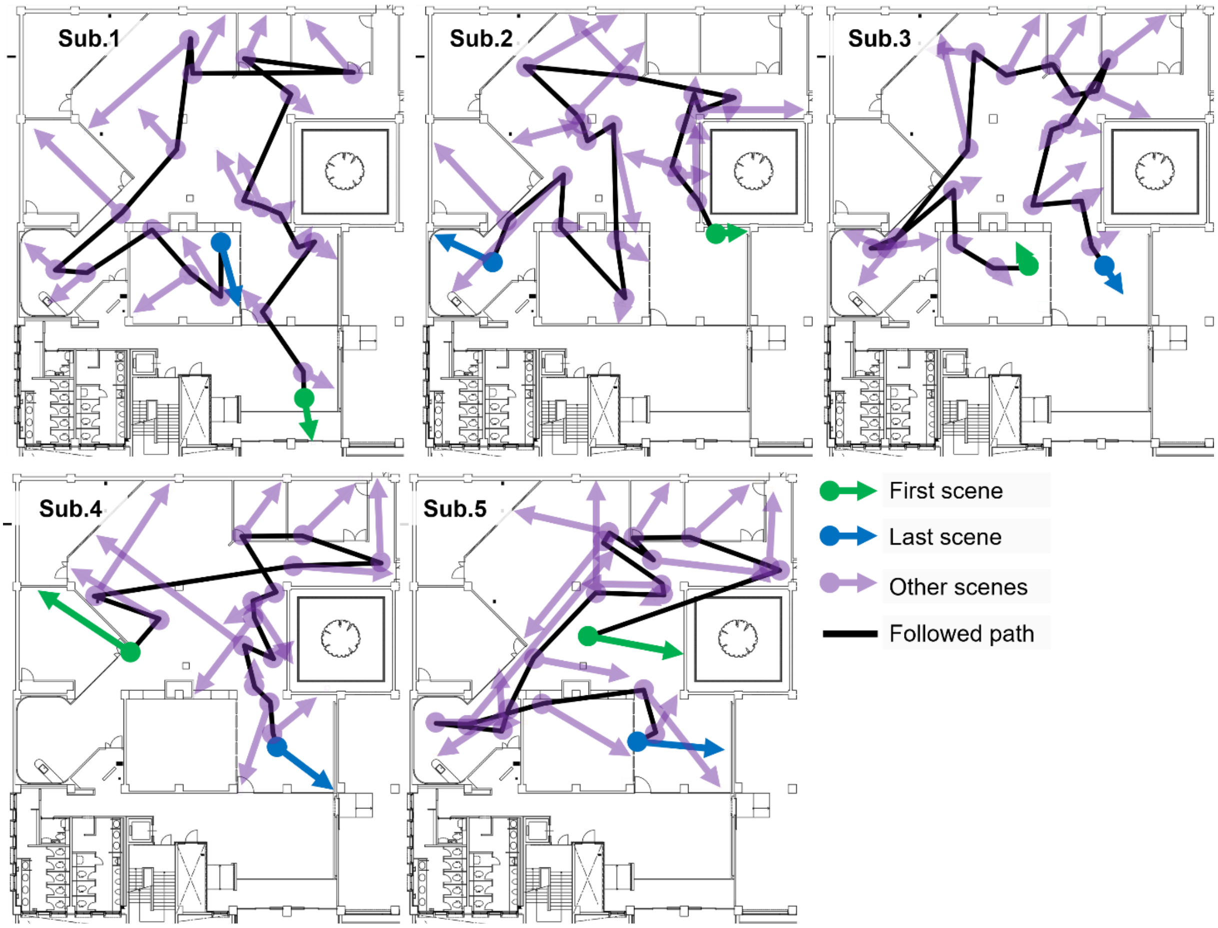


Figure 20: An illustration of the reported scenes and temporal paths of each participant within the same group.

5.5. Experiment procedures in the virtual environment

In the virtual model, date and sky conditions were set identical to that during the real environment experiment. The experiment in IVE was conducted during December 20-24th from 11 am to 12 pm. The experiment was conducted in a dedicated workstation room. The room had three windows facing Northeast and Northwest; shutters were fully closed (during, before, and after the experiment) to not distract the participants with ambient daylight from the windows. In UE4, the virtual environment sky model was set to an overcast sky on December 18th at 11:30 pm, based on the average time during which the experiment in the real environment was conducted.

As shown in (Figure 18b), participants were introduced to the experiment room, shown a computer-based brief about the experiment's purpose and procedures, and checked a submission checkbox as consent. Then, they were given a simple questionnaire on demographics, experience in VR and daylight aspects, and physical symptoms to confirm their physical eligibility. Furthermore, they proceeded to an introduction about the investigated model and its accessible areas. Afterward, they were introduced to a tutorial for motion controls to learn how and what they can control within the IVE. Finally, an explanation of the tasks to be fulfilled during the experiment was provided. Participants spent an average adaption time of 10 minutes in the experiment room before wearing the VR headset.

Afterward, participants were asked to put on the HMD and try a sample scene familiar to the IVE system and controls (Figure 19 right). Participants were instructed to stand and move physically within a limited range to benefit from the system's 6DoF, which allowed the participants to change their views directions and occasionally lean forward to have closer looks (Figure 21). After a participant got familiar with the IVE system, the virtual model was loaded with the entrance lobby as the starting point. Participants were asked to use the controllers to move around and explore different areas within the building for one minute. Afterward, participants were asked to report their brightness perception for freely chosen scenes using the same verbal order illustrated in Section 5.4.2. Participants were free to take as many snapshots as they wanted and freely switched between different virtual model areas.

As conducted in the real environment, each time participants took a snapshot; they were asked to verbally report what they meant to look at and their perceived brightness of that snapshot on the 4-point scale. Following research recommendations suggesting that prolonged time in VR increases motion sickness probability (Buhler, Misztal, and Schild 2018; Ruddle 2004), the experiment time in VR was limited to 20 minutes. To accurately capture the time spent inside VR, the system was equipped with a screen recorder whenever the VR model was active. Once participants finished their tasks, they were asked to take off the HMD and respond to a presence questionnaire.

Figure 21: Participants in VR exploring the environment non-horizontal view directions through the 6 DoF offered by the system.

The presence questionnaire was introduced in a computer-based format to evaluate participants' perceived presence inside the virtual environment and assess the degree of immersion and interaction within the developed system. The questionnaire consisted of seven questions labeled from Q1 to Q7 (Table 4), where a 5-point scale with verbal anchors was used for evaluation ('not so much' matching 1 point, 'very much' matching 5 points). The selection of questions was based on the presence questionnaires introduced by Heydarian et al. and Chamilothori et al. (Chamilothori et al. 2018; Heydarian, Carneiro, et al. 2015). For Q7, a collection of images for the real environment was provided as a reference for comparison.

Table 4: 5-Point Presence Questionnaire for VR participants

Q1.	How realistic and natural was your sense of moving around in the virtual environment?
Q2.	How much did you feel like “being there” in the virtual space?
Q3.	How much did you quickly feel familiar to the VR space?
Q4.	How much did you feel objects scale to be natural?
Q5.	How much did you feel your scale to be natural?
Q6.	How much did the virtual space become the reality for you?
Q7.	How much did the virtual space look consistent with reality?

5.6. Collective perceptions visualization

This study adopts an interactive methodology that enables participants to freely report scenes of interest, and their respective brightness perception. Unlike the previous IVE based research, this methodology does not force a predefined view of which all participants have to evaluate. Therefore, a large variety of data points could be obtained from the thirty-six participants in this experiment, where each point indicates the standing position, target scene, and brightness rating of the snapshot. This additional layer of spatial data enabled the visualization of the participant’s occupancy patterns and daylight brightness perception in a collective form. It also enabled a quantitative investigation of the discrepancies between participants’ perceptions in reality and IVE.

Figure 22 shows the methodology of visualizing brightness perceptions and participants’ positions. First, selected scenes and their evaluations were exported as image files, using the snapshotting tool in the VR system, and smartphones in the real environment. In 3DS Max software, the output images were matched and recreated as camera objects, where the camera position defines the participant’s standing point at the time of snapshot, and the target scene is defined as the center point of the field of view falling on the nearest surface. A Maxscript code was developed to automatically export the XYZ coordinates of all cameras and their respective targets as a CSV file. In Rhino 3D software, the parametric plugin “Grasshopper” was used to populate all the points within the test environments (Figure 23). Points were tagged by shape and color to discern medium and brightness, respectively.

Figure 24 shows the resultant 3D map illustrating center points of the reported scenes, the medium they have been reported in, and their respective brightness perception. The observational analysis of the map can show a high concentration of perceived bright and very bright scenes around the courtyard, with a considerable concentration at the entrance gates and lounge entrance. On the contrary, a high density of perceived dark and very dark scenes could be found mainly in the conference hall area followed by the semi-closed areas. In both cases, a nearly uniform distribution of reality and VR scenes could be observed. The area surrounding the starting point had a relatively low concentration of reported scenes across the two environments. Following a similar methodology, (Figure 25) collectively illustrates participants' positions for every scene reported. The map detects a high occupancy pattern at the lounge area and around the courtyard, with slightly higher occupancy in the real environment.

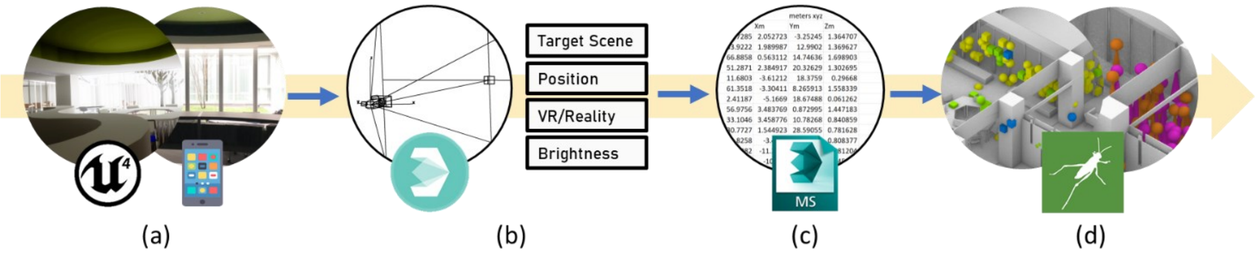
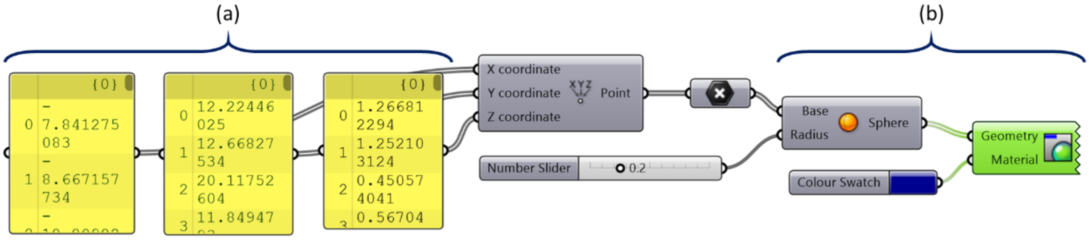


Figure 22: Methodology of visualizing participants' perceptions and positions within the test environment. (a). evaluated snapshots in reality and VR. (b) Recreating output scenes as camera objects in 3DS Max, defined by four parameters (center point of the target scene, user position, taken in VR or reality, and brightness evaluation). (c) Using Maxscript, a list of the xyz coordinates for each camera target and position and its evaluation and medium is exported as csv list. (d) In Grasshopper, the xyz coordinate lists define the populated points, which overlaid over the 3D model.



```
{0}
-
0 7.841275
  083
-
1 8.667157
  734
-
```

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{0}
0 12.22446
  025
1 12.66827
  534
2 20.11752
  604
3 11.84947
```

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{0}
0 1.26681
  2294
1 1.25210
  3124
2 0.45057
  4041
3 0.56704
```

Figure 23: Grasshopper parametric definition for visualizing target scenes in Grasshopper. (a). xyz coordinates list for all points of the same evaluation and medium (e.g. very dark, reality). (b). populated point list is defined as the center of a sphere with a given radius and color to identify the medium (VR/reality) and brightness.

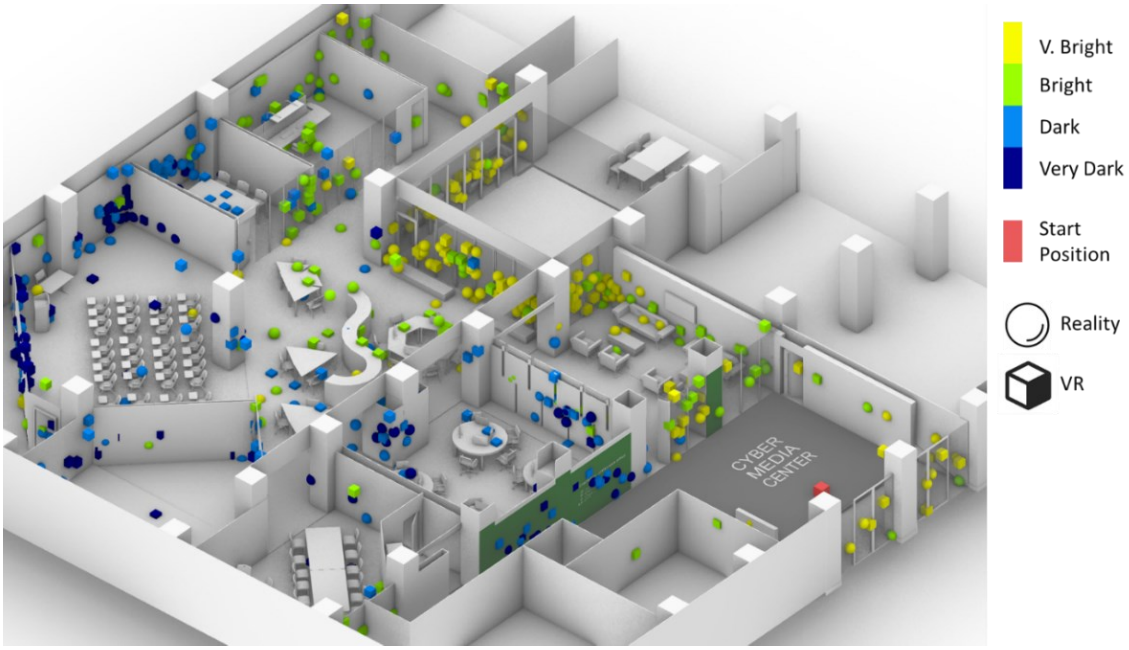


Figure 24: Representation of evaluated target scenes within the test environment and their respective perceived brightness.

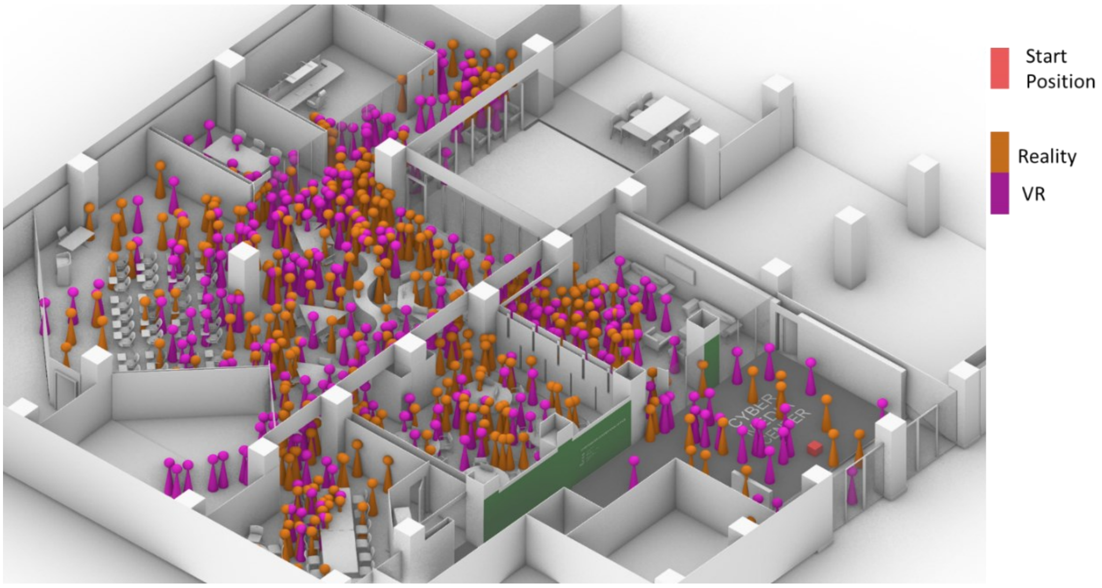


Figure 25: Representation of the participants' positions within the test environment at snapshotting time.

5.7. Comparing participants' outputs across IVE and reality

The previous visualization method enabled a spatial interpretation of the trends and patterns of the participants' perceptions in the two environments. However, a statistical comparison method was essential to quantitatively investigate the consistency between the perceptual outputs across VR and reality. Due to the interactive nature of the used method, the evaluated snapshots varied widely between the two environments, which adds a challenge to unify an independent variable in the comparison method. Two methods were developed to conduct the comparative analysis between participants' outputs regarding positions and perceptions.

The first comparison methodology was based on the number of positions at the time of snapshotting for a given volume of the test environment (Figure 26). In Python, an algorithm was developed to define the division and counting criteria (Figure 27). First, the 3D coordinates of all the evaluated snapshot positions were imported as a CSV file, where the minimum and maximum coordinates were defined to create a bounding box of all points. Then, a grid spacing count was defined to divide the bounding box uniformly. The selected count was 12,13,1 for the x, y, z axes, respectively. Furthermore, the algorithm counts the number of points in each of the resultant 156 volumes. Through this method, the frequency of participants' positions at each volume was statically compared across reality and IVE.

While the previous method enabled a dynamic resolution of the comparison grid in response to the number of scenes reported, it was not used in comparing perceptions due to limitations in two aspects:

1) It uniformly divides the test volume regardless of the focus areas.
2) Some division volumes may include two sides of the same wall, which does not reflect that the compared perceptions relate to different areas.

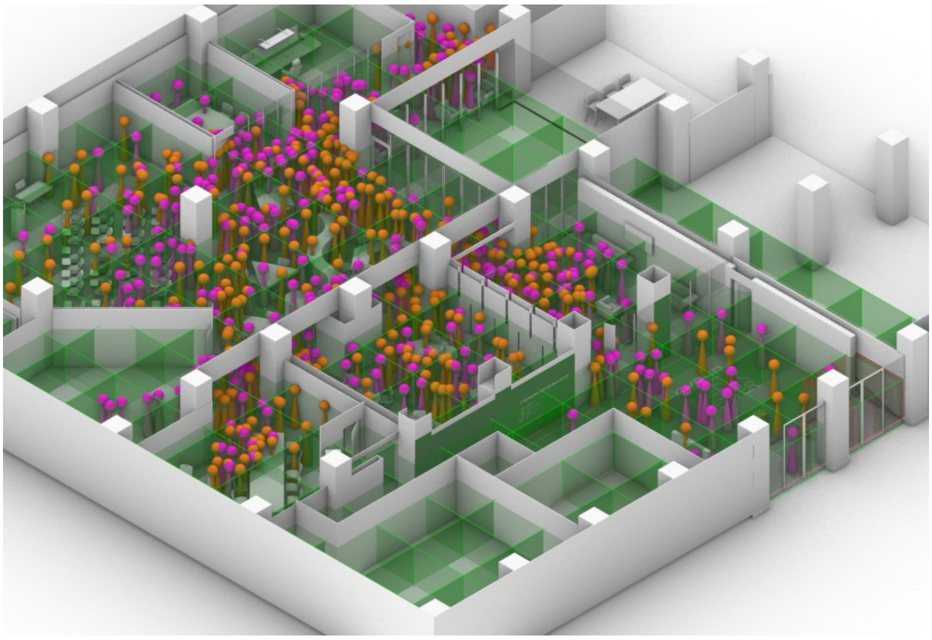
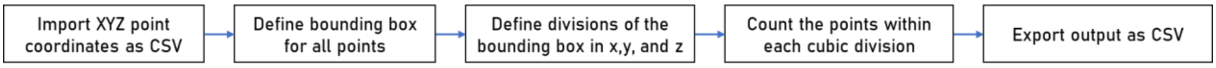


Figure 26: The resultant division grid within the test environment volume bounding captured participants' position points (division count: x=12, y=13, z=1).



```
f = open('filename./.csv')
reader = csv.reader(f)
```

```
if maxX < float(row[n]):
    maxX = float(row[n])
if minX > float(row[n]):
    minX = float(row[n])
...
```

```
divX = 12
divY = 12
divZ = 12
unitX = (maxX -minX)/divX
unitY = (maxY -minY)/divvY
unitZ = (maxZ -minZ)/divZ
```

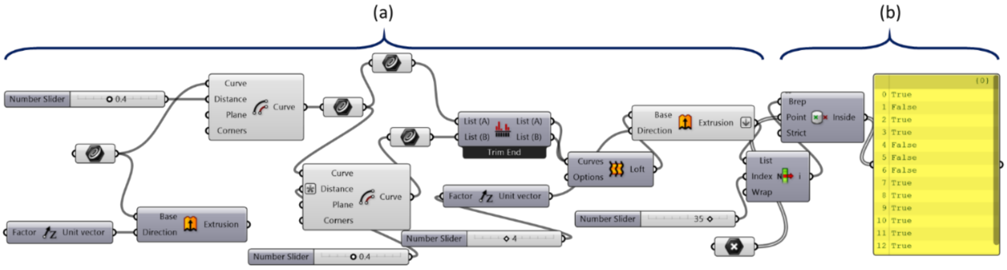
```
p_distr = np.zeros((divX, divvy,
divZ))
vr_distr = np.zeros((divX, divvy,
divZ))
nx = int(float(row[4])/unitX)
ny = int(float(row[5])/unitY)
nz = int(float(row[5])/unitZ)
```

```
print('unitX = ' + str(unitX))
print('unitY = ' + str(unitY))
print('unitZ = ' + str(unitZ))
```

Figure 27: The workflow (in Python) of the algorithm used to create uniform cubic divisions of the test environment and calculate their respective position count.

As most of the reported scenes were focused on walls, a further methodology was developed to compare the number of reported scenes of each brightness level per wall surface across VR and reality. In Grasshopper plug-in, an algorithm was developed to define each wall surface and calculate intersections with the scene points of similar brightness perceptions (Figure 28), where the two faces of each wall were modeled separately. (Figure 29) shows the 47 resultant walls, where the algorithm calculated the intersection surfaces with scenes at each of the four brightness levels across VR and reality, leading to 368 calculation scenarios by the algorithm.

Furthermore, to unify the variables within the comparative analysis, the four brightness perception levels were aggregated into one unified perceptual brightness score for each wall, based on the number of reported scenes and their evaluation on the 4-point scale. (Figure 30) shows the aggregation method, where the count of scenes with extreme evaluations -very dark or very bright- was doubled to compensate for the magnitude of perception, while scenes evaluated as dark or very dark were signed as negative values. The sum of weighted counts for all the scenes per wall generated a unified brightness score representing the aggregated brightness perception (bright or dark) and the density of scenes.



```
{0}
0 True
1 False
2 True
3 True
4 False
5 False
6 False
7 True
8 True
9 True
10 True
11 True
12 True
```

Figure 28: Definition in Grasshopper; (a) defining wall lines, thickness, and height. (b) detecting points intersecting with the wall.

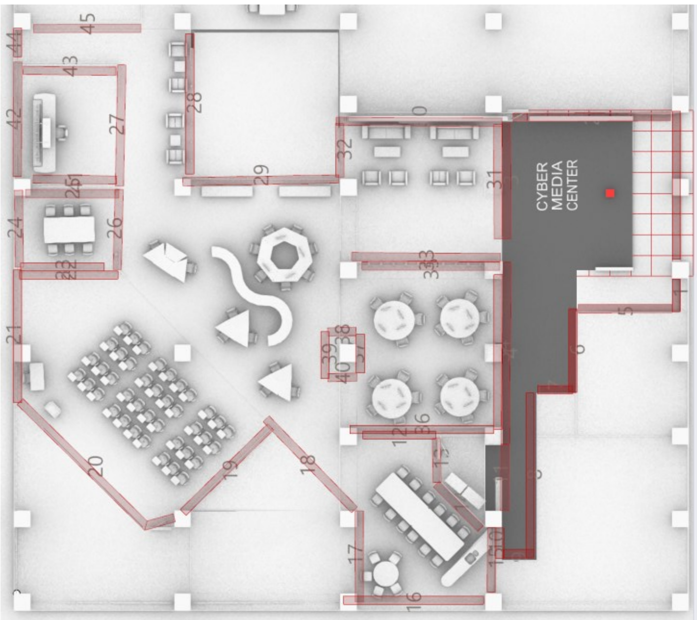


Figure 29: Generated mesh volumes for walls marked by unique index numbers, both sides of each interior wall were generated separately.

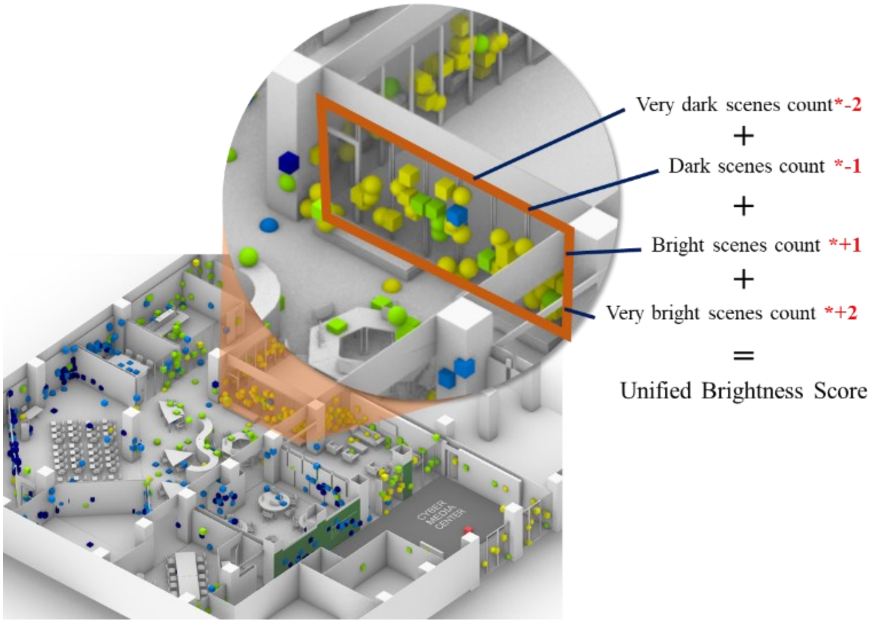


Figure 30: Aggregation method for unifying perceptual brightness levels per wall.

5.8. Results and analysis

5.8.1. Presence questionnaire

Following the participants' experience in VR, a computer-based presence questionnaire was introduced to evaluate the perceived presence of participants inside the virtual environment and their evaluation of the degree of immersion and interaction within the developed system. The questionnaire consisted of seven questions, where a 5-point scale with verbal anchors was used for evaluation ('not so much' matching 1 point, 'very much' matching 5 points). The selection of questions was based on the presence questionnaires introduced by Heydarian et al. and Chamilothori et al. (Chamilothori et al. 2018; Heydarian, Carneiro, et al. 2015). In Question 7 "How much did the virtual space look consistent with reality?" a set of images for the real environment was provided as a reference.

Figure 31 shows the distribution of participants' responses to the presence questionnaire. The observational analysis shows that questions regarding the perceived object scale and self-scale received the highest ratings, with 83% and 55% "very much" responses, respectively. On the contrary, the question regarding the sense of movement received a mixed response, with neutral and unfavorable responses at 33% and 39%, respectively. Further analysis of the mean and standard deviation values emphasizes the previous results, where questions on "object scale" and "self-scale" have shown a mean evaluation of 4.72 and 3.78 and SD values of 0.75 and 1.00, respectively. Moreover, the "sense of being there" question also showed a highly positive mean response of 4.22 with an SD value below 1. However, in contrast to the observational analysis, the "sense of movement" question also showed a relatively high mean value (3.94) but with a high variance of responses at an SD value of 1.16.

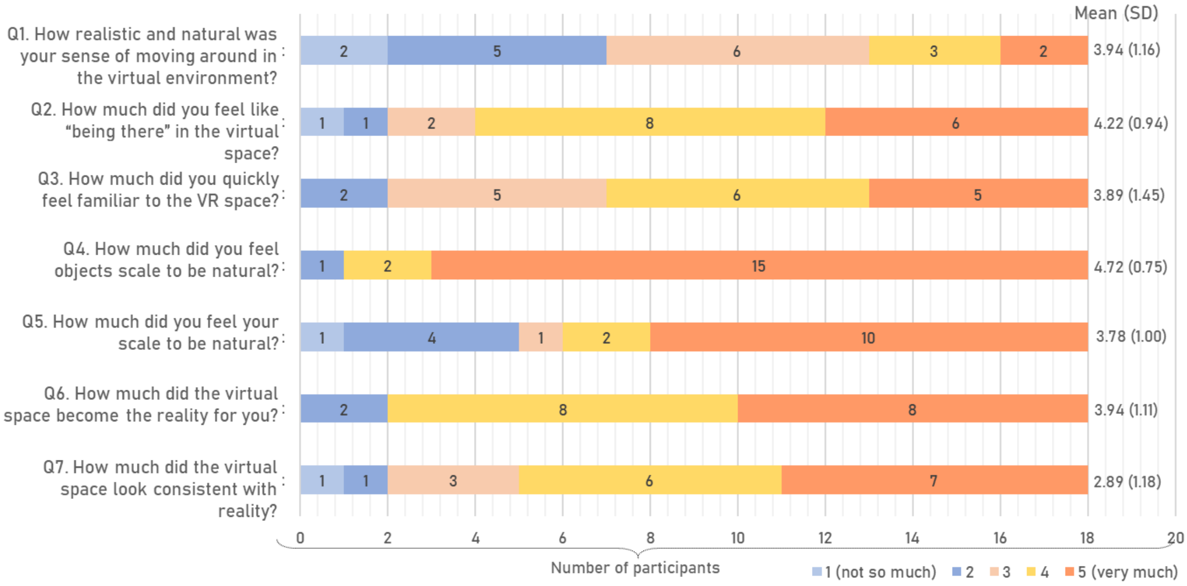


Figure 31: Distribution of the participants' responses to the presence questions, where each bar shows the number of participants' responses to each scale point (N=18).

5.8.2. Distribution of reported snapshots

Participants were asked to tour freely through different areas, and report their brightness perception through snapshotting the scenes they perceive as one of the following: very dark, dark, bright, or very bright (Figure 32). Participants slightly reported more scenes in the real environment than that in virtual ones at 345 and 330 snapshots, respectively. Similarly, on the 4-point scale provided, mean brightness rankings were primarily consistent in reality and VR, with a value of 2.26 and 2.47, respectively, showing a balanced range of bright and dark scenes perceived in both environments.

Figure 33 shows the distribution of snapshots per area and their corresponding rating. A general consistency could be found through observational analysis between the total number of reported snapshots in both reality and VR across different areas. An exception to this consistency is the kitchen area, where a significantly higher number of snapshots were reported in reality than in VR (29, 17 snapshots, respectively). In both media, participants reported most scenes in the co-work area in reality and VR, while reported the least in the Fab lab area. The presentation room showed the lowest variance between reports in reality and VR (16 snapshots in both).

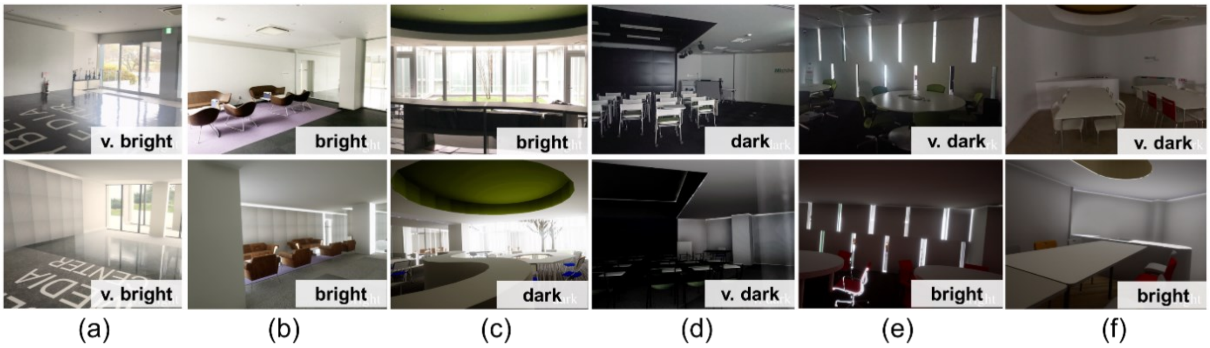


Figure 32: A sample of participants' snapshots in real (upper) and virtual (lower) environments at similar areas, with corresponding brightness perception ranking for each snapshot. (a) entrance (b) lounge (c) co-work (d) conference hall (e) workshop room (f) kitchen.

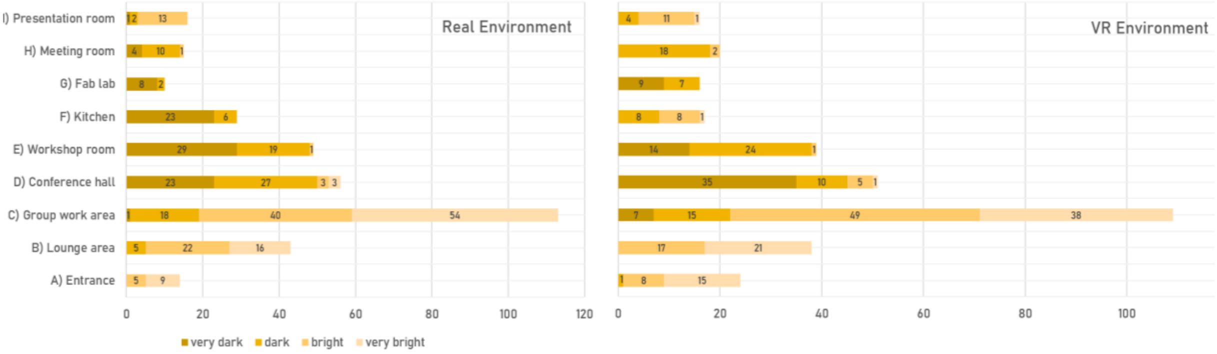


Figure 33: Distribution of the participants' snapshots in each area in real and virtual environments, where each bar shows the number of snapshots for each brightness rating.

Furthermore, reported snapshots were analyzed concerning the 4-scale points (very dark to very bright) per each area in reality and VR (Table 5). In the case of "very dark" snapshots, participants' reporting was concentrated mainly in the conference hall (23 snapshots) and the workshop room (35 snapshots) in VR and reality, respectively. However, the average number of shots for both media was higher in the conference hall (29 snapshots). The entrance hall and lounge area showed the lowest variance in reports between reality and VR, where no participants reported any “very dark” scenes. On the other hand, the kitchen area illustrated the highest variance between the two media, with 23 very dark snapshots in the real environment against no corresponding snapshots in VR.

Similarly, in the case of “dark” snapshots, the conference hall (27 snapshots) and workshop room (24 snapshots) had the highest number of snapshots in reality and VR, respectively, with the workshop room having higher mean snapshots in both media (M=21.5). The highest variance between reports could be found in the conference hall, where participants in the real environment reported 27 dark scenes against ten scenes in the virtual environment. The entrance hall showed the most consistent feedback across the two media, with 1 scene reported in VR against no scenes in reality.

Table 5: Distribution of snapshots rating per each area in real and virtual environments. (R=Reality, V=Immersive Virtual Environment)

	Very Dark			Dark			Bright			Very Bright			Total Snapshots		
	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R
A) Entrance	0	0	0	0	1	0.5	5	8	6.5	9	15	12	14	24	19
B) Lounge	0	0	0	5	0	2.5	22	17	19.5	16	21	18.5	43	38	40.5
C) Co-work	1	7	4	18	15	16.5	40	49	44.5	54	38	46	113	109	111
D) Conf. hall	23	35	29	27	10	18.5	3	5	4	3	1	2	56	51	53.5
E) Workshop	29	14	21.5	19	24	21.5	1	1	1	0	0	0	49	39	44
F) Kitchen	23	0	11.5	6	8	7	0	8	4	0	1	0.5	29	17	23
G) Fab lab	8	9	8.5	2	7	4.5	0	0	0	0	0	0	10	16	13
H) Meeting	4	0	2	10	18	14	1	2	1.5	0	0	0	15	20	17.5
I) Presentation	1	0	0.5	2	4	3	13	11	12	0	1	0.5	16	16	16

On the other hand, more consistent results across the two environments could be found in “bright” scenes, where the co-work area had the highest number of snapshots in both cases (40, 49 in reality and VR, respectively Mean=44.5). Highly varied results could be found in the kitchen area, where eight snapshots were reported in VR against no reports in reality. On the contrary, participants in both media reported no bright scenes in the fab lab area. Finally, “very bright” scenes were similarly concentrated in the co-work area, emphasizing a mutual perception across real and virtual environments as the brightest area. However, in this case, a significantly higher number of scenes were reported in reality than in VR (54, 38 snapshots respectively), while the fab lab (in addition to the meeting room) maintained the lowest variance between reported scenes in reality and VR, with no scenes reported as very bright in both cases.

5.8.3. Percentage of brightness ratings per investigated area

As the total number of reported snapshots in each area was different across VR and reality, further analysis was needed to fully illustrate the distribution trends of each brightness rating across different areas of the investigated space. In this context, percentages of each brightness rating to the total snapshots in each area were compared (Figure 34). For all the areas combined, the comparison shows that the percentages of brightness ratings to total snapshots were similar across VR and reality for very bright and dark scenes (23.3% and 26.4% in VR, 23.8%, and 25.8% in reality, respectively). However, In VR, participants reported a relatively higher percentage of bright scenes (30.6%) and a lower percentage of very dark scenes (19.7%) than in reality (24.6%, 25.8%, respectively).

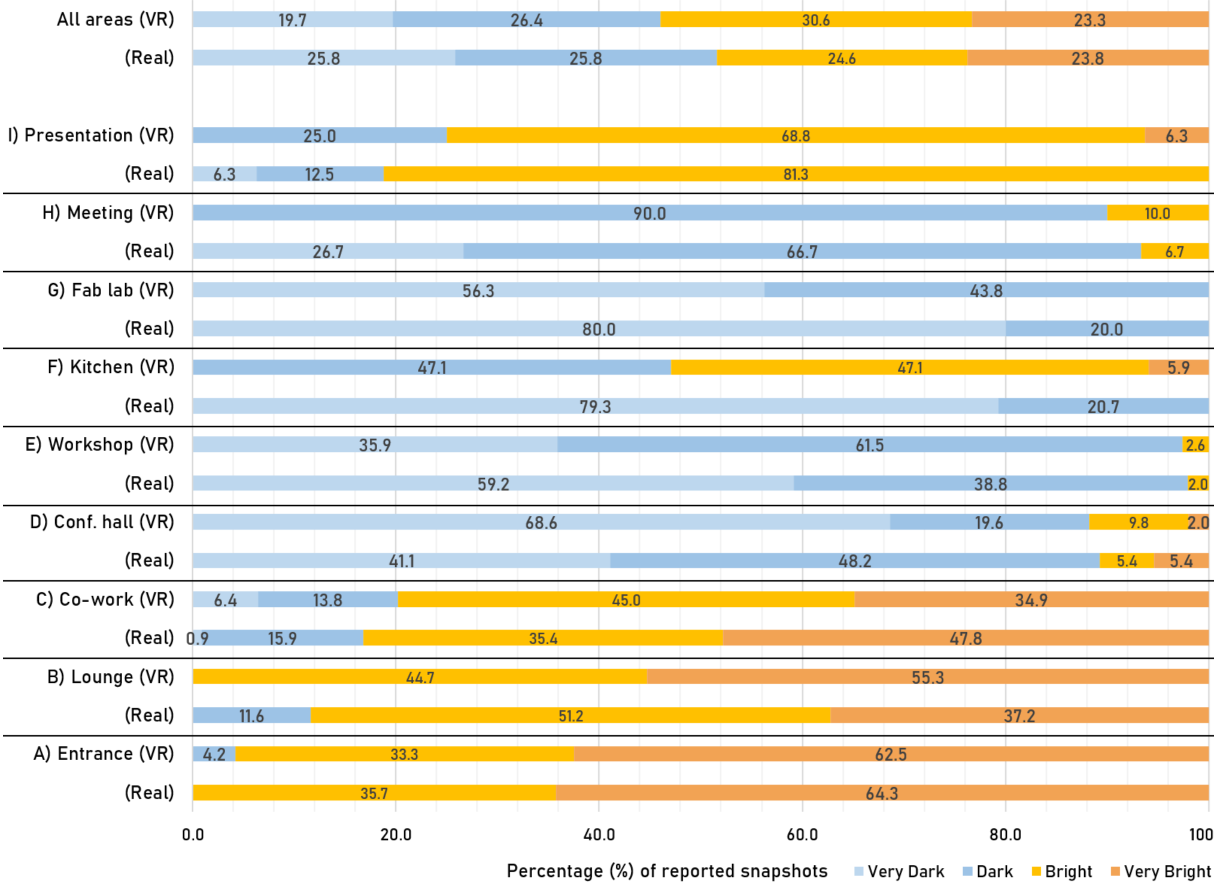


Figure 34. Snapshot distribution percentages by different brightness ratings across each area in reality and VR.

For the entrance area, a high similarity was found between brightness ratings, where very bright scenes and bright scenes comprised 64.3% and 35.7% of the total snapshots in this area in reality, and 62.5% and 33.3% in VR, respectively. For the lounge area, bright and very bright scenes comprised 100% and 88.4% of the total snapshots in VR and reality, respectively. In reality, a small percentage of snapshots (11.6%) were reported as dark, while no dark scenes were reported in the real lounge. A similar constancy in snapshot distribution across VR and reality could be found in the co-work area, where bright and very bright snapshots accounted for 79.9% and 83.2% of the total snapshots, respectively. However, participants in VR reported a notably higher percentage of very dark snapshots (6.4% compared to 0.9% in reality) and a relatively lower percentage of very bright snapshots (34.9% compared to 47.8% in reality).

Unlike the previous three areas, the conference hall showed a majorly higher percentage of dark and very dark scenes in VR and reality. While participants in the real environment reported a balanced distribution of very dark and dark scenes (41.1% and 48.2%), participants in VR perceived the majority of reported scenes as very dark (68.6%), while only 19.6% were perceived as dark. A similar tendency could be found in the workshop area, which is semi-closed, where most scenes were reported as dark or very dark in both environments. The percentage of very dark scenes was higher in reality than in VR (59.2% and 35.9%, respectively). Among all areas, the kitchenette area showed the highest variation between brightness rating perceptions between VR and real environment. In reality, participants reported the vast majority of snapshots as very dark (79.3%), with 0% of snapshots reported as bright or very bright. However, In VR, the tendency of brightness ratings was the opposite, with 47.1% of the reported snapshots as bright, 5.9% reported as very bright, while only 47.1% as dark.

In the Fab lab area, while all scenes were reported as dark or very dark in both environments, a higher percentage of very dark scenes were reported in reality (80% compared to 56.3% in VR). A similar trend was found in the meeting area, where 90% of snapshots in VR were dark, total percentages of dark and very dark snapshots were primarily similar in reality (93.4% combined), with a minority of snapshots rated as bright (6.7% in reality, 10% in VR). Finally, snapshots in the presentation room were majorly rated as bright in both environments, with a relatively higher percentage in reality (81.3% compared to 68.8% in VR). Generally, it could be observed that the distribution of brightness ratings for snapshots in each area followed a similar pattern across the two environments, with the exception of the kitchenette area, where a strong sense of darkness dominated ratings in reality, unlike the mixed ratings distribution in the virtual space.

5.8.4. Perceptual Light Maps

The analysis in Section 5.8.2 illustrated the trends of participants' brightness perceptions in real and virtual environments, observationally showing consistency in perceiving darkness and brightness of a given scene across similar areas in the two environments. In contrast to questionnaires, the self-expressive feedback methodology provided detailed spatial data about participants' positions and target scenes for each response and thus enabled mapping those responses over smaller sections within each of the investigated areas. In a similar context, this experiment aims to quantitatively validate the reliability of the developed IVE system for investigating the perception of daylit environments against physical settings, which necessitates further analysis of participants' responses as quantitative outputs for a more robust statistical comparison.

As discussed in chapter 3, Perceptual Light Maps (PLMs) are proposed as a visualization approach to the collective perception of participants in this experiment. In definition, PLM is similar to a false-color illuminance map, but rather than being based on physical light simulation data, it is based on human brightness perception, represented in the participants' rated snapshots as stochastically distributed sensor points. Participants' responses could be collectively overlaid through this approach to illustrate areas of highly perceived brightness or darkness and confusion areas where participants contradictorily perceive brightness levels of the same scene.

5.8.5. Generating PLMs

Figure 35 shows the framework of generating the perceptual light maps to visualize the participants' collective perceptual reports based on the methodology briefly discussed in Section 3.5. First, the reported snapshots were collected as image files (using the integrated snapshotting tool in UE4 and participant's self-reported photos in reality) and tagged according to brightness perceptions on the 4-point scale. Then, in 3DS Max software, each snapshot was recreated in the 3D model of the test environment as a target camera object, where the position point and the target scene were mapped. The exported images were converted to identical cameras using the "Perspective Match" tool integrated into 3DS Max, which creates a perspective identical to a given image by aligning the vanishing lines of the X, Y, and Z axes, which enabled replicating each reported scene as a camera object with an identical position, field of view, and target.

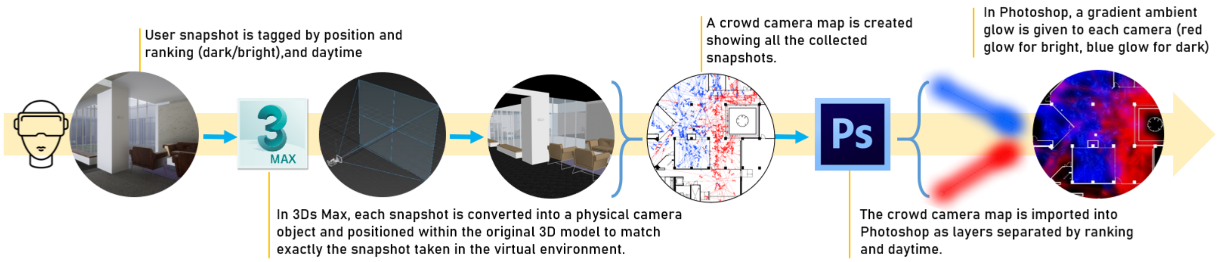


Figure 35: Framework for generating perceptual light maps from participants' responses.

By color-coding cameras of perceptually dark scenes as blue and the bright ones as red, a crowd visualization of all the reported scenes was generated, camera object of each scene was defined by participant's position at the time of reporting, target (center of the surface they were looking at) (Figure 36). Furthermore, each camera object was exported as a wireframe vector image. The generated vectors were positioned as separate layers over a raster image of the test environment floor plan (resolution 28 pixels/centimeter) in Photoshop software, based on each brightness level. A color glow effect was overlaid over each layer at the following settings (Blend mode: screen, Opacity:40%, Spread: 30%). The glow radius was set at 1 meter, based on calculating the average distance between the participant's position and center of the target scenes (6 meters) within the macular vision angle range (18°). The glow color was set at (R=255, G=0, B=0) for scenes perceived as bright and (R=0, G=0, B=255) for the dark ones.

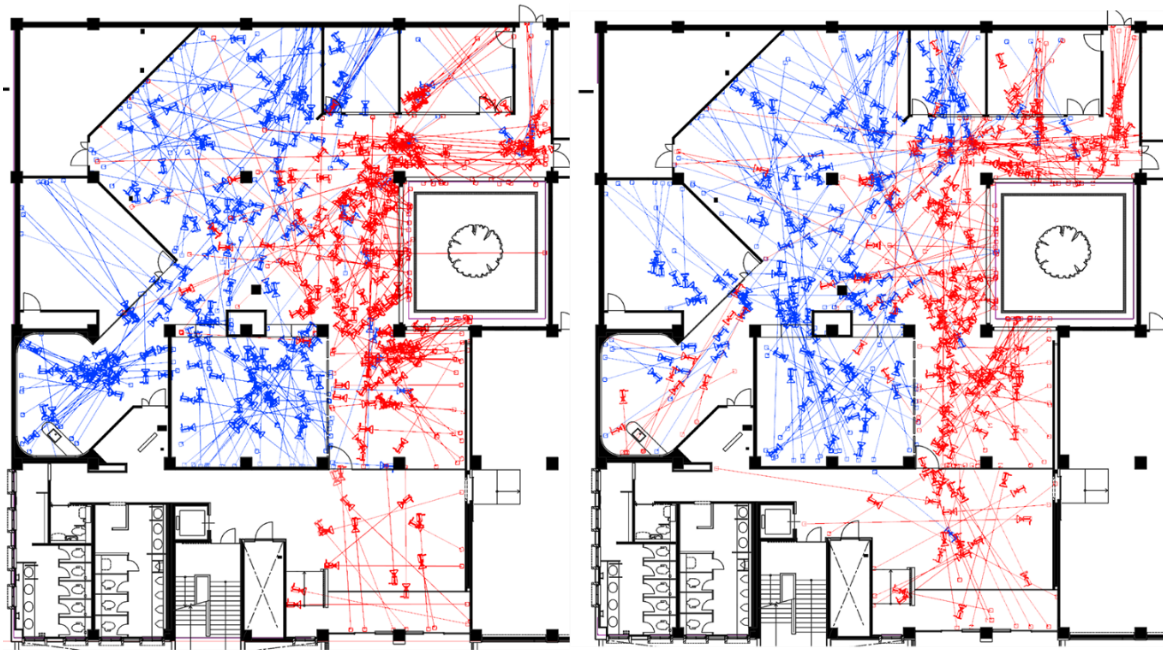


Figure 36: Output camera crowds in reality (left) and VR (right) after mapping participants' position and target points for each reported snapshot.

Layers corresponding to scenes perceived at the extremes of the scale (very dark, very bright) were duplicated to compensate for the intensity of the color glow. Through this approach, areas with a higher number of snapshots with the same brightness were visualized with a more saturated (opaque) color glow. Moreover, areas, where both dark and bright perceptions overlapped could also be pinpointed as "mixed perception areas", where participants perceived the brightness of similar scenes differently (illustrated in violet).

The methodology followed to produce the maps could already generate the full viewing frustum of each snapshot. However, the analysis showed that limiting the attributes visualized in the heatmaps to the camera position, sightline, and target is more relevant due to the following factors:

1) In principle, visualizing the full frustum of each snapshot diminishes the readability of the perceptual light map. As shown in (Figure 37 right), rendering the full frusta of cameras in each reported scene leads to an oversaturated representation, providing no readable information about areas perceived as highly bright or highly dark by the participants. On the contrary, limiting the visualization of the collective feedback to camera position, target, and the connecting line (Figure 37 left) can illustrate high concentration areas perceived as dark or bright (Figure 37, area a and b, many camera targets), as well as areas of high occupancy rates (Figure 37, area c, many camera positions). The sightline also provides visual data on the viewing angles of different reported scenes. For example, in area (b), it can be seen that participants viewed this given wall from different angles, but all reported it as dark. The same implications would apply to the finalized heatmap with the generated glow gradient.

2) In the context of the above point, visualizing the frustum could also lead to a misleading representation of perception. In other words, as the distance between the camera position and target increases, the frustum volume will increase. In most cases, the volume will extend to areas that were not actually in the participant's field of view, shown in area (d) of (Figure 37), where multiple rooms inaccessible to participants are covered within the frusta range.

3) The primary function of the generated maps is to provide an occupant-oriented evaluation of daylighting complementing simulation-based quantitative metrics. In other words, the heatmap does not aim to visualize the full viewing frusta perceived by the participants but to pinpoint the areas of the views/areas of interest where glare-inducing (bright-very bright) or underperforming (dark-very dark) daylighting scenarios may occur, which is illustrated in the experiment procedures where the participants are required to confirm their target of focus for each snapshot as the center of the reported scene. The peripheral view surrounding this target is represented within the macular vision range (18°) but does not include the entire field of view. Therefore, the heat map visualizes the aggregation of multiple target points in proximity, pinpointing the collective perceived brightness of this given area within the test environment.

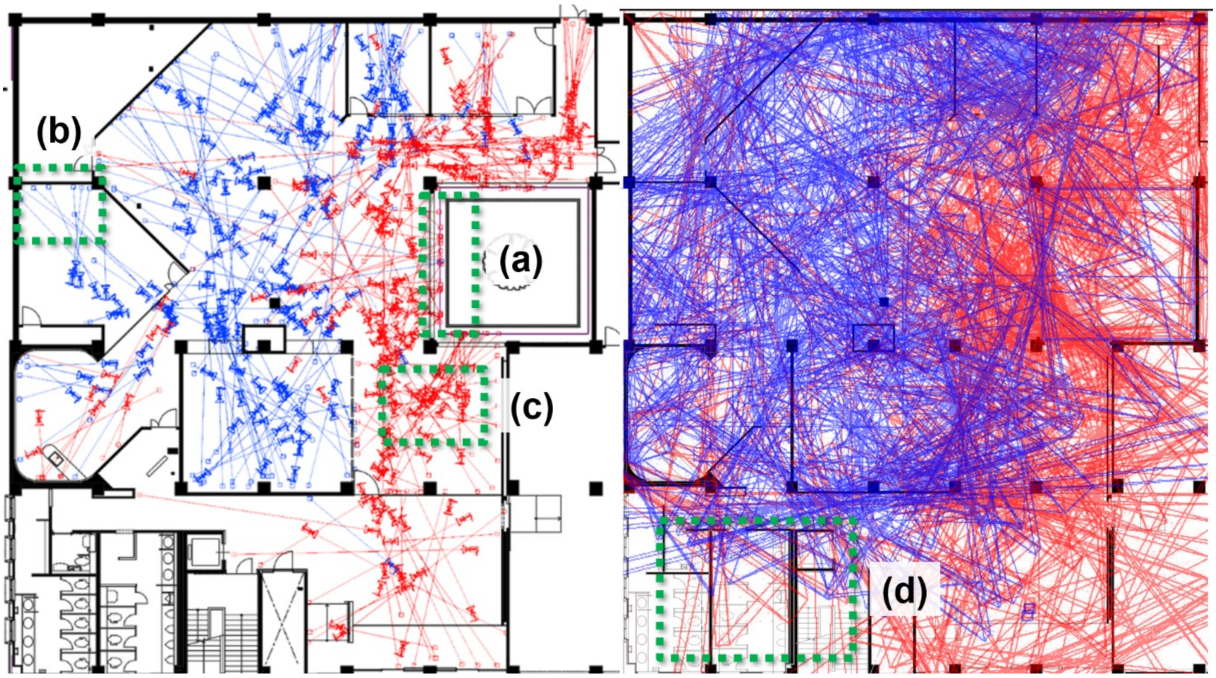


Figure 37: (Left) visualization of the 330 snapshots in VR limited to camera path line, (right) visualization of the snapshots with the viewing frustums. Perceived bright scenes and dark scenes are visualized in red and blue, respectively.

5.8.6. Comparing PLMs in real and virtual environments

As shown in (Figure 38), perceptual light maps could provide a more comprehensive representation of perceived brightness reported by the participants through snapshotting, utilizing the extended set of data acquired from this feedback approach, such as concentration of presence and snapshots at any given point. A broken-down comparison of snapshots in reality and VR by ratings (Figure 39) could emphasize the results acquired in (Section 5.8.2), where a consistent distribution of snapshots could be found in reality and VR among different areas of the investigated environment. The highest density of bright and very bright reported scenes could be found consistently outlining the courtyard in the co-work area and gates at the entrance hall, in both reality and VR. However, for the same area, a denser perception was found in VR. Similarly, a higher density of dark and very dark scenes was reported inside the workshop areas in both media. In the case of the kitchen area, high variance in results could be indicated by the map, where a high density of dark scenes was reported in the real environment, against a lower density of mixed ratings for the same area in VR.

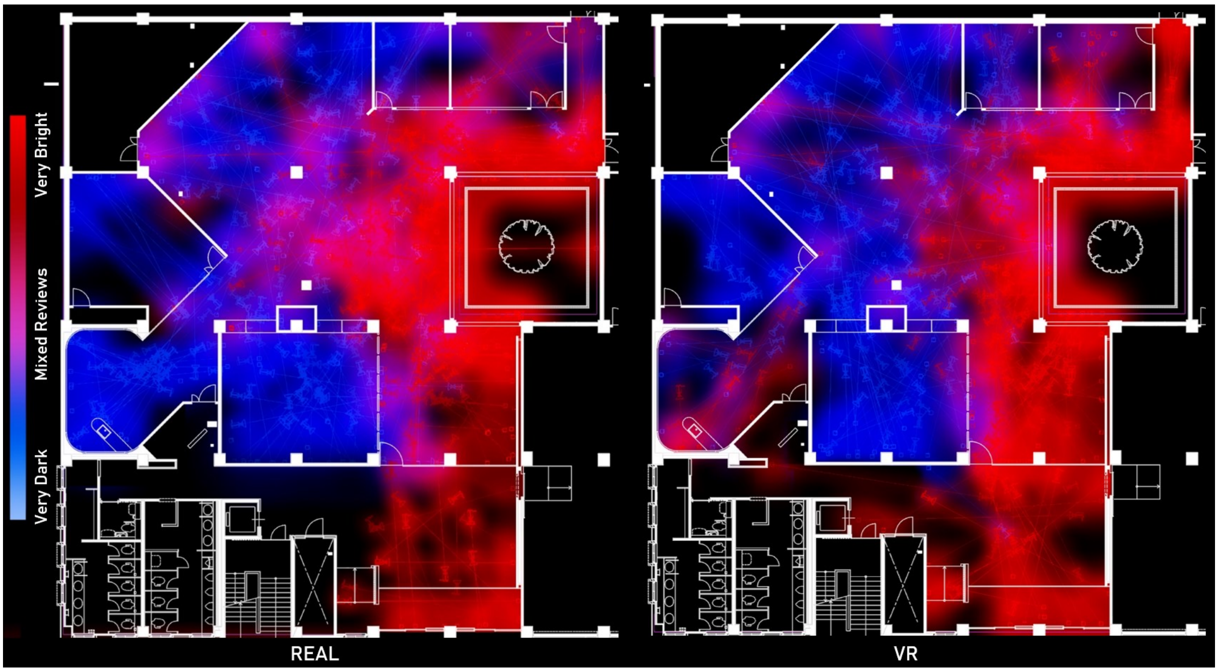


Figure 38: Perceptual light maps in real and virtual environment

Building on the comprehensive data provided by the generated maps, (Figure 40) shows heat maps isolated by standing positions and target scenes in reality and VR for every snapshot taken. An observational analysis of the two maps could emphasize the higher concentration of standing positions and target scenes around the courtyard, concluding that the participants tended to snapshot target scenes at close distances in both environments. More mixed ratings between dark and bright were found in the real environment at the center of the co-work area, compared to a homogenous pool of bright ratings for the same area in VR.

5.8.7. Quantitative comparison of PLMs in real and virtual environments

As discussed in the previous section, the generated PLM represented brightness levels across different areas of the investigated model, as perceived by the participants through snapshotting. Moreover, it enabled a visual analysis of the trends and variances in scene ratings across real and virtual environments. Since this study investigates the adequacy of immersive virtual environments in subjective assessment of daylit spaces-with a focus on game engines as a real-time simulation tool-, a concrete conclusion on the consistency of participants' feedback in reality and VR necessitated a quantification method of the acquired PLMs for statistically comparable outputs.

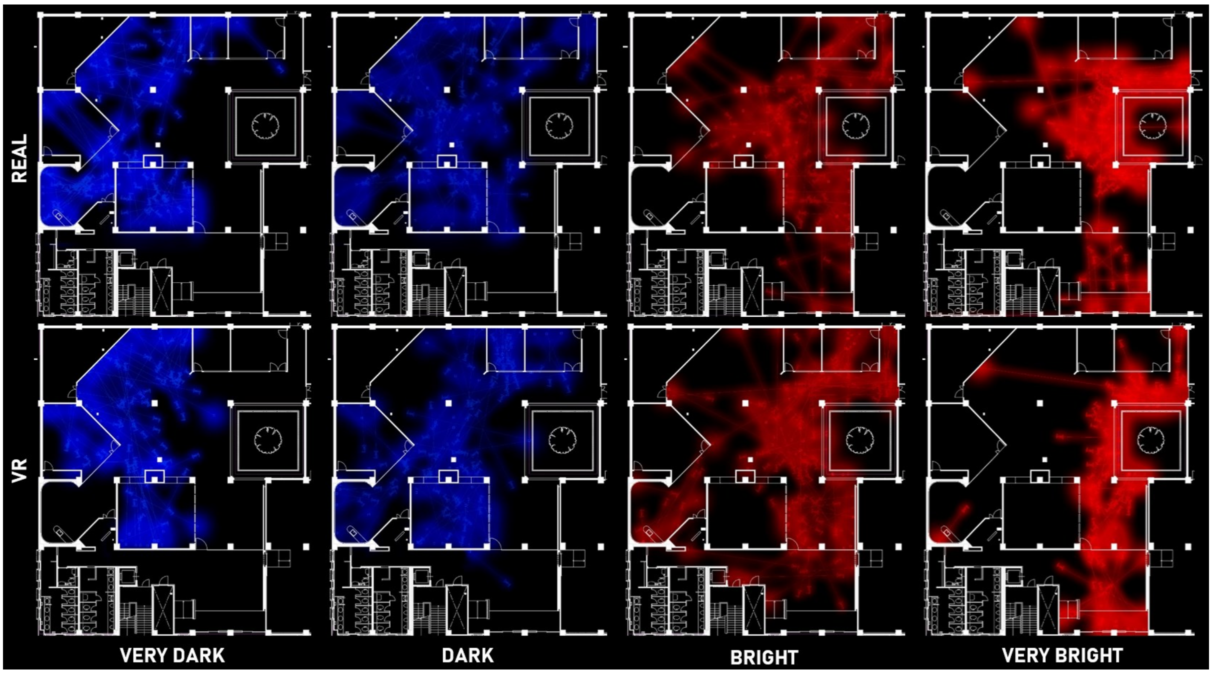


Figure 39: Comparison between perceptual light maps in reality and VR for each ranking point.

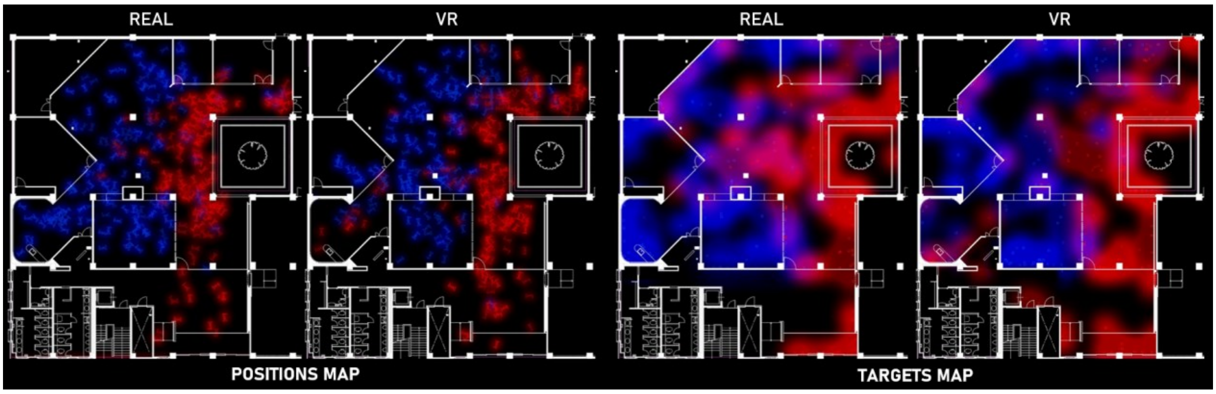
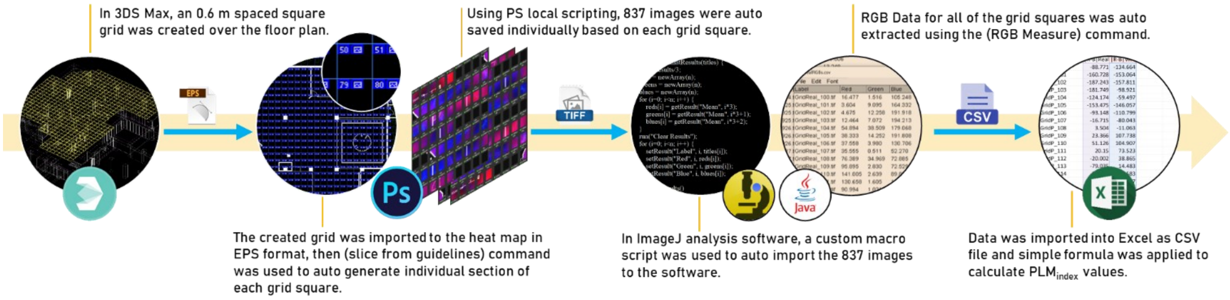


Figure 40: Comparison between perceptual light maps in reality and VR broken down by participants' positions and target scenes.

Data obtained from PLMs could be categorized into two variables: surface area (given point where brightness is investigated) and its perceived brightness (very dark to very bright). In that aspect, brightness values within the PLM are represented by a range of red to blue tones, where a denser color saturation of red or blue would illustrate an area perceived as brighter or darker, respectively. By calculating tonal values of red and blue channels (0 to 255 on RGB scale) through a histogram analysis, a numerical indication on the perceived brightness level could be deduced as the difference between tonal values of red and blue channels for a given area. In this study, such value is proposed as PLM_{index}, which could be calculated by the following equation: $|R - B|.C$, where R and B are the average tonal values of red and blue channels respectively for a given area. As both R and B values have the same tonal range yet opposite perceptions (B=dark, R=bright) C was added as a constant value to distinguish between dark and bright scenes, where C=1 if R>B and C=-1 if B>R. In that aspect, the minimal and maximal values of PLM_{index} ranges from -255 (darkest areas) to 255 (brightest area), representing the spectrum of highly perceived dark and bright areas, respectively.

5.8.8. Data quantification methodology

Figure 41 shows the framework of calculating PLM_{index} values from the generated heat maps. First, in 3DS Max, a calculation grid of 0.6x0.6m spacing was overlaid on the building model. This spacing was selected based on the recommendations of the US Green Council for a calculation grid of no more 0.6m spacing for calculating spatial daylight autonomy (sDA) and annual solar exposure (ASE) (U.S. Green Building Council 2019). This approach generated a set of 837 calculation grid squares over the floorplan, where every square was assigned a unique ID. After overlaying the specified grid over the generated heat maps, JavaScript was used to automatically slice heat maps into square slices as defined by the grid spacing (coded by ID), each as a separate TIFF raster image. In ImageJ software- a scientific imaging processing tool (Abràmoff, Magalhães, and Ram 2004)- a macroscript was created to automatically calculate RGB tonal values for all the exported slices. After omitting G values (green channel), tonal values of red and blue channels were exported from ImageJ as a CSV file. Finally, the PLM_{index} equation (discussed in Section 5.8.7) was applied to the derived values to calculate the final indices across all the grid points in reality and VR.


In 3DS Max, an 0.6 m spaced square grid was created over the floor plan.

Using PS local scripting, 837 images were auto saved individually based on each grid square.

RGB Data for all of the grid squares was auto extracted using the (RGB Measure) command.

The created grid was imported to the heat map in EPS format, then (slice from guidelines) command was used to auto generate individual section of each grid square.

In ImageJ analysis software, a custom macro script was used to auto import the 837 images to the software.

Data was imported into Excel as CSV file and simple formula was applied to calculate PLM_{index} values.

Figure 41: Framework of quantifying PLM data based on reported brightness levels

5.8.9. Comparing quantified perceptual brightness in real and virtual environments

The calculated PLM_{index} represents the collective perceived brightness level at a given area as reported by participants. To investigate the consistency of participants' responses in reality and VR, SPSS software was used to conduct further comparative analysis. As shown in (Figure 42), a scatterplot was created between PLM_{index} values in reality and VR for a total of 703 grid points, after excluding grid points with 0 values (not ranked by participants). Furthermore, a bivariate Pearson correlation test (two-tailed) was conducted (Table 6), where a significant positive correlation could be found between PLM_{index} values in real and virtual environments, with a *p-value* lower than 0.01. The correlation coefficient (*r-value*) was 0.787. According to various studies (Akoglu 2018; Dancey and Reidy 2014; Moore and Kirkland 2007), the resultant *r-value* expresses a strong correlation between variables, suggesting a significant consistency between participants' brightness perception (represented in PLM_{index} values) in real and virtual environments.

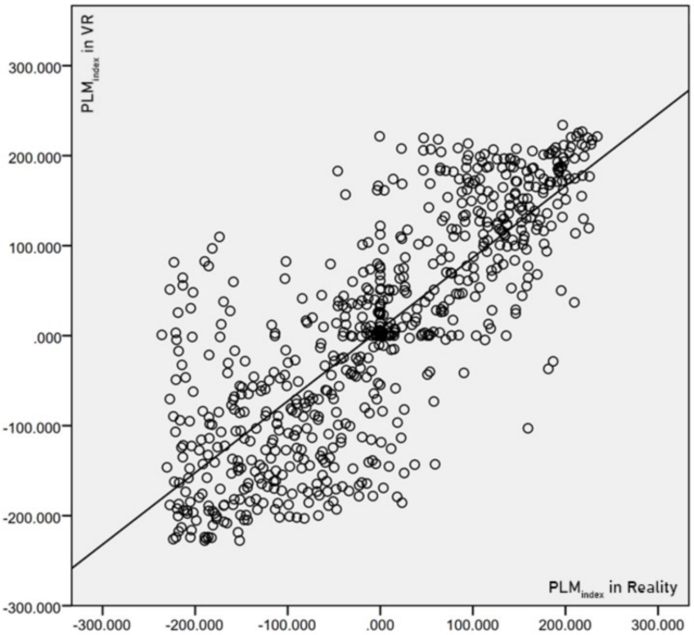


Figure 42: A scatter plot illustrates the correlation between PLM_{index} values of each grid area in reality and VR.

Table 6: Two-tailed Pearson correlation test results between PLM indices in real and virtual environments.

		PLM_{index} Reality	PLM_{index} VR
PLM_{index} Reality	Pearson Correlation	1	.787**
	Sig. (2-tailed)		.000
	N	703	703
PLM_{index} VR	Pearson Correlation	.787**	1
	Sig. (2-tailed)	.000	
	N	703	703

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

5.9. Comparing perception consistency across reality and IVE

In this study, the interactive method adopted to capture brightness perceptions enabled a further interpretation of the participant's occupancy behavior and scenes of interest, which allowed a further investigation on the influence of experiencing the environment in the developed virtual system on the participant's selection of scenes, brightness evaluation, and positioning. A quantitative comparison methodology was discussed in (Section 5.6) to divide the test environment into uniform volumes. Following this methodology, the distribution of participants' positions at each snapshot is illustrated (Figure 43) in a scatter plot. Each data point corresponds to the number of positions in each volume; the x and y axes indicate the physical and virtual environments, respectively. A strong correlation coefficient of 0.85 could be deduced from the scatter plot, indicating that participants experiencing the VR environment behaved similarly to those in the real environment when they positioned for a snapshot.

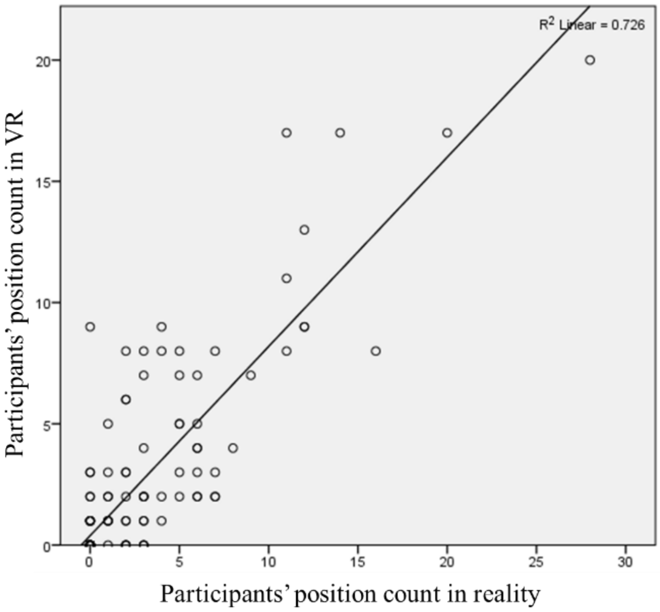


Figure 43: Correlation between the number of participants' standing positions in VR and reality at time of snapshotting, for every cubic volume of the floor plan (R=0.85, N=156).

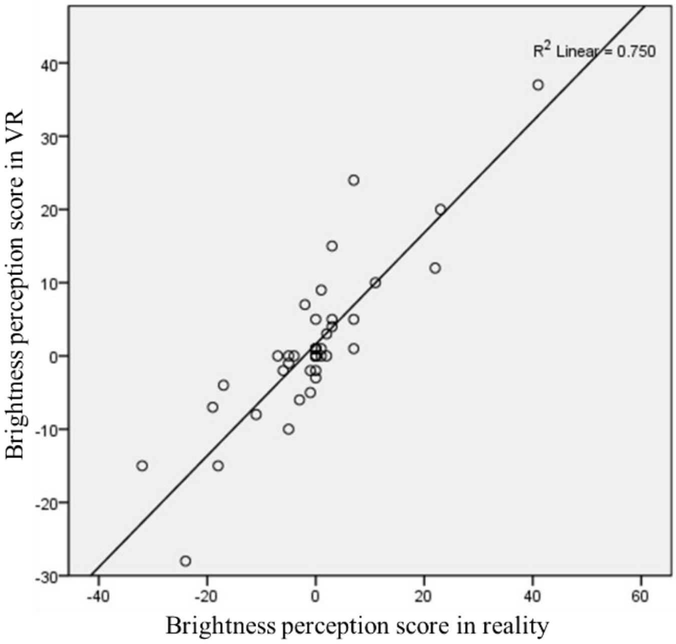


Figure 44: Correlation between brightness perception scores in VR and reality per wall, higher means perceived brighter by more participants (R=0.87, N=46).

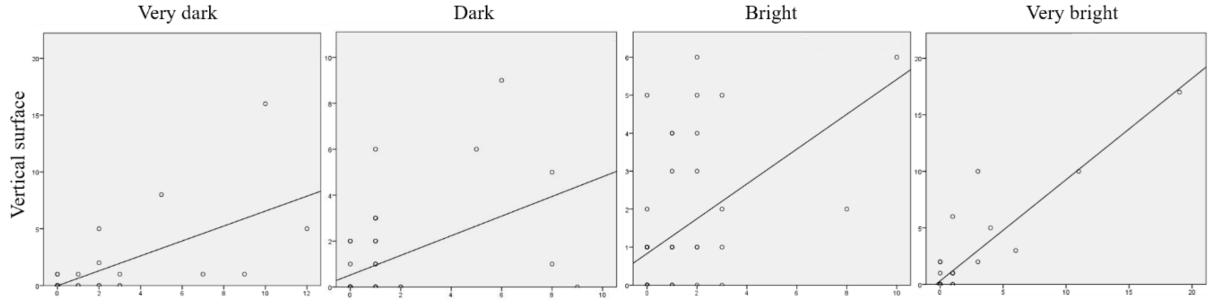


Figure 45: Scatter plot comparing frequency of each brightness perception level in VR (Y-axis) and reality (X-axis), per wall.

Following the aggregation methodology illustrated in (Section 5.7), a correlation analysis was conducted between the perceptual outputs of participants across the two environments. (Figure 44) shows a scatter plot between the unified brightness perception score per wall, where VR and reality scores are graphed on the X and Y axes, respectively. A high correlation coefficient of 0.87 was found between perceptions across reality and VR. A further correlation study -broken down by each of the four brightness levels-was conducted between scene evaluations in VR and reality (Figure 45). As shown in (Table 7), a high correlation between responses in reality and VR per wall was found in the case of very bright scenes (0.9), followed by very dark scenes (0.67), which indicates that the participants experiencing the virtual environment tend to detect areas of extreme brightness levels (very dark-very bright) similar to those experiencing the real environment. A lower correlation (0.49) was found between responses of mid-brightness levels (dark-brightness). However, as was found in (Table 5), the kitchen sub-area reflected a very high discrepancy between perceptions in the two media. By excluding perceptions within the kitchen from the comparison (six walls), a noticeable improvement in the correlation could be drawn across all brightness levels, with the exception of very bright scenes as the correlation was maintained at 0.9.

Table 7: Correlation coefficient between perception in VR and reality per wall, for each perceived brightness level.

	Very dark	Dark	Bright	Very bright
Walls (N=46)	0.67	0.49	0.49	0.9
Walls excluding Kitchen area (N=40)	0.74	0.53	0.54	0.9

5.10. Discussion

In the presence questionnaire provided for IVE participants, for questions regarding “consistency to reality”, “sense of being there”, and “virtual space as reality”, highly favorable feedback (4 and 5 points) was given at 72%, 78%, and 89% for each question, respectively. These results illustrate a pattern of consistency to the results of a related study conducted by Chamilothori et al.(Chamilothori et al. 2018), where favorable replies were 56%, 60%, and 64% for the same questions, respectively, despite it being a within-subject experiment. Similarly, for the “realistic sense of movement” question, a relatively favorable mean of responses at 3.94 (SD=1.16) was found. In a comprehensive study by Heydarian et al. (Heydarian, Carneiro, et al. 2015) with a larger sample size, the same question drew a mean of 3.12 (SD=0.95). This fair steadiness of results across the two experiments, despite the variance in sample sizes, suggests that the sense of movement in the virtual environment is still facing challenges in providing realistic locomotion techniques. This finding could be emphasized by a post-experiment discussion we conducted with the participants, where a few of them perceived the motion technique in the developed IVE to “need some time to get familiar to”.

A comparison between participants’ feedback in reality and VR showed a fair consistency in the total number of reported snapshots in the two media, which might have been motivated by the fixed starting point at the entrance lobby and experiment time of 20 minutes in both media. This result could also be found among various areas in the building model, where the collective perception of brightness at each area was consistent across reality and VR. However, the kitchen area recorded the highest variance in responses, where participants in VR tended to perceive it as bright in a notable contradiction to a strong darkness perception of it in reality. As the kitchen area was the farthest from direct daylighting, this finding encourages more investigation of game engines' limitations in simulating multiple light bounces and global illumination techniques of indirectly daylit environments (Meneghel and Netto 2015).

Additionally, the proposed perceptual light maps represented an occupant-oriented visual approach to pinpoint areas of needed attention regarding daylight design during conceptual stages, without the need to scroll through each data point provided by users. It is essential to state that these subjective heat maps are not meant to replace other known quantitative metrics in lighting design but to support them. The further quantification of spatial data provided by these heat maps has enabled a statistical comparison between perceptions across real and virtual environments.

The strong positive correlation found between reported perceptions in reality and VR suggests the potential of the developed IVE system (and subsequently the employed game engine) to represent luminous environments in VR at different lighting conditions accurately and thus to stimulate the same perceptual responses to light intensity. This consistency would complement the findings of the related studies by Chamilothori et al., and Heydarian et al. (Chamilothori et al. 2018; Heydarian, Carneiro, et al. 2015), where aspects of subjective perceptions, reading performance and sense of presence were investigated in IVE, and an identical physical environment and no significant differences were found between responses in both settings, stating the reliability of IVE as a tool to measure end-user behavior and gain feedback to enhance design evaluation. This result also aligns with the positive findings by Natephra et al. (Natephra et al. 2017) in their validation of the accuracy of light simulation in Unreal Engine against sensor measurements. Despite this body of evidence, we yet argue not to generalize these findings given the urge for a broader range of sample sizes, independent variables, virtual environment types, sky conditions, and comparative studies for other types of subjective responses other than brightness perception.

An approach to visually represent the spatial evaluative data was developed to pinpoint areas of needed attention regarding daylight design during conceptual stages, without the need to scroll through each data point provided by the participants. However, it is essential to state that the developed visualization does not replace the quantitative metrics in lighting design (e.g., horizontal illuminance), but further supports them. Moreover, the further quantification of spatial data provided by the developed visualizations has enabled a statistical comparison between perceptions across real and virtual environments. A robust positive correlation could be found between the aggregated brightness perception of each wall in reality and VR. A categorized correlation study by each brightness level showed a similar strong consistency on the extremes of the scale (very dark and very bright) and a lower consistency for middle anchors of the scale, whether the comparison was calculated for all walls or with excluding the kitchen area.

This finding can highlight a potential limitation of the system, where it can adequately represent extreme luminous environments but lacks the dynamic range to reflect environments with low contrast in brightness. In addition, it was found that the participants in VR were positioned similarly to those experiencing the real environment at each scene snapshot, showing that being in a virtual environment did not motivate users to follow different exploration behavior than those in reality.

The concluded consistency between the perceptual outputs in VR and reality complements the findings of the related studies by Chamilothori et al. and Heydarian et al. (Chamilothori et al. 2018; Heydarian, Carneiro, et al. 2015). In these studies, the aspects of subjective perceptions, reading performance, and sense of presence were investigated in IVE, and an identical physical environment and no significant differences were found between responses in both settings, stating the reliability of IVE as a tool to measure end-user behavior and gain feedback to enhance design evaluation. This result also aligns with the positive findings by Natephra et al. (Natephra et al. 2017) in their validation of the accuracy of light simulation in Unreal Engine against sensor measurements. However, we argue not to generalize these findings given the urge for a broader range of sample sizes, independent variables, virtual environment types, sky conditions, and comparative studies for other types of subjective responses other than brightness perception.

5.11. Conclusions

In this chapter, the perceptual accuracy of the proposed IVE system and perception evaluation method was validated. Two groups explored and evaluated daylight perception in real multi-purpose space and its digital replica as an IVE. The following findings could be concluded:

1) In a 5-point Likert questionnaire, participants who experienced the virtual space majorly reported a high sense of "being there" (M=4.22) as well as high accuracy of scale representation (M=4.72).

2) Perceptual Light Maps of participants' perceptions in reality and VR were generated and compared, where a significant positive correlation was found (R=0.79).

3) The aggregated brightness perceptions of each wall in reality and VR were compared, where a higher significant positive correlation was found (R=0.87).

The findings in this chapter showed that participants' perceptions and preferences in the developed virtual environment were similar to that in reality, especially in perceiving high lit scenes, suggesting the validity of perceptual accuracy of the proposed method. The following chapter will apply the proposed system and method to a larger-scale case study with special daylighting conditions. The implications and possible analytical studies drawn from this approach will be investigated.

Chapter 6. **An interactive approach to investigate brightness perception of daylighting in Immersive Virtual Environments: Case study of Kimbell Art Museum by Louis Kahn**

6.1. Introduction

The previous chapters investigated the photometric and perceptual accuracy of the proposed system and method. This chapter builds upon the positive results found in the previous chapters regarding the accuracy of the proposed approach through presenting an application to game-engine-based IVEs for measuring brightness perception of daylighting in architectural spaces, 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. A case study on a large-scale art museum was conducted, where twenty-four participants were recruited to collect their daylighting preferences and evaluate the system usability and daylight qualities of the museum. Further analysis of this experiment's outcomes is conducted to evaluate the subjective qualities of daylighting in the evaluated museum compared to quantitative metrics.

6.1.1. 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. This building was chosen as the case study due to the following factors:

1) Its unconventional daylight utilization through the use of cycloid vaults, skylights, and reflectors (Kacel and Lau 2013)
2) Being a public building expands the pool of its potential users to virtually anyone, unlike the limited usability of office environments.
3) 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 few studies have discussed various quantitative and subjective aspects of the luminous environment in Kimbell Art Museum (Kacel and Lau 2013; Pierce 1998; Roginska-Niesluchowska 2016; Varzgani 2015), 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 chapter.

6.1.2. Experiment setting

The designed virtual model followed the detailed spatial planning of the original museum, which comprised six cycloid vaults with a total width of 56 meters and a total length of 96 meters over three bays. The floor plan covered an area of 3380 m^2 and consisted of 6 main areas (main lobby, three galleries, cafeteria, and library) (Figure 46).

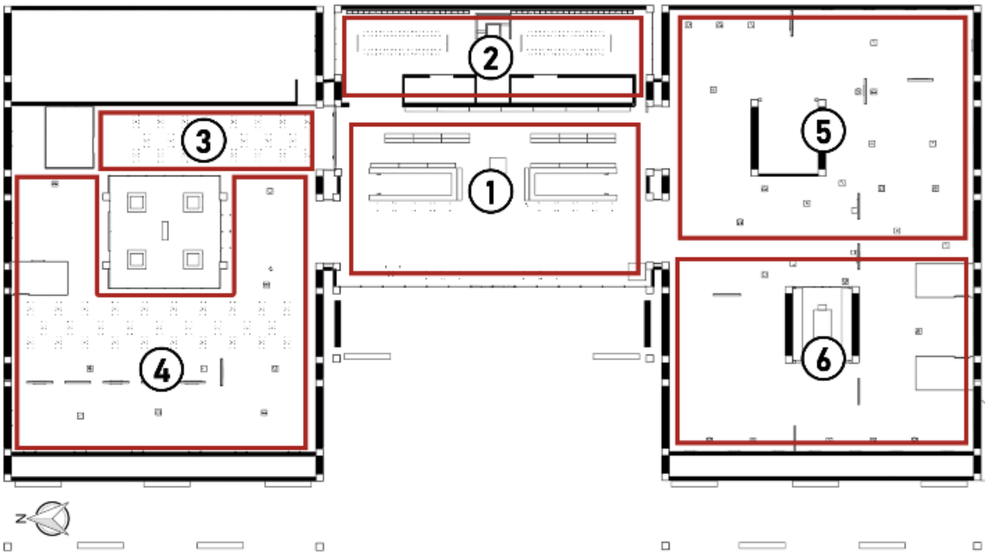


Figure 46: Floor plan of the virtual model showing main areas as follows; 1) Lobby 2) Library 3) Café 4) North gallery 5) South gallery A 6) South gallery B.

Kahn designed the museum in which "light is the theme". Therefore, the architectural morphology of the space was geometrically driven to create a distinctive visual experience of daylighting. To harvest daylighting, each vault had a longitudinal roof opening along its center equipped with narrow plexiglass skylights with wing-shaped pierced aluminum reflectors that hang below to maximize natural light gain on the concrete ceiling (Figure 47, Figure 48 right). Also, walls and arched walls contained narrow light slits. The model had one central courtyard in the north gallery (Figure 48 left) and two small courtyards in the south galleries.

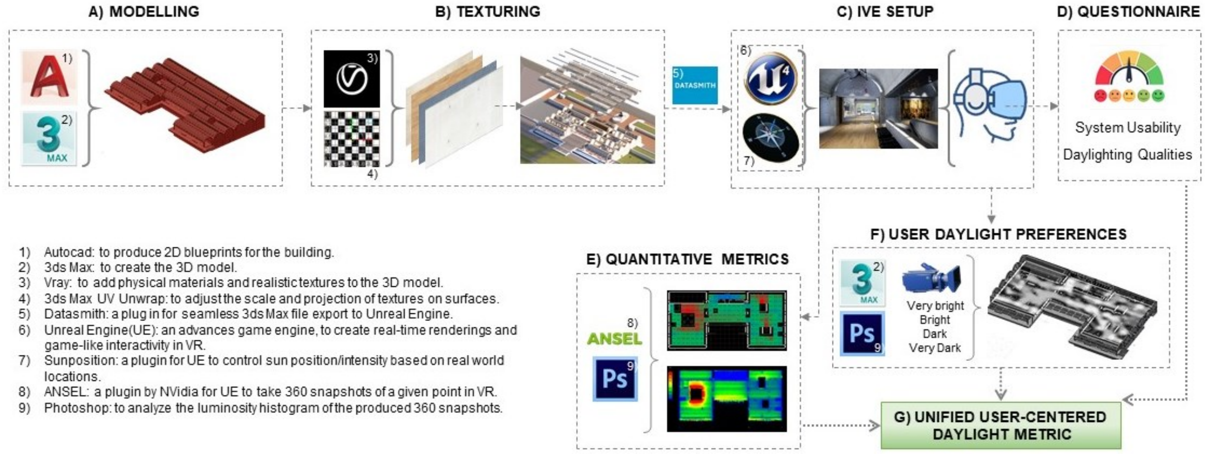
Figure 47: Daylighting strategy in Kimbell museum through light reflector devices (Kimbell Art Museum 2020).

Figure 48: (Left) Close-up for the reflector and vault slit (right) Main courtyard (Kimbell Art Museum 2020).

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 to not distract participants' perception with ambient sunlight from the outside. The experiments took place from March to May 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 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.

6.1.3. Model setup



1) Autocad: to produce 2D blueprints for the building.
2) 3ds Max: to create the 3D model.
3) Vray: to add physical materials and realistic textures to the 3D model.
4) 3ds Max UV Unwrap: to adjust the scale and projection of textures on surfaces.
5) Datasmith: a plug in for seamless 3ds Max file export to Unreal Engine.
6) Unreal Engine(UE): an advances game engine, to create real-time renderings and game-like interactivity in VR.
7) Sunposition: a plugin for UE to control sun position/intensity based on real world locations.
8) ANSEL: a plugin by NVidia for UE to take 360 snapshots of a given point in VR.
9) Photoshop: to analyze the luminosity histogram of the produced 360 snapshots.

Figure 49: A diagram showing the experiment workflow and outputs.

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 49A). 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 (Figure 50).

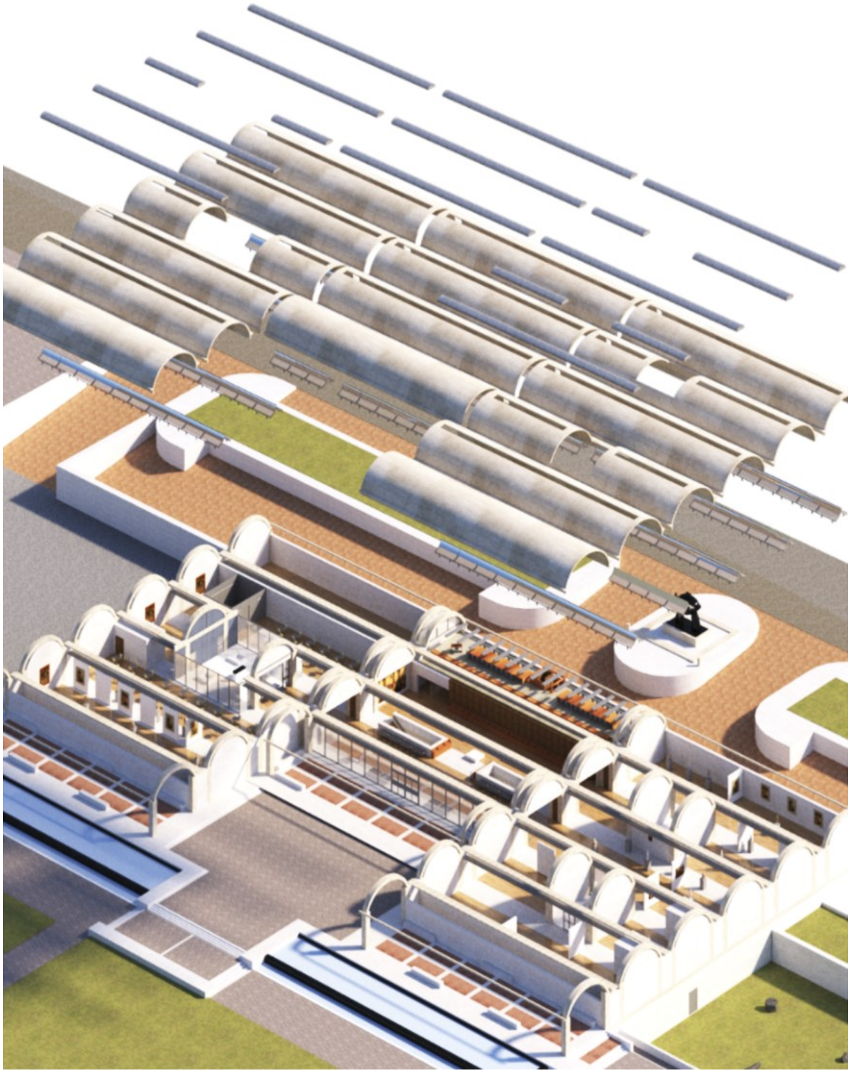


Figure 50: Axonometric of the designed model, showing roof structure and spaces.

Using VRay renderer (ChaosGroup 2021), 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 (Figure 51). Textures were scanned and stitched using a library of photos for the museum's interior, whereas their scales were adjusted using 3DS Max UV mapping tools (Figure 49B).

Figure 51: Preview renderings of the museum model using VRay renderer.

6.1.4. Daylighting setup

After finishing the full textured model in 3DS Max and VRay, 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 or reflective values were recreated from scratch in the UE material editor to ensure accurate light simulation.

For daylighting setup, a single directional light source was used to simulate the sun, linked to a sun position plugin to automatically control intensity, tone, and position of the directional light and sky sphere according to actual location data (Figure 49C). 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 pre-calculated separately at two day times (9 and 18) at the highest lighting quality, and each timing was stored as a different game level (Figure 52).

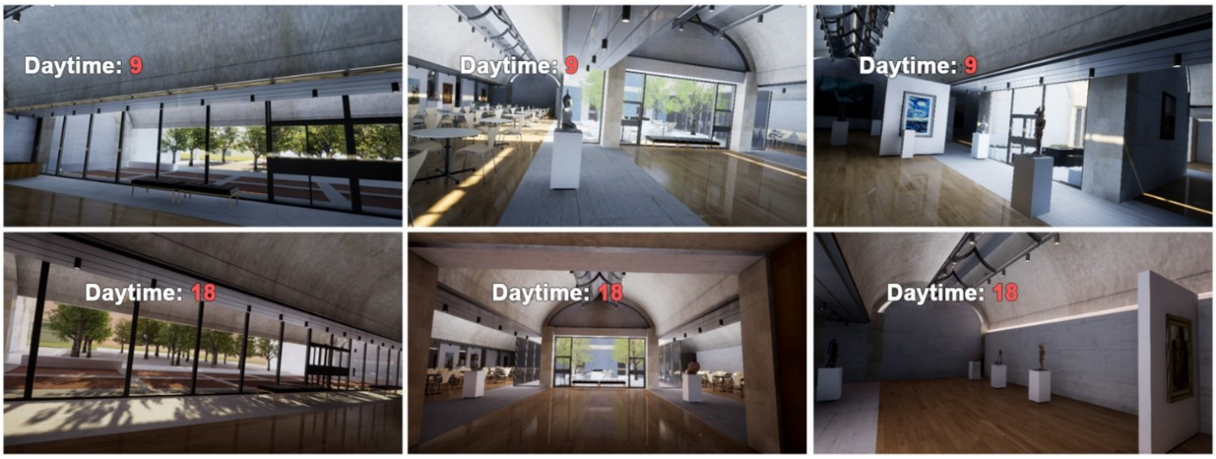


Figure 52: Daylighting conditions in different areas of the virtual museum at the two designated day times.

6.1.5. 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 luminance 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, (Iversen et al. 2013; Labayrade, Jensen, and Jensen 2009). The 3D model was imported from 3DS Max, 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 (Table 8). 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 53). 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 Visualizer was calculated as an absolute value, based on the formula:

$$\frac{|investigated\ value - reference\ value|}{reference\ value} \times 100$$

The maximal error percentage of UE4 rendering was 19.9%, and 25.0%, respectively for 9 am and 6 pm. The average errors were 7.1% and 7.0% for all measurements at 9 am and 6 pm, respectively.

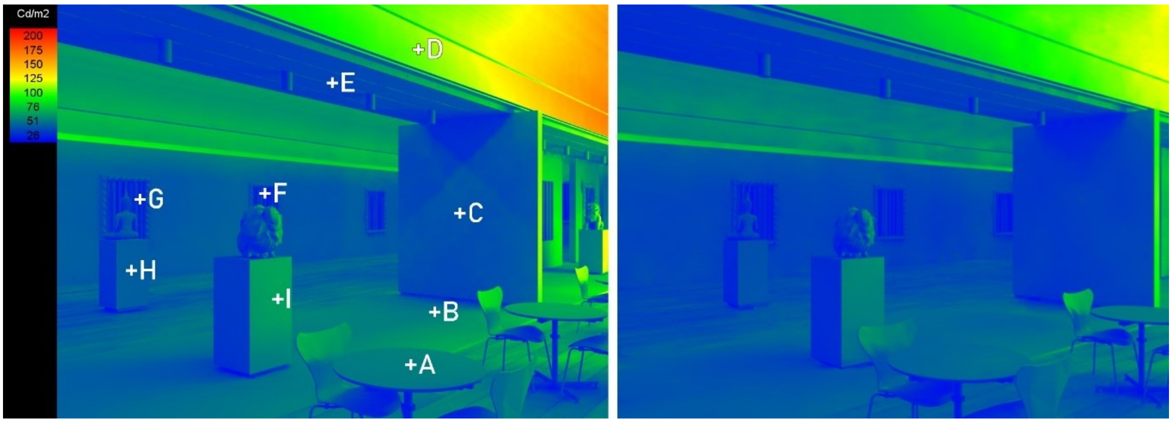


Figure 53: Luminance distribution of an identical scene in Daylight Visualizer (left) and UE4 (right) at 9 am.

Table 8: Luminance in Velux Daylight Visualizer and UE4, showing error percentage of each measurement.

Point	9:00 am			6:00 pm		
	Luminance (cd/m^2)		UE4 error (%)	Luminance (cd/m^2)		UE4 error (%)
	Velux	UE4		Velux	UE4	
A	103.9	97.3	6.4	32.6	28.3	13.2
B	348.9	306.3	12.2	77.6	68.2	12.1
C	430.5	360.8	16.2	96.0	87.8	8.5
D	208.0	193.6	6.9	90.6	81.0	10.6
E	118.7	95.1	19.9	35.2	30.7	12.8
F	36.5	34.1	6.6	12.8	9.6	25.0
G	20.6	19.7	4.4	10.9	11.3	3.7
H	34.4	35.1	2.0	17.1	19.0	11.1
I	53.3	56.8	6.6	12.9	13.5	4.7
Average			7.1			7.0

6.1.6. 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 x 1600 pixels combined screen resolution and 90Hz refresh rate, Vive motion controllers, and two tracking stations were connected to the system.

Participants' daylighting preferences were collected at two daytimes (9 AM and 6 PM) through walking around different areas within the museum and snapshotting the spots they felt brighter/darker than average (Figure 49F). These snapshots were stored in the system and converted to identical cameras in 3DS Max to generate a collective overlook of user-based daylight heatmap comparable with various quantitative daylight (Figure 49E). Also, a post-experience questionnaire was provided to collect participants' evaluation of the usability of the system as well as simulated daylight properties (Figure 49D).

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 49G) to evaluate (and later optimize) daylight performance of architectural spaces in early stages of design, considering both human-related factors and energy/sustainability recommendations.

6.1.7. 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 3 participants were recruited. However, they offered extensive feedback, which helped bypass the system's limitations 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.

6.1.8. Participants

A set of 24 participants (15 males, and 9 females) were recruited in this study. The recruitment was conducted through email invitations to university students. This sample size was found consistent with several previous studies that involved subjective assessments in virtual environments, where sample sizes ranged between 16 and 40 (Abd-Alhamid et al. 2019; Cauwerts and Bodart 2011; Cha et al. 2019; Chamilothori et al. 2018; Franz et al. 2005; Heydarian, J. Carneiro, et al. 2014). For further validation of the selected sample size, power analysis for the study was performed using Wilcoxon signed rank test. A priori power analysis was conducted using G*Power software (Faul et al. 2007). Maintaining a statistical power of 0.8, our sample size of 24 was found adequate to detect medium effects as defined by Cohen (Cohen 1992), with an effect size (Cohen's d) of 0.62.

The participants were 58.3% Master's students and 37.5% Bachelor's students and were aged between 18 to 24 (66.7%) and 25 to 39 (33.3%). While the participants were majorly engineering students, they had limited knowledge of daylight metrics and evaluation, which was essential to ensure unbiased feedback towards the system. For gaming experience, 50% of participants reported they do not play video games at all, while 29.2% play up to 10 hours weekly. Similarly, VR experience among participants seemed to be limited, where 37.5% have never tried an HMD and 45.8% tried it only once.

It is worth mentioning that 3 participants had complained of mild motion sickness after conducting the study. However, all the 24 participants were eventually able to fulfill the needed tasks.

6.1.9. Experiment protocol

First, participants were introduced to a computer-based form, where they were asked to read a brief about the research topic and the evaluation procedures in general and checked a submission checkbox as a consent. Then, they were given a simple questionnaire on demographics, experience in VR and daylight aspects, and physical symptoms to be sure of their physical eligibility. Furtherly, they proceeded to an introduction about the Kimbell Art Museum, including a video walkthrough in different parts of the building. Afterward, they were introduced to a tutorial for motion controls where they were instructed what and how they can control within the IVE. Finally, an explanation of the tasks to be fulfilled in IVE was provided. Participants spent an average adaption time of 10 minutes in the experiment room before wearing the VR headset.

Second, participants were asked to put on the HMD and try a sample scene to get used to the IVE system and controls. The sample scene was designed to resemble the museum model in a simple manner. It was a matte white vaulted space with a main hall, staircase and a small room, where no textures or furniture were applied (Figure 54). In the sample scene, participants were asked to test the motion controllers to do the following tasks: move to the second floor, change scene daytime from 9 am to 6 pm, and finally snapshot what they see. To make use of the system's 6DoF, participants were instructed to stand and physically move within a limited range.

Figure 54: The virtual pilot model used to familiarize participants with the IVE settings and controls.

Third, after participants felt familiar with the HMD and controllers, the full virtual museum model was then loaded. By default, the participants were positioned at the lobby hall in the virtual model at VR time of 9 am. They were asked to use the controllers to move around and explore different areas within the building for 30 seconds. The experiment time in VR was limited to 20 minutes. Moreover, participants were free to finish earlier if they wanted. To accurately capture the time spent inside VR, the system was equipped with a screen recorder whenever the VR model was active (Figure 55).

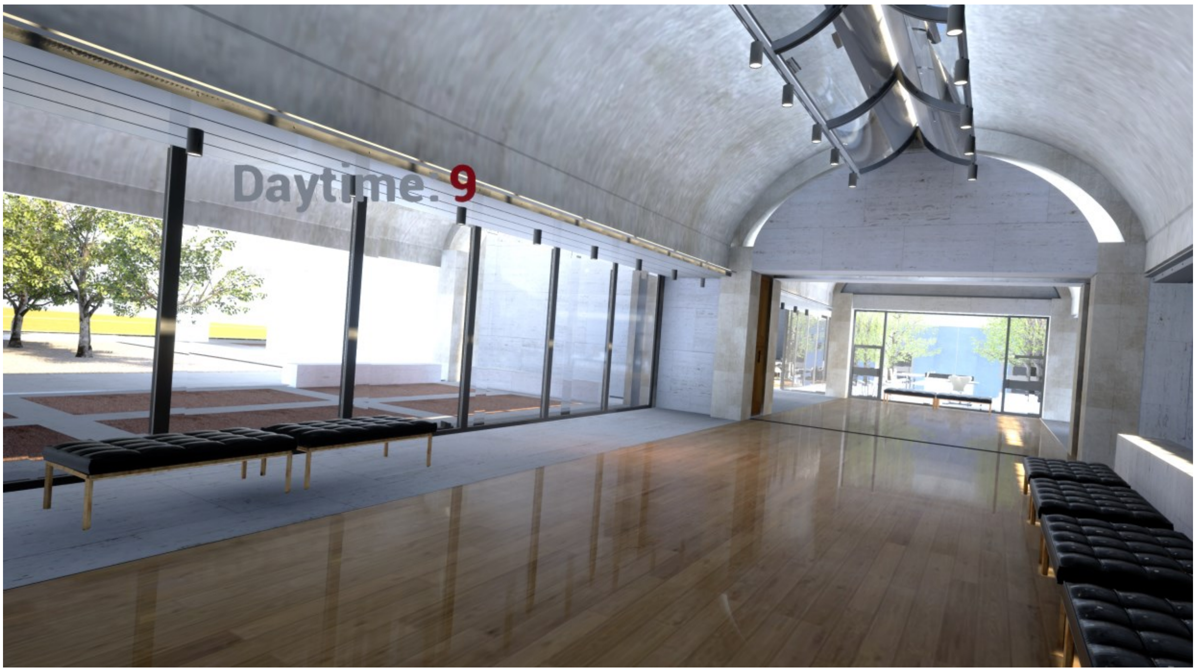


Figure 55: A participant's walkthrough in the lobby area of the virtual museum.

Afterward, participants were verbally instructed 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". Participants were instructed to report at least one dark, one bright spot in each of the six areas they could explore at both scene times. As evaluations had to rely solely on perception, the participants were neither provided any quantitative data on the scene brightness nor asked to estimate a quantitative value for the brightness of their snapshotted scenes. Participants were free to take as many snapshots as they wanted and freely manage to switch between the two scene times. Each time a participant took a snapshot, he/she was asked to verbally report what they meant to look at and their perceived brightness of that snapshot. Once participants finished their tasks, they were asked to take off the HMD. Eventually, they were told that the experiment was over and thanked for participation.

6.2. Perceptual Light Maps

Figure 56 shows the generated PLMs for the virtual museum on scene settings of 23 June, at 9 am and 6 pm as perceived by the participants in immersive VR. Unlike simulation-based analyses, PLMs do not cover all the space within the floor plan, but only highlight the areas reported by users in terms of daylight. As a result, it may directly pinpoint areas that require the most attention for the designer to consider regarding daylight performance (i.e., very dark or very bright areas). The observational analysis of the two PLMs in (Figure 56) can show that at both day times, the highest density of bright snapshots was around courtyards and at the entrance lobby as expected. While the two south galleries showed a high number of reported dark scenes, the library entrance is shown to be the most ranked as “very dark”. Shown in violet, several spots were found to overlap both “bright” and “dark” snapshots. These areas are introduced in this study as “mixed perception” areas, where the same scene at same VR daytime was perceived by one or more participants as bright, while others perceive it as dark (Figure 62, Figure 63). A further quantitative analysis on mixed perception areas would be discussed in Section 6.4.3.

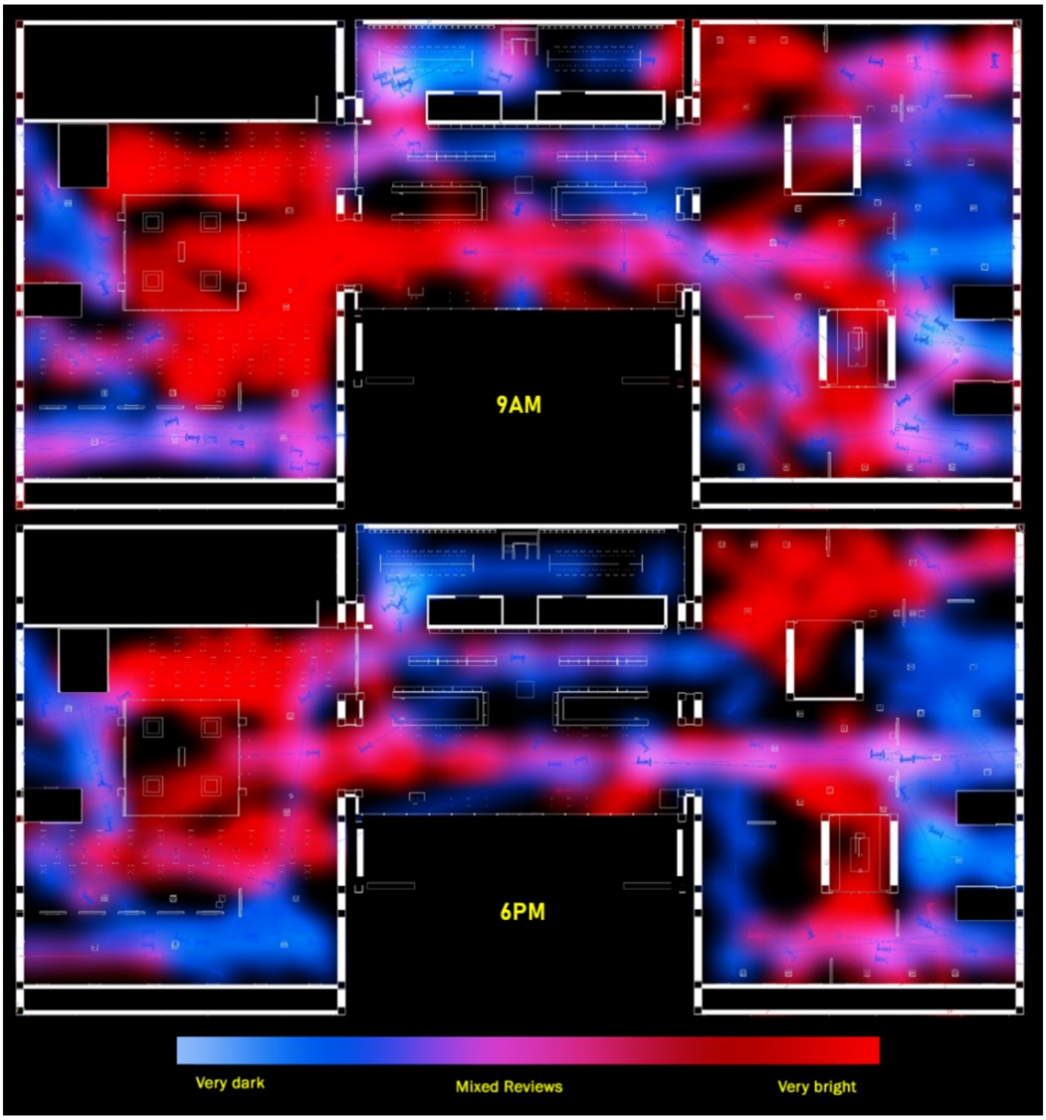


Figure 56: Perceptual Light Maps (PLMs) for the virtual model generated at two VR scene times.

As the generated PLM highlighted several areas of high perceptual concentrations and few contradictions, it also raised a subsequent question of whether a given scene brightness was persistently perceived among participants because they looked at it from the same position/angle. This issue can be interpreted in the context of view direction, which is defined as the location where gaze is directed through the rotation of the body, head, and eye in horizontal and vertical directions (Sarey Khanie and Andersen 2013). In the aspect of daylighting, view direction can affect the vertical lux levels and, subsequently glare perception (Bian, Leng, and Ma 2018; Lou et al. 2016). In this study, the collected data for each reported scene included the view direction (head angle), defined in the camera object created as the line connecting the target scene and the participant's position.

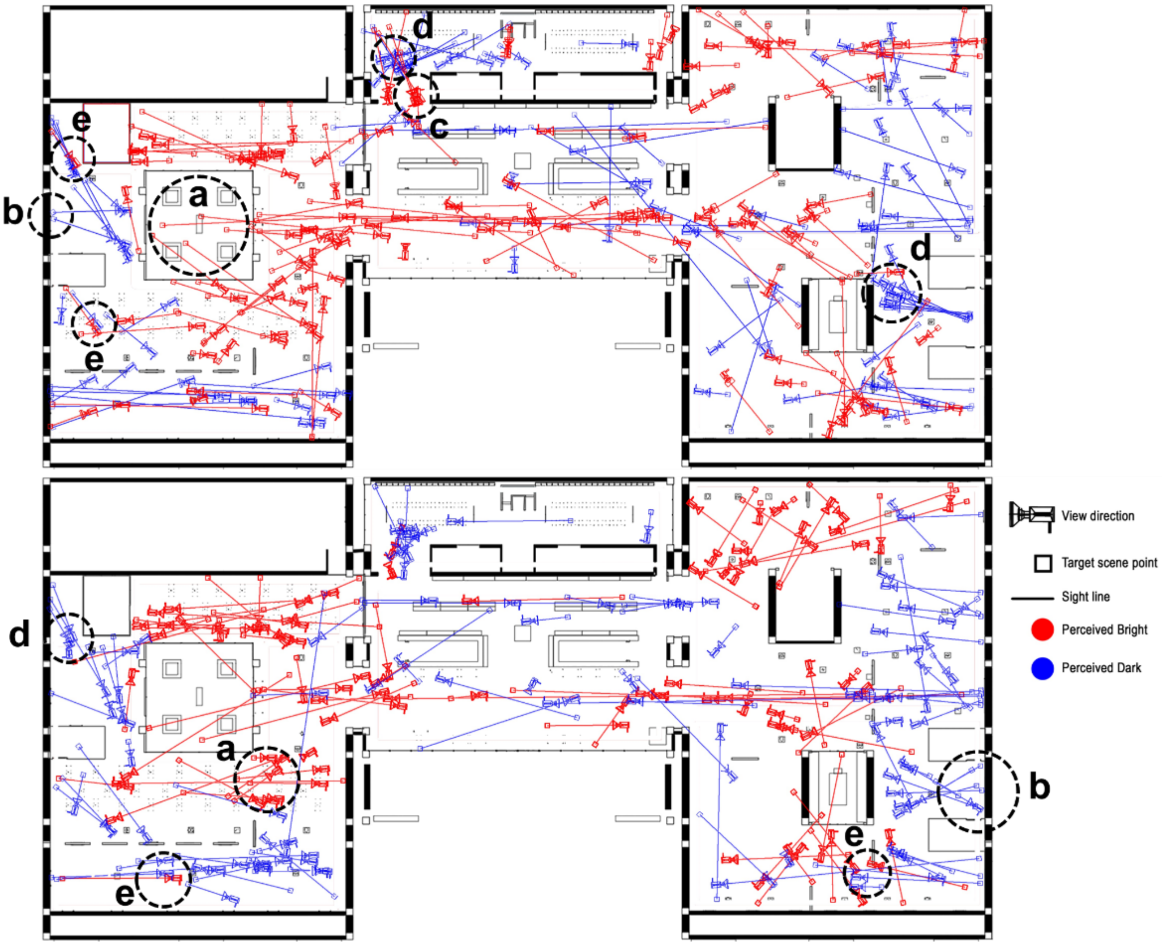


Figure 57: Stochastic visualization of view directions and target scenes at 9 am (upper) and 6 pm (lower).

Comparing view directions is usually more straightforward when the view position is fixed among the viewers. However, the enhanced interactivity in this study allowed the participants to freely walk in and look around the test environment, and thus both the view direction and positions were uncontrolled. To visualize the stochastic nature of the participants' feedback, a collective mapping of target scenes and positions was generated (Figure 57) in an approach similar to the PLMs. The observational analysis of the generated plot can show that, in general, the participants' view directions were scattered widely across different locations and target scenes. By revisiting the areas with consistent brightness perception, such as the courtyard and library entrance, it could be found that view directions and positions varied widely, whether the area is collectively perceived as dark or bright (Figure 57 areas a, b). In fewer areas, consistent bright perception was also accompanied by similar view directions (Figure 57 areas c, d).

Another implication of considering view directions is the interpretation of mixed perception scenes. In other words, whether participants perceived the same scene differently because they looked at it from different directions. As seen in (Figure 57 area e), the view directions of two or more participants were primarily similar in several cases of mixed perception. This finding can also be emphasized by revisiting the snapshots of the reported scenes perceived differently (Figure 63), where a discrepancy between positions and view direction was minimal despite the contractive brightness perception. While the observational analysis of the generated maps in (Figure 56) and the snapshots of mixed perception scenes (Figure 62) suggests that view directions had no effect on the consistency or the contrast of the perceived brightness for a given scene, further quantitative analysis is required before generalizing such findings.

Table 9: The post-experience questionnaire items.

Aspect	Sub-aspect	Question
System Usability	Quality and Immersion	Q1: I felt the virtual environment was consistently similar to the images of the real building.
		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.
		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.
	Interaction Quality	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.
	Comfort	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.
		Q13: Position of the "Daytime" label was convenient.
Lighting simulation perception	Uniformity	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.
	Intensity	Q16: Sunlight intensity was sufficient during the two daytimes.
		Q17: I didn't experience any glare effect (excessive light) inside the virtual space.
	Variability	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.
	Aesthetics and Perception	Q25: I had a pleasant feeling while being in the virtual space.
		Q26: Shadows and shades generated by sunlight gave beautiful patterns on walls and floors.

6.3. Results and analysis

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 (Table 9). In response to Q1 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 58Q1). 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 58Q4).

Regarding system controls, 83.3% of participants found the controllers to be responsive (Q8), while 50% found the system easy to get familiar with 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 a strong agreement (4 to 5 scale points) that the intensity of simulated sunlight was generally sufficient in the two reviewed day times (9 AM and 6 PM) (Figure 58Q16) 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.

6.3.1. 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 56). 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 59 shows the distribution of reported scenes at two daytimes in VR across the main six areas of the museum, ranked from very dark to very bright. Participants produced 419 snapshots in total, with a nearly equal distribution between bright and dark reported scenes (217, 202 respectively) (M=2.52, SD=0.76). However, 14.6% more snapshots were taken at 9 am settings than 6 pm (226,193, respectively). Moreover, the three areas that include courtyards (North gallery and both South galleries) represented 66% of the total scenes perceived by participants.

More scenes were perceived by participants as bright and very bright at 9 am than at 6 pm (58.5%), with the highest density of bright snapshots at both times located in the North Gallery and South Gallery A (26.3%, 22.1% respectively). The North Gallery also had the highest number of dark snapshots at both times (29.7%). On the other hand, the library area recorded 79% of all scenes perceived as very dark at both daytimes, while 39% of the scenes perceived as very bright occurred in the café area.

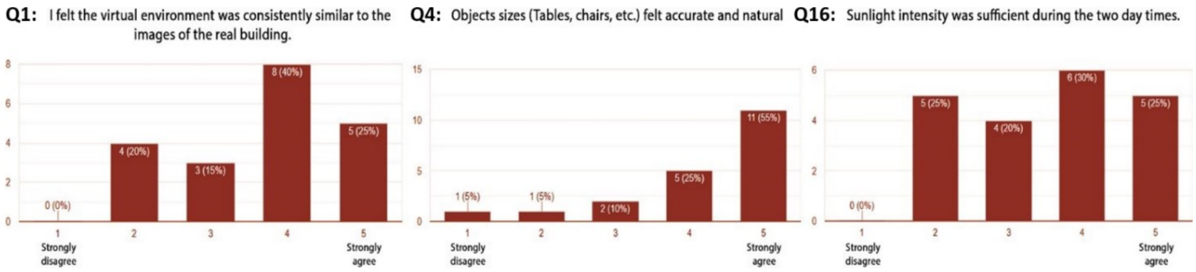


Figure 58: Participants' ratings for system realism and simulated daylighting.

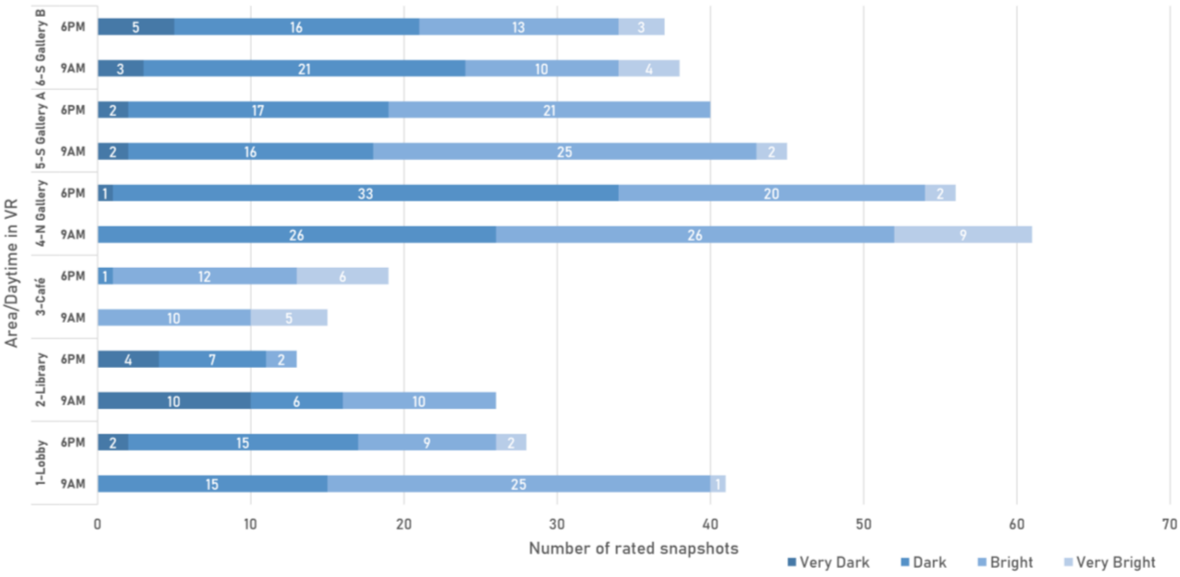


Figure 59: Participants' snapshots distribution at 9 AM and 6 PM.

Figure 60: Sample of scenes perceived by participants as “very bright” (upper row) and “very dark” (lower row) at the two-day time settings.

The perceptual light maps in (Figure 56) shows user daylight evaluation 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" areas (violet color), where participant's perceptions contrasted for the same area/ view, 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.

6.4. Comparing subjective responses against quantitative metrics

As game engines are considered a new medium for daylight simulation, it is necessary to understand the consistency between simulation-based daylight metrics and perceived daylighting in game engine-based IVEs. Besides emphasizing the validation studies on IVE adequacy for daylight subjective assessment (discussed in Section 2.6), consistency between perceived brightness in IVE and corresponding simulations can potentially validate the game engine usability in representing daylight subjective qualities. In hypothesis, a high discrepancy between brightness perception in IVE within this study and the corresponding quantitative metrics would potentially suggest the inaccuracy of the luminous values in the scenes rendered by the game engine, which we hypothesize against. On the other hand, consistent results would not necessarily render the generated perceptual heat maps as redundant, as they still represent a missing human factor in physically-based daylight simulations, and thus hold potential as a supplement tool to the designer to address user perceptions and the potentially problematic areas in daylighting at early stages of design.

As discussed in Section 2.3, various quantitative metrics have been compared to occupant-related daylight assessments, yet some show a low correlation to subjective responses. For instance, the widely used horizontal illuminance may not be reliable as a comparative metric to perceived brightness in this study, as it calculates the quantity of luminous flux falling on a horizontal work plane (e.g., floors, desks). On the other hand, the generated PLMs were based on brightness perception in the field of view of each snapshot through an average evaluation of all surfaces (Figure 61).

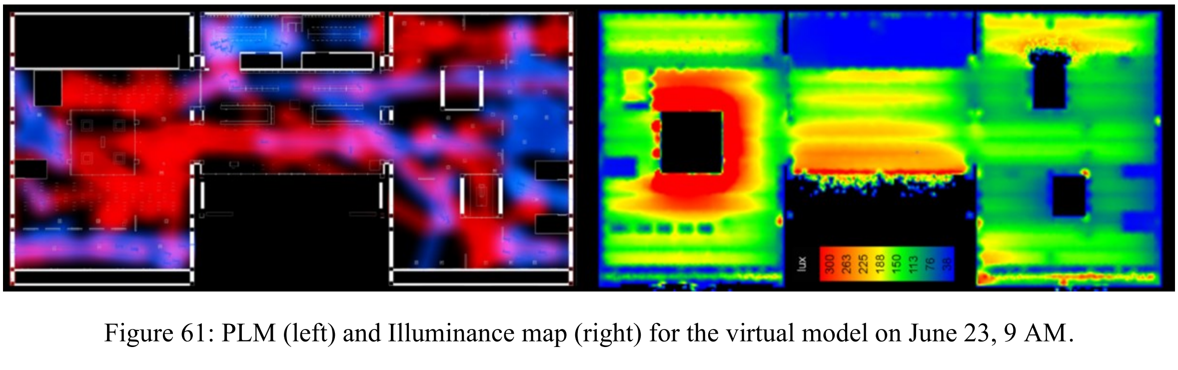


Figure 61: PLM (left) and Illuminance map (right) for the virtual model on June 23, 9 AM.

6.4.1. Mean illuminance and luminance

As discussed in Section 2.3, metrics related to vertical illuminance and luminance showed promise as predictive indicator of perceived lighting. In addition to mean luminance, mean illuminance of each scene was included as it incorporates both horizontal and vertical illuminances and could be one indicator of daylight intensity in each scene. The comparison was set up between the nominal subjective ratings of each snapshot (on the 4-point scale), and its corresponding mean illuminance (in Lux) and mean luminance (in cd/m^2) calculated in a verified simulation tool. To extract validated quantitative measurements for daylighting in each reported scene, an identical digital model of the museum was created in Velux Daylight Visualizer (VDV). Then, each of the collected 419 snapshots in the virtual environment was recreated in VDV as cameras with identical spatiotemporal and view angle settings to its corresponding scene in VR. Then, a false-color rendering was generated to each snapshot, where mean illuminance and luminance of all surfaces were calculated (Figure 64), where the average illuminances and luminances ranged from 0.7 lux to 360.2 lux (M=69.2lux, SD=68.1) and from 0.3 cd/m^2 to 186.1 cd/m^2 (M=33.8cd/m^2, SD=36.3).

SPSS software was used to conduct further comparative analyses. A bivariate Pearson correlation test (two-tailed) was conducted. As shown in (Table 10), at both daytime settings, perception in IVE illustrated a statistically significant positive correlation with mean illuminance ($P<0.001$) with a coefficient (r) of 0.650 and 0.663 at scene settings of 9:00 am and 6:00 pm, respectively. Similarly, a higher correlation coefficient was found in case of mean luminance, with 0.670 and 0.675 at scene settings of 9:00 am and 6:00 pm respectively.

6.4.2. Vertical eye illuminance and luminance distribution

In contrast to horizontal illuminance, vertical illuminance at human eye position can be one indicator of visual comfort and light sensation (Suk 2019) and is often measured at occupant eye's position over different looking directions. In this study, the field of view for each participant was bound to the HMD. Thus, vertical eye illuminance was measured as the average illuminance of the display at each rated snapshot using a luxmeter positioned inside the HMD. Vertical eye illuminances were found between 0.33 lux and 99.1 lux (M= 36.6 lux, SD=24.9). (Table 10) shows that at both time settings, subjective responses were positively correlated with the corresponding display illuminance recorded at eye level. However, the correlation was notably lower in the case of the brighter daytime (9 am), with an r-value of 0.541 compared to that of 0.670 for later daytime (6 pm). Moreover, in a few scenes, reported perceptions were found contradicting with the actual illuminance at the observer's eye (Figure 65). In these scenes, participants tended to perceive high brightness despite the reasonably low display illuminance, and vice versa.

To address this finding, it was crucial to confront mean luminance metrics to luminance distribution to investigate the effects of luminous uniformity and contrast ratios on brightness perception in IVE. In this context, luminance ratio was calculated for every rated snapshot as an indicator of the difference between the brightest and darkest areas in each scene. In VDV, each of the reported scenes was exported as an HDR image maintaining luminance data of the scene. Afterward, Hdrscope software (Kumaragurubaran and Inanici 2013) was used to calculate luminance ratios based on the image-based methodology proposed by Newsham et al.(Newsham et al. 2008) by retrieving the upper 75th percentile and lower 25th percentile number of pixels and calculating the ratio of the mean values of luminance within these regions (Kumaragurubaran and Inanici 2013). Luminance ratios were found between 13.1:1 and 1.8:1 for all the rated snapshots (M=7.4, SD=2.5). As shown in (Table 10), the correlation coefficient between luminance ratio and perceived brightness was found to be 0.468 at 9 am, with a higher correlation coefficient of 0.578 at 6 pm. Thus, luminance ratio showed the lowest correlation with perceived brightness among the four investigated metrics, specifically at 9 am settings.

Table 10: Two-tailed Pearson correlation test results between brightness perception in IVE, mean illuminance, mean luminance, display illuminance at observer's eyes, and luminance ratio at 9:00 and 6:00 pm scene settings.

	Mean illuminance		Mean luminance		Vertical eye illuminance		Luminance ratio	
	9 am	6 pm	9 am	6 pm	9 am	6 pm	9 am	6 pm
Correlation coefficient (r-value)	0.650**	0.663**	0.670**	0.675**	0.541**	0.670**	0.468**	0.578**

**. Correlation is significant at the 0.01 level (2-tailed). N=226 at 9 am and N=193 at 6 pm

6.4.3. Quantitative indicators of "mixed perception" scenes

One of the benefits of the improved interactivity in the developed IVE system was enabling the participants to experience the investigated daylit spaces in full rather than seeing individual still views. As a result, the participants freely explored various areas of the virtual model, changed daytime of the environment at will, and voluntarily selected the scenes that they considered worthy of evaluation in terms of brightness. Thus, this added layer of interaction enabled the acquisition of spatiotemporal data (standing position, target scene, and daytime) over the participants' feedback each time they report their perceived brightness. As one application of this interactive approach, the generated perceptual light maps could visualize the daylight conditions as perceived by the participants, in a collective approach that covers most areas of the investigated floorplan.

As these maps could overlap the participants' perceptions in a spatiotemporal manner, it could pinpoint the areas where perceived brightness among participants contradicted for the same view, hereby referred to as "mixed perception" areas and illustrated as violet areas in the generated perceptual light maps (Figure 56). Through the observational analysis of the perceptual maps and confrontation with reported snapshots at such areas, several scenes where prominent mixed perception occurs could be detected (Figure 63). Across the two investigated daytimes, scenes of mixed perception occurred in all areas of the virtual museum, with the exception of the café area adjacent to the main courtyard, where no major perceptual conflicts could be found.

While the analysis in Sections 6.4.1 and 6.4.2 showed that the perceived brightness by the participants positively correlated with the four investigated metrics in the selected scenes, mixed perception scenes illustrated a set of unexpected responses against this correlation, given that the participants experienced the same luminance and illuminance levels at each of these scenes. Thus, in order to investigate the defining luminous qualities of mixed perception scenes, average values of mean illuminance, mean luminance, illuminance at the eye, and luminance ratio for the detected scenes were confronted with average values of the same metrics across all the scenes reported by the participants in the virtual environment (Table 11). The average values across mixed perception scenes were 52.7 lux, 31.8 cd/m^2, 28.1 lux, 11.63:1 for mean illuminance, mean luminance, illuminance at the eye, and luminance ratio, respectively. Compared to the average values of all reported scenes, mixed perception scenes were found to have noticeably lower values in the case of mean illuminance and vertical eye illuminance (-23.8% and -23.2%, respectively), with much less discrepancy in the case of mean luminance (-5.9%). On the other hand, the average luminance ratio in the mixed perception scenes was significantly higher (56.1%) than that of all reported ones, suggesting that in scenes where mixed perception occurred, the contrast between bright and dark areas tended to be higher than average.

Table 11: Average values of selected quantitative daylight metrics for mixed perception scenes compared to that of all reported scenes in the virtual environment.

	Mean illuminance (lux)	Mean luminance (Cd/m^2)	Vertical eye illuminance (lux)	Luminance ratio
Average values for all scenes reported by the participants	69.2	33.8	36.6	7.45:1
Average values for mixed perception scenes	52.7	31.8	28.1	11.63:1
Relative change	-23.8%	-5.9%	-23.2%	+56.1%

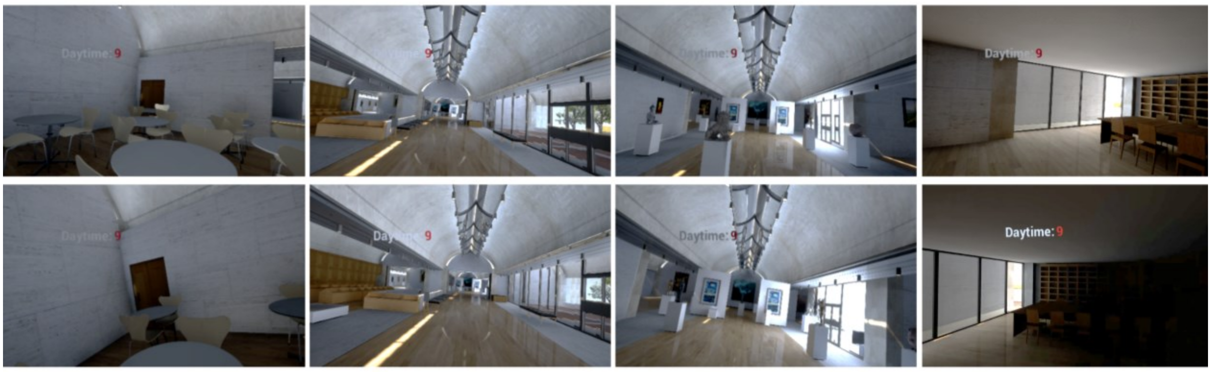


Figure 62: Several areas of mixed perception, where the same scene was perceived as bright (upper row) by at least one participant while perceived as dark (lower row) by others.

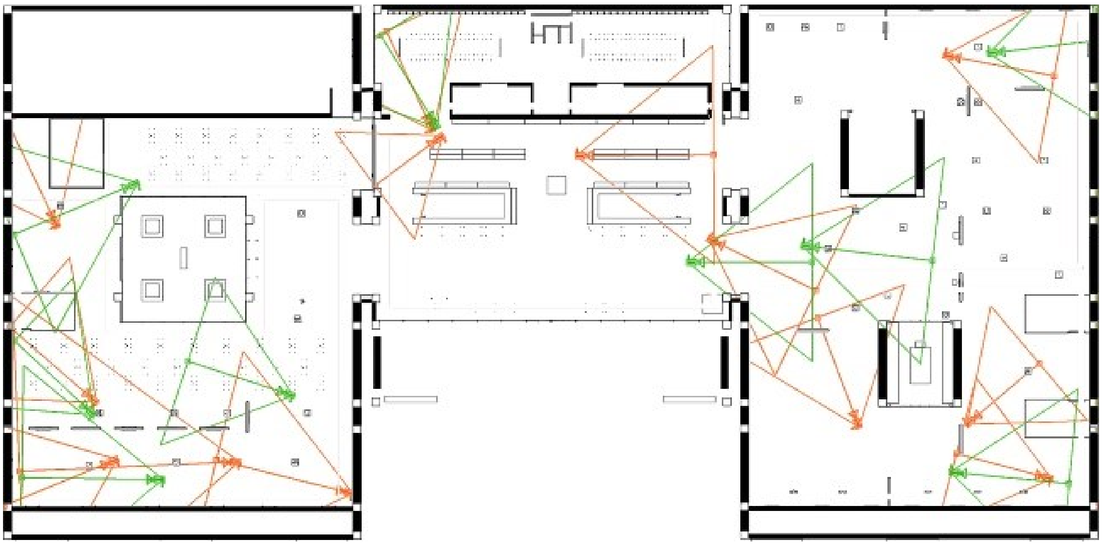


Figure 63: Detected scenes of mixed perception in the virtual museum at 9 am (in orange) and 6 pm (in green).

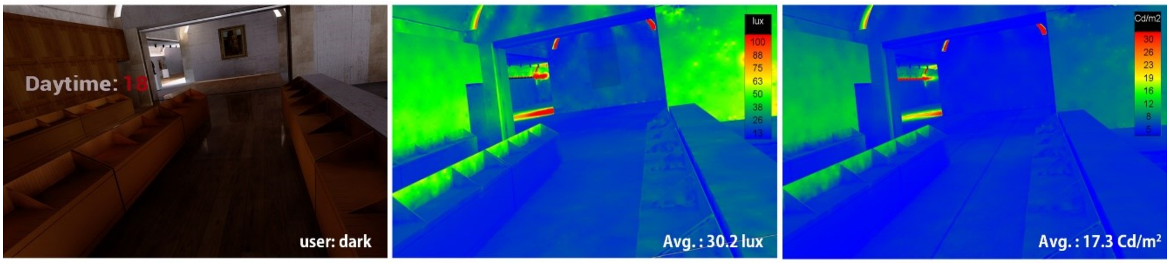


Figure 64: User-rated snapshot in the IVE (left), illuminance (center), and luminance (left) of an identical false-color rendering.

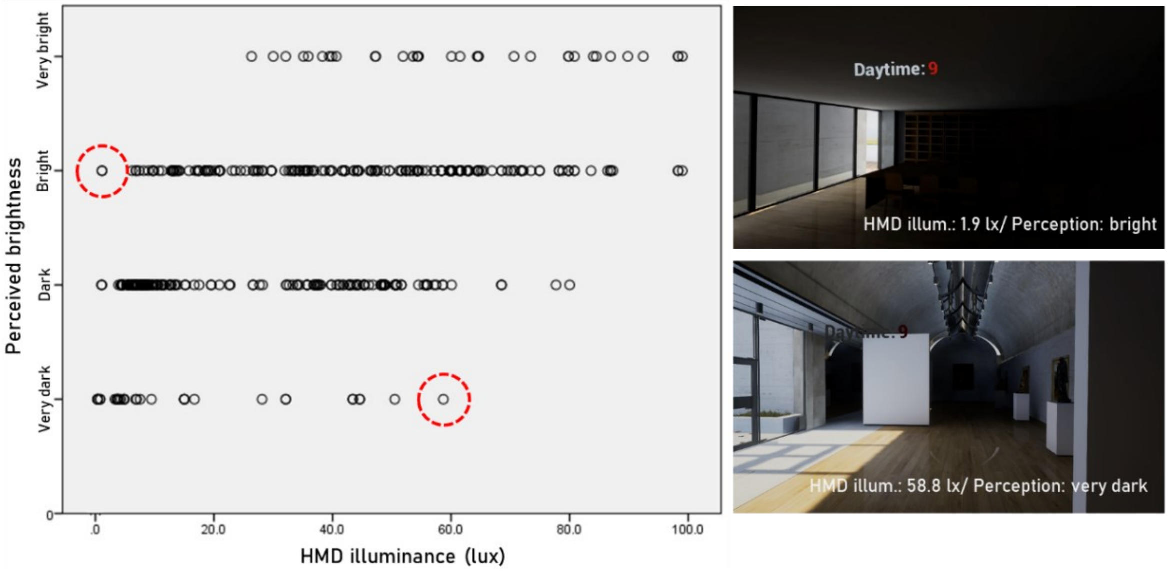


Figure 65: Correlation plot between display illuminance at each snapshot and their perceived brightness (left). The circled points represent two snapshots (right) where participant's perception contradicted recorded display illuminance.

6.5. Analysis of cycloid vaults using PLM data

The cycloid vaults in Kimbell art museum are one of the unique features of its daylighting design. The central slits opened longitudinally through these vaults with the use of reflectors led to the delicate illumination effects of the vaults through reflected sunlight without interfering with the exhibited objects (Park, Joo, and Yang 2007). Using the data provided by the generated PLM, snapshots showing cycloid vaults were surveyed across all participants' snapshots at the two virtual daytimes (Table 12).

Table 12: Distribution of participants' snapshots that show cycloid vaults among bright, dark, and mixed perceptions categories.

	Total		Bright		Dark		Mixed	
	9:00 am	6:00 pm	9:00 am	6:00 pm	9:00 am	6:00 pm	9:00 am	6:00 pm
All snapshots	226	193	127	90	99	103	10	8
Snapshots showing cycloid vault	209	169	118	83	91	86	8	7

In total, cycloid vaults were shown in about 90.2% of participants' snapshots as a major focal point. Similarly, out of the 18 snapshots where mixed perceptions occurred, 15 (83%) snapshots showed cycloid vaults in the center of the participant's field of view (Figure 66). Given this high percentage, further analysis was conducted to investigate whether the high brightness of cycloid vaults was a factor triggering mixed perception effect among participants. The 15 detected mixed perception scenes with cycloid vaults were compared to typical scenes with highly agreed brightness perceptions. In each scene, the ratio between average luminance (cd/m^2) of the vault and that of the other surfaces in the scene was calculated using luminance data provided by the utilized game engine (Figure 67). In scenes of mixed perception, the average ratio between the vault's luminance and other surfaces was found to be 1.21, which suggests that on average, the vault's brightness tends to be equal to or higher than the rest of the scene. In scenes with uniform perceptions, this ratio was found noticeably lower at 0.38, suggesting that, on average, the vault's brightness was low compared to other surfaces in the areas where participants have similar perceptions.

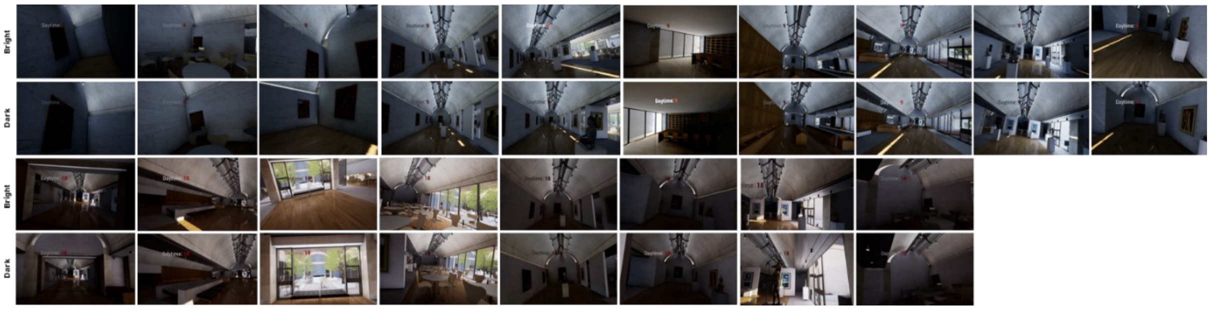


Figure 66: Detected scenes where mixed perceptions occur. In these scenes, participants took similar snapshots at the same daytime but contradictorily perceived brightness of the scene as bright or dark.

Further, a Pearson correlation test was conducted using statistical analysis software to investigate the correlation between high luminance ratios of the cycloid vault and the occurrence of mixed perception. A significant correlation was found between the two variables with a correlation coefficient of 0.593. This finding suggests that the high brightness of the vaults due to the reflected natural light, specifically in scenes with ratios higher than 2:1 (Figure 68), is one potential factor in triggering contradictory perception among participants, and thus the occurrence of mixed perception phenomenon.

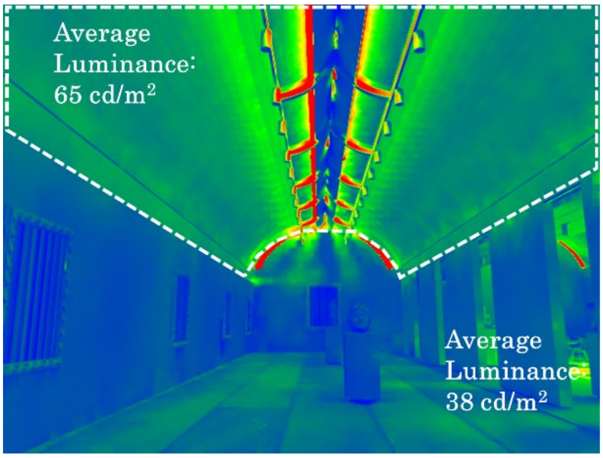


Figure 67: Average luminance of cycloid vaults compared to that of other surfaces in the reported scene.

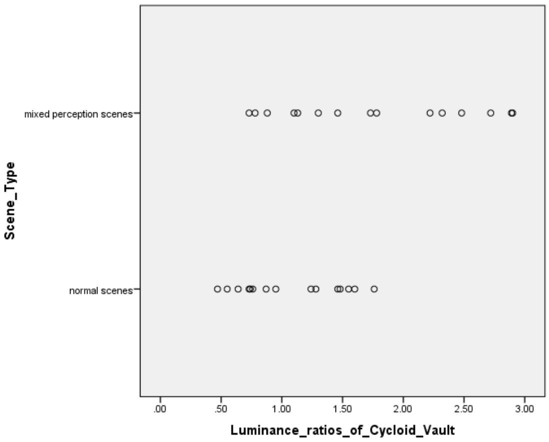


Figure 68: Scatter plot showing the correlation between scene type and luminance ratio of the cycloid vaults.

6.6. Discussion

In this experiment, the proposed IVE 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 et al. 2016, 2018). These advantages emphasize the 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. Several participants reported motion sickness while in IVE. While this is a known limitation of VR (Langbehn, Lubos, and Steinicke 2018), around a 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 experiences 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 valuable resource to investigate users’ “wandering” behavior inside the virtual space and thus to predict 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 several spots, which is inapplicable in quantitative measurements. Mixed perception phenomenon was visualized as violet spots in PLMs. As a lighting metric, PLMs showed consistency with results drawn from quantitative mean brightness values to identify daylight intensity in different areas. Knowing the underlying information that PLMs offer, this finding shows their potential as a supplement to quantitative metrics and their advantages as a rich indicator of daylight performance, of which accuracy is improved as the number of snapshots feedback increases.

Given the limitations of the current VR hardware, specifically in representing high dynamic range environments, it was essential to validate the visualization and evaluation methodologies through emulating an accessible physical space and comparing how significant is the discrepancy between brightness perceptions across real and virtual environments. The strong correlation between the aggregated PLM data per square meter in both environments showed that despite the display limitations, user perceptions of daylight brightness in the developed IVE system were not significantly different from reality. This consistency is also supported by the findings of related research by Chamilothori et al. and Heydarian et al. (Chamilothori et al. 2018; Heydarian, Carneiro, et al. 2015). In these two studies, subjective impressions, reading performance, and sense of presence were investigated in an IVE and an identical physical environment, and no significant differences were found between responses in both settings.

As an application to the developed visualization system and evaluation method, daylighting experience in a virtual model of Kimbell art museum was investigated. Despite the evenly distributed users' responses between darkly and brightly perceived scenes, there was a marginally higher number of responses at the morning time settings. As observed in the post-experiment discussions with participants, this may be partly led by the fact of a generally brighter environment at 9:00 am than that at 6:00 pm in IVE, encouraging more exploration in crisper detailed scenes. However, a concrete finding in this regard would require drawing back to the studies addressing subjective qualities like pleasantness and interest in virtual environments (Chamilothori et al. 2016, 2018). This motivates a more thorough analysis to the factors contributing to user responses, especially contrast and uniformity of lighting.

Following the contribution of melanopsin cells to vision (Zele et al. 2018), melanopic metrics are gaining ground in visual comfort studies related to the built environment, as these metrics are better than the photopic ones in predicting alertness and Melatonin suppression. However, as discussed in Section 2.3, well-established occupant-centric daylight metrics in building design are majorly based on photopic illuminance, namely horizontal and vertical-eye illuminances. This fact is evident when surveying different rating systems for daylighting performance in buildings, where the recommendations are based on Spatial Daylight Autonomy (sDA) and Annual Solar Exposure (ASE), both based on photopic lux. Only one rating system (WELL building standard) has so far introduced Equivalent Melanopic Lux (EML) as a standard of lighting performance in certain types of buildings (Lowry 2018). EML is defined by the photopic lux multiplied by the melanopic ratio of the light source. As this study focuses solely on daylighting, the melanopic ratio is close to 1 (Sangraula and Uprety 2020), and thus the discrepancy between photopic and melanopic illuminances is neglectable. Thus, based on the literature review, this study compared perceptual evaluations of daylit environments to four predominant metrics in visual comfort studies; mean illuminance, mean luminance, vertical eye illuminance, and luminance ratio.

Subjective responses in IVE showed a statistically significant positive correlation with the four investigated quantitative metrics at both daytime settings, where perceived brightness correlated with measurement-based expectation. Amongst the four investigated metrics, mean luminance correlated best with the brightness perceived by the participants in the virtual environment. Moreover, mean illuminance also showed a statistically significant positive correlation with brightness perceptions across the two daytime settings. In that aspect, the mean illuminance was not limited to horizontal work planes but across all the surfaces in the observer's field of view. While these two metrics were simulation-based, the measured illuminance of the display at the eye position was not adequately predictable of perceived brightness in scenes with higher daylight availability, while showing slightly better performance at 6 pm. This finding motivates further investigation of the display brightness limitations within current VR headsets and their impact on user perception of daylighting effects in virtual settings. Finally, among the four investigated metrics, luminance ratio correlated the least with participants' brightness perceptions, where the luminance ratio of each rated scene was not highly representative of participants' brightness rating.

While few studies have addressed mean luminance and illuminance in comparison with brightness perceptions in virtual reality, the findings in this study could be emphasized by a body of research that compared metrics to perception in real environments. In an early study by Parpairi (Katerina Parpairi 2004) on library buildings, a strong correlation could be found between the log of illuminance of the evaluated views and user impressions, while luminance ratio was unsuccessful in predicting perception in the daylit environment. Similar to the findings of this study, Cuttle (Cuttle 2004) stated that luminance-based metrics would show a better correlation to the subjective acceptance and preferences of the lighting environments among occupants rather than illuminance-based ones. Moreover, in a study on office spaces (Van Den Wymelenberg et al. 2010b), scene-based mean luminance produced a strong correlation with user satisfaction of computer screen brightness. In a critical study to pinpoint which lighting metrics are best associated with subjective measures of human visual preference (Van Den Wymelenberg and Inanici 2014), simple luminance and vertical illuminance of the view were more reliable in predicting user satisfaction with vertical surfaces, while luminance ratio did not yield adequate correlation with the subjective visual comfort ratings. Likewise, Manav (Manav 2007) found a strong correlation between mean illuminance levels of walls and desks in a real test room, and user perceptions of comfort, spaciousness, brightness, and saturation. Such studies show that even though the developed system had limitation in display brightness, it followed a similar pattern of matching user preferences in reality with vertical luminance and illuminance metrics rather than contrast ratios.

Despite the correlation between measurement-based expectation and actual answers from participants, there were several scenes where participants gave an unexpected brightness perception for areas of known illuminance and luminance values. Moreover, this discrepancy goes beyond quantitative metrics to include contradictions between participants' perceptions themselves. In these areas, referred to as "mixed perception" scenes, one or more participants would perceive a scene as bright, while others would perceive the same scene as dark. By confronting the average values of the four quantitative metrics at these specific scenes to that of all reported scenes, it was found that luminance ratio was significantly higher than average in areas of mixed perception. While high luminance ratio can be a simple indicator towards glare, the study could not conclude whether every detected mixed perception scene would necessarily have high discomfort glare probability, mainly due to the limited control of various variables within this study as well as the limited luminance range of the current head-mounted displays. Using perceptual lightmap data, the museum's cycloid voids, one of the main lighting features of the building, were investigated as a triggering factor of the mixed perception phenomenon. By comparing average luminance of vaults in mixed perception scenes against scenes of uniform perception, the study found a moderate correlation between the occurrence of mixed perception and the presence of cycloid vaults in the reported scenes.

The results of this study raise awareness of the ability of gaming technologies and techniques to improve engagement and immersion in virtual reality in daylight assessment research. The employed game engine showed a promise in bridging the gap between simulation accuracy and a convincing virtual experience through enabling daylight simulation and tone mapping in real-time. In the same context, using game engines as renderers enabled a more interactive workflow to enhance user experience within the investigated virtual environment through applying gaming principles, such as non-linearity (Collins 2007) and non-invasive goal recognition (Min et al. 2017). These principles, which go in line with the crucial concepts of immersion and interaction, enabled the participants in this study to spend time exploring the virtual environment, "playing" with different settings, and decide which areas they should report. As seen in the produced perceptual lightmaps, this resulted in expressive responses among the participants and, despite its large scale, provided a collective perception of almost all areas of the virtual model.

6.7. Conclusions

In this chapter, 24 participants explored a virtual replica of Kimbell art museum in the proposed IVE system, reported their brightness perceptions of different scenes of interest, and took a questionnaire on various aspects of the space. Perceptions of scene brightness were compared against daylight quantitative metrics; mean illuminance, mean luminance, vertical eye illuminance, and luminance ratio.

The cycloid vaults of the museum were investigated as a source of mixed perception. The following findings could be concluded:

1) The majority of participants agreed on the realism of the virtual model (65%) and positively evaluated scale perception (80%). In evaluating daylighting qualities, participants majorly appreciated daylighting in terms of intensity (75%), tone (79%), and shadow patterns (54%). However, 41% preferred that artificial lights would be used to illuminate the exhibited artwork.
2) Participants' perceptions majorly agreed with the luminance of each evaluated scene, which validates the quantitative accuracy of daylight representation in the system.
3) The responses showed a correlation between perceptions and the four quantitative metrics, with the highest with mean luminance (R=0.670) and the lowest with luminance ratio (R=0.468).
4) The consistency found between quantitative metrics, and PLM outputs may raise the question about the need for PLMs. In this context, data drawn from PLMs can surpass quantitative metrics in the following aspects:
    a. Quantitative metrics measure light amount in a given 2D plan (horizontal or vertical). In comparison, PLMs can indicate the average lightness (brightness) in 3D space due to their reliance on human-field of view.
    b. Quantitative metrics are absolute. In other words, they cannot indicate lighting conditions where occupants can perceive differently. PLMs could visualize these conditions in the form of “mixed perception” areas.
    c. The position data recorded within the PLM can be helpful in investigating users’ “wandering” behavior inside the virtual space and thus predicting views of interest and high-occupancy areas at an early design stage.
5) In investigating scenes that participants perceived inconsistently (mixed perception scenes), lower mean illuminance (-23.8%) and vertical eye illuminance (-23.2%) were found in these scenes than average. Also, luminance ratio of these scenes was significantly higher than the average (56.1%).
6) 83% of mixed perception scenes included the vaults as a central focal composition. It was found that the higher the luminance ratio between the vault and other scene compositions, the higher the occurrence of mixed perception (R=0.593).
7) Analysis of the cycloid vaults showed that the reflected daylighting on the vaults might impact participants' perception of the environment's brightness.

Chapter 7. **Conclusions and future research**

7.1. Conclusions

The aims of this study were three-fold: (i) to propose a novel method to extend the capability of IVE in evaluating daylighting perception in architectural spaces using real-time rendering (ii) to validate the accuracy of the proposed method in terms of perceptions and quantitative measurements (iii) to validate the applicability of the method by a case study, where subjects evaluated a virtual model of Kimbell Art Museum. A summary of the methods and findings of this study is described as follows:

In Chapter 1, a brief background of the study highlighting daylight significance in the built environment and literature on its assessment in IVE was introduced. Furthermore, it comprised the problem statement and research gaps, research objectives, and thesis framework.

In Chapter 2, a narration of the state-of-art was provided, focusing on daylight performance in quantitative measures or occupant-oriented indicators. Principles of immersion and interaction were discussed concerning their influence on user engagement and perception. (IVEs) were surveyed as an effective tool in the subjective assessment of daylighting in the current studies. Game engines as a real-time daylight simulator were discussed.

In Chapter 3, an overview of the proposed methods and systems was provided. It described the interactive virtual environment development framework as well as the evaluative criteria. It also introduced the methodology of developing Perceptual Light Maps (PLMs) as a visualization tool for collecting user perceptions and interpreting the different values of these maps.

In Chapter 4, the photometric accuracy of real-time rendering in game engines for simulating daylighting was investigated. Unreal Engine 4 (UE4) was selected as a case study. Two daylit test models were simulated, and illuminance measurements at several points were compared across the game engine, a validated physically-based renderer (Radiance), and luxmeter measurements in reality. Two simulation techniques were tested in UE4; baked lightmaps and real-time raytracing (RTX) with two quality settings. In one test model, the average error percentage of UE4 RTX outputs was 15.8% compared to sensor readings, while 15% in the validated physically-based renderer. The findings in this chapter showed that UE4 RTX could produce accurate renderings of daylit architectural spaces, with an average error close to the results of validated renderers. Two limitations of this technique were the artifacts (noise) in the produced images and the low framerate. Thus, a hybrid technique combining RTX and conventional baked lightmaps was adopted in the proceeding experiments.

In Chapter 5, the perceptual accuracy of the proposed method in representing daylit architectural spaces was validated. Thirty-six subjects were recruited in two groups to explore and evaluate daylight perception in real multi-purpose space and its digital replica in VR. In a 5-point Likert questionnaire, subjects who experienced the virtual space majorly reported a high sense of "being there" (M=4.22) as well as high accuracy of scale representation (M=4.72). Perceptual Light Maps of subjects' perceptions in reality and VR were generated and compared, where a significant positive correlation was found (R=0.79). In addition, the aggregated brightness perceptions of each wall in reality and VR were compared, where a higher significant positive correlation was found (R=0.87). The findings showed that subjects' perceptions and preferences in the developed virtual environment were similar to that in reality, especially in perceiving high lit scenes, suggesting the validity of perceptual accuracy of the proposed method.

In Chapter 6, the proposed method was applied in a distinctive daylit architectural space. Kimbell Art Museum of Louis Kahn was selected as a case study, where 24 subjects explored a virtual replica of the museum at two virtual daytimes, reported their brightness perceptions of different scenes of interest, and took a questionnaire on various aspects of the space. The majority of subjects agreed on the realism of the virtual model (65%) and positively evaluated scale perception (80%). In evaluating daylighting qualities, subjects majorly appreciated daylighting in terms of intensity (75%), tone (79%), and shadow patterns (54%). However, 41% preferred that artificial lights would be used to illuminate the exhibited artwork.

Perceptions of scene brightness were compared against daylight quantitative metrics; mean illuminance, mean luminance, vertical eye illuminance, and luminance ratio. The responses showed a correlation between perceptions and the four metrics, with the highest with mean luminance (R=0.670) and the lowest with luminance ratio (R=0.468). In investigating scenes that subjects perceived inconsistently (mixed perception scenes), lower mean illuminance (-23.8%) and vertical eye illuminance (-23.2%) were found in these scenes than average. Also, luminance ratio of these scenes was significantly higher than the average (56.1%).

In this context, the cycloid vaults of the museum were investigated as a source of mixed perception. 83% of mixed perception scenes included the vaults as a central focal composition. It was found that the higher the luminance ratio between the vault and other scene compositions, the higher the occurrence of mixed perception (R=0.593). The findings showed that subjects positively evaluated the virtual environment for accuracy, realism and appreciated the simulated daylighting effects. Also, subjects' perceptions majorly agreed with the luminance of each evaluated scene, which validates the quantitative accuracy of daylight representation in the system. The analysis of the cycloid vaults showed that the reflected daylighting on the vaults might impact subjects' perception of the environment's brightness.

In Chapter 7, the findings and conclusions obtained from the whole study are summarized, the limitations of the study are discussed, and future research work is suggested to extend the applicability of the proposed method in architectural planning research.

7.2. Possibilities of research findings in architectural planning

The findings of this research highlight the possible applications of IVE in architectural design as a tool to acquire an occupant-oriented evaluation of various aspects of design proposals in real-time, without the need to construct physical models or advanced architectural literacy of occupants. The capabilities of the developed system can be used to shorten the design revision cycle and let users participate in the decision-making. The analysis of Kimbell Art Museum showed that certain design elements could affect how users perceive the brightness of the architectural space, such as the cycloid vaults. The proposed perceptual lightmaps (PLMs) could provide a collective visualization for brightness perception in large-scale architectural spaces. These maps could highlight the areas architects should address in design for being too bright, too dark, or perceived inconsistently by users, supplementing quantitative metrics such as luminance. Validating the accuracy of raytracing techniques of game engines encourages architectural professionals to integrate this technology into their design thinking and quantitatively evaluate daylighting conditions in the proposed designs.

The conclusions of this research allow the following possibilities regarding architectural planning:

1) Immersive virtual environments can offer architectural planners an interactive tool to evaluate the visual look of design proposals and engage future occupants in the evaluation process in real-time.
2) Using game engines allows the application of immersion and interaction at high levels when exploring the built environment. It also allows the occupants to freely express their scenes of interest in the architectural environment rather than evaluating one given view/scene.
3) The proposed system can enable user-participatory design evaluation in those characteristic spaces that are difficult to evaluate using physical indicators.
4) The generated perceptual lightmaps can help the architects and lighting designers to pinpoint the areas of high brightness (potential glare) or low brightness (inadequate lighting) through the collective perception of a subsample of building occupants.
5) One of the unique outputs of perceptual lightmaps is the ability to detect areas of which brightness is perceived inconsistently among users, termed in this study as “mixed perception” areas. These areas cannot be detected by quantitative simulations and can encourage further research on human factors of architectural design through investigating the relationship between façade elements (skylight, reflectors, windows) and visual perception of the architectural space.

7.3. Limitations and future research

The IVE system proposed in this study provided several enhancements in terms of immersion and interaction. However, further improvements to the system could be proposed; first, integrating different tools (e.g., converting user snapshots in UE4 to camera objects in 3DS Max) could be automated to offer faster workflows. Second, other locomotion techniques in VR, such as teleportation (Langbehn et al. 2018) could be applied to investigate the impact it has on user comfort (e.g., motion sickness). As stated by Chamilothori et al. (Chamilothori et al. 2018), the limited FOV, display resolution, and refresh rate of the current VR hardware may cripple a robust application of virtual reality for accurate perceptual-based assessments. At this moment, few cutting-edge hardware has already overcome these limitations, providing 170° FOV and 8K HDR display (Smith 2020). The adoption of such technologies in lighting research can unlock a further horizon of IVE applications to lighting design and its perceptual aspects. Moreover, further study of different dynamic tone mapping algorithms is needed to investigate their perceptual accuracy under various lighting conditions in IVEs.

In order to broaden the application of the findings in this study beyond the investigated space, further personal factors (age, gender, personality) and environmental factors (experiment time, room temperature) may be considered. Moreover, while the selected case study offered a combination of functions, it yet shows the need to reproduce the experiment on a broader range of case studies at different time settings and different envelope morphology. Adequacy of the developed IVE was validated by comparing brightness perception in VR and an identical physical environment. However, extending this validation process to include more human comfort indicators (e.g., glare and productivity) could shed more light on the limitations of the proposed methodology.

While the selected "between subjects" methodology mitigated the presentation order bias, it meant that the reported perceptions represented the relative brightness of each reported scene. Thus, extending the experiment to a within-subject study with randomization in the order of presentation between virtual and real environment would be helpful to compare whether the absolute brightness of a particular area in the real environment is the same as the perception of that area in a virtual environment. Moreover, considering comparing PLMs with annual climate-based metrics (e.g., spatial daylight autonomy, useful daylight illuminance) necessitates further improvements to the methodology to cover a more comprehensive time range for evaluation and considering the estimated occupied hours for the investigated space.

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 generalize the findings of this study. When surveying candidate museums as a case study of the IVE system, Kimbell museum was selected due to its daylight-based design profile and wide availability of documentation. However, the fact that the actual building was not accessible by the researchers is one limitation of this study. Therefore, we aim to extend the application of the system to another museum building that is accessible, so that luminous measurements and perceptions can be assessed in reality compared to that in simulations. Another limitation to the system is the high record of motion sickness reported by users, making it challenging to sustain user immersion for long times. We aim to overcome this limitation by developing less motion sickness-inducing locomotion techniques (e.g., teleporting) (Langbehn et al. 2018)).

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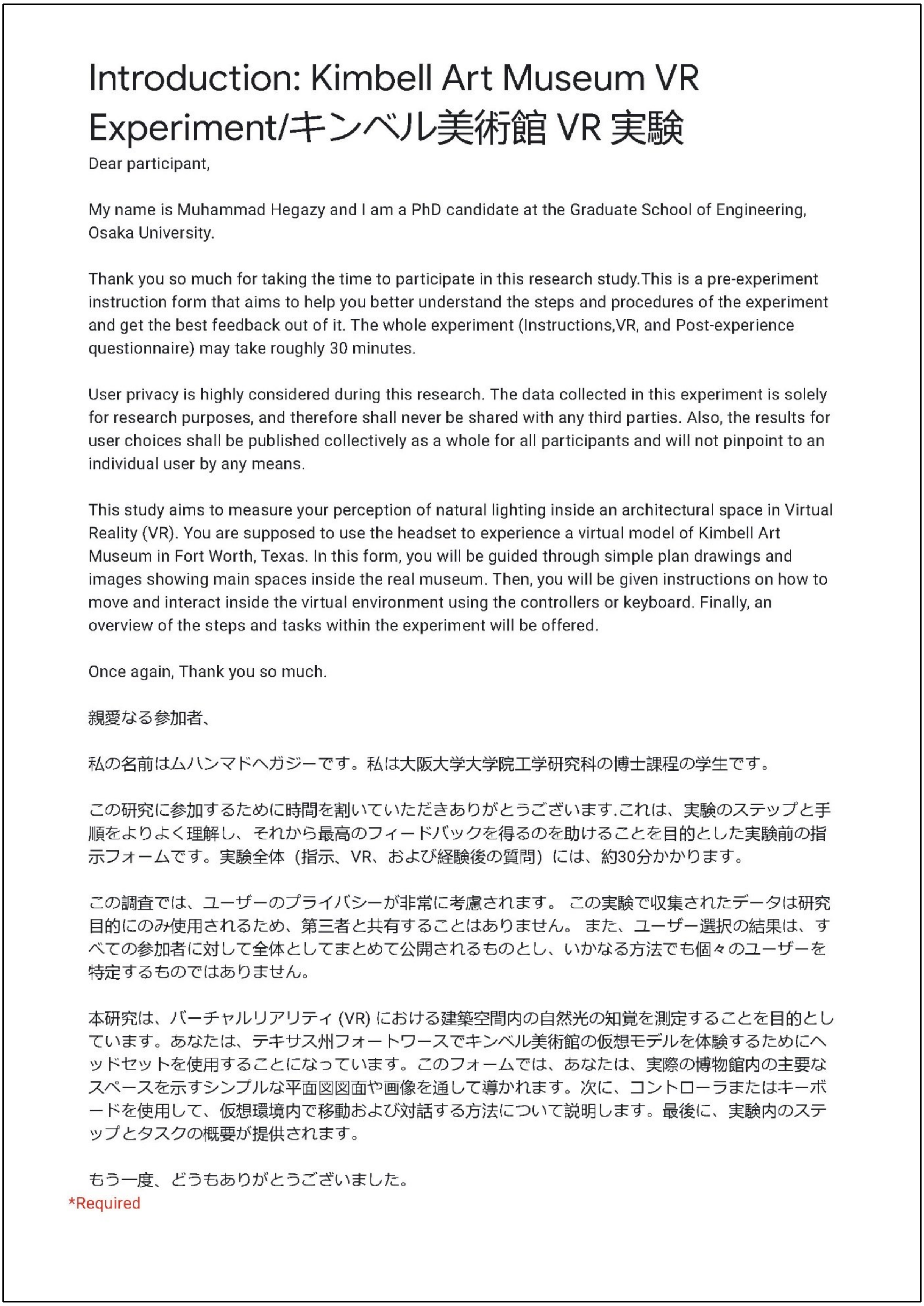
Appendix

Table 13: Relative errors for measured points compared to references for the two case models.

Point		Reality	Radiance		UE4 No RTX		UE4 RTX3		UE4 RTX7	
			value	Error %	value	Error %	value	Error %	value	Error %
Shoebox Model (9 am)	A01	-	2957	-	1406	52.5	1540	47.9	2857	3.4
	D01	-	1920	-	1392	27.5	817	57.4	1300	32.3
	G01	-	1010	-	1362	34.9	490	51.5	850	15.8
	J01	-	426	-	1330	212.2	302	29.1	610	43.2
	A03	-	6362	-	5638	11.4	5400	15.1	6650	4.5
	D03	-	2194	-	1390	36.6	751	65.8	1890	13.9
	G03	-	1177	-	1360	15.5	436	63.0	867	26.3
	J03	-	596	-	1342	125.2	360	39.6	740	24.2
	A05	-	1446	-	1392	3.7	733	49.3	1152	20.3
	D05	-	1412	-	1360	3.7	514	63.6	1115	21.0
	G05	-	906	-	1342	48.1	387	57.3	810	10.6
	J05	-	579	-	1343	132.0	320	44.7	670	15.7
	A07	-	820	-	1392	69.8	265	67.7	664	19.0
	D07	-	835	-	1360	62.9	305	63.5	760	9.0
	G07	-	659	-	1342	103.6	304	53.9	669	1.5
	J07	-	436	-	1333	205.7	252	42.2	570	30.7
	A09	-	576	-	1392	141.7	251	56.4	601	4.3
	D09	-	569	-	1360	139.0	301	47.1	649	14.1
	G09	-	497	-	1342	170.0	296	40.4	594	19.5
	J09	-	372	-	1331	257.8	256	31.2	523	40.6
	A11	-	371	-	1392	275.2	264	28.8	437	17.8
	D11	-	398	-	1364	242.7	310	22.1	507	27.4
	G11	-	362	-	1352	273.5	308	14.9	460	27.1
	J11	-	278	-	1339	381.7	254	8.6	367	32.0
Average				-		126.1		44.2		19.8
Complicated Office (11 am)	A11	943	948	0.5	850	9.9	818	13.3	979	3.8
	B11	330.5	301	8.9	184	44.3	292	11.6	339	2.6
	C11	216.5	230	6.2	211	2.5	188	13.2	215	0.7
	D11	174	156	10.3	170	2.3	101	42.0	169	2.9
	E11	175	164	6.3	176	0.6	110	37.1	178	1.7
	F11	164.9	159	3.6	191	15.8	96	41.8	156	5.4
	G11	215	221	2.8	172	20.0	203	5.6	223	3.7
	H11	156.3	193	23.5	73	53.3	79	49.5	145	7.2
	I11	244.6	207	15.4	76	68.9	134	45.2	240	1.9
	J11	66.4	56	15.7	77	16.0	31	53.3	74	11.4
	K11	101.7	129	26.8	128	25.9	49	51.8	94	7.6
Complicated Office (2 pm)	A14	253.7	241	5.0	467	84.1	221	12.9	278	9.6
	B14	44	62	40.9	182	313.6	63	43.2	76	72.7
	C14	52.8	62	17.4	211	299.6	49	7.2	55	4.2
	D14	43.6	39	10.6	170	289.9	41	6.0	53	21.6
	E14	36.8	44	19.6	176	378.3	42	14.1	48	30.4
	F14	31.7	51	60.9	191	502.5	47	48.3	56	76.7
	G14	48.9	56	14.5	172	251.7	36	26.4	58	18.6
	H14	39.1	33	15.6	73	86.7	19	51.4	44	12.5
	I14	49.8	52	4.4	76	52.6	21	57.8	47	5.6
	J14	13.6	13	4.4	71	422.1	9	33.8	14	2.9
	K14	17.3	20	15.6	128	639.9	16	7.5	25	44.5
Average				15.0		162.7		30.6		15.8

Figure 69: Pre-Questionnaire introduction form for participants.



Introduction: Kimbell Art Museum VR Experiment/キンベル美術館 VR 実験

Dear participant,

My name is Muhammad Hegazy and I am a PhD candidate at the Graduate School of Engineering, Osaka University.

Thank you so much for taking the time to participate in this research study.This is a pre-experiment instruction form that aims to help you better understand the steps and procedures of the experiment and get the best feedback out of it. The whole experiment (Instructions,VR, and Post-experience questionnaire) may take roughly 30 minutes.

User privacy is highly considered during this research. The data collected in this experiment is solely for research purposes, and therefore shall never be shared with any third parties. Also, the results for user choices shall be published collectively as a whole for all participants and will not pinpoint to an individual user by any means.

This study aims to measure your perception of natural lighting inside an architectural space in Virtual Reality (VR). You are supposed to use the headset to experience a virtual model of Kimbell Art Museum in Fort Worth, Texas. In this form, you will be guided through simple plan drawings and images showing main spaces inside the real museum. Then, you will be given instructions on how to move and interact inside the virtual environment using the controllers or keyboard. Finally, an overview of the steps and tasks within the experiment will be offered.

Once again, Thank you so much.

親愛なる参加者、

私の名前はムハンマドヘガジーです。私は大阪大学大学院工学研究科の博士課程の学生です。

この研究に参加するために時間を割いていただきありがとうございます.これは、実験のステップと手順をよりよく理解し、それから最高のフィードバックを得るのを助けることを目的とした実験前の指示フォームです。実験全体（指示、VR、および経験後の質問）には、約30分かかります。

この調査では、ユーザーのプライバシーが非常に考慮されます。 この実験で収集されたデータは研究目的にのみ使用されるため、第三者と共有することはありません。 また、ユーザー選択の結果は、すべての参加者に対して全体としてまとめて公開されるものとし、いかなる方法でも個々のユーザーを特定するものではありません。

本研究は、バーチャルリアリティ (VR) における建築空間内の自然光の知覚を測定することを目的としています。あなたは、テキサス州フォートワースでキンベル美術館の仮想モデルを体験するためにヘッドセットを使用することになっています。このフォームでは、あなたは、実際の博物館内の主要なスペースを示すシンプルな平面図図面や画像を通して導かれます。次に、コントローラまたはキーボードを使用して、仮想環境内で移動および対話する方法について説明します。最後に、実験内のステップとタスクの概要が提供されます。

もう一度、どうもありがとうございました。

*Required

1. Participant Code (by researcher) *

About Kimbell Art Museum/キンベル美術館について

Please read these excerpts about the museum from the official website:

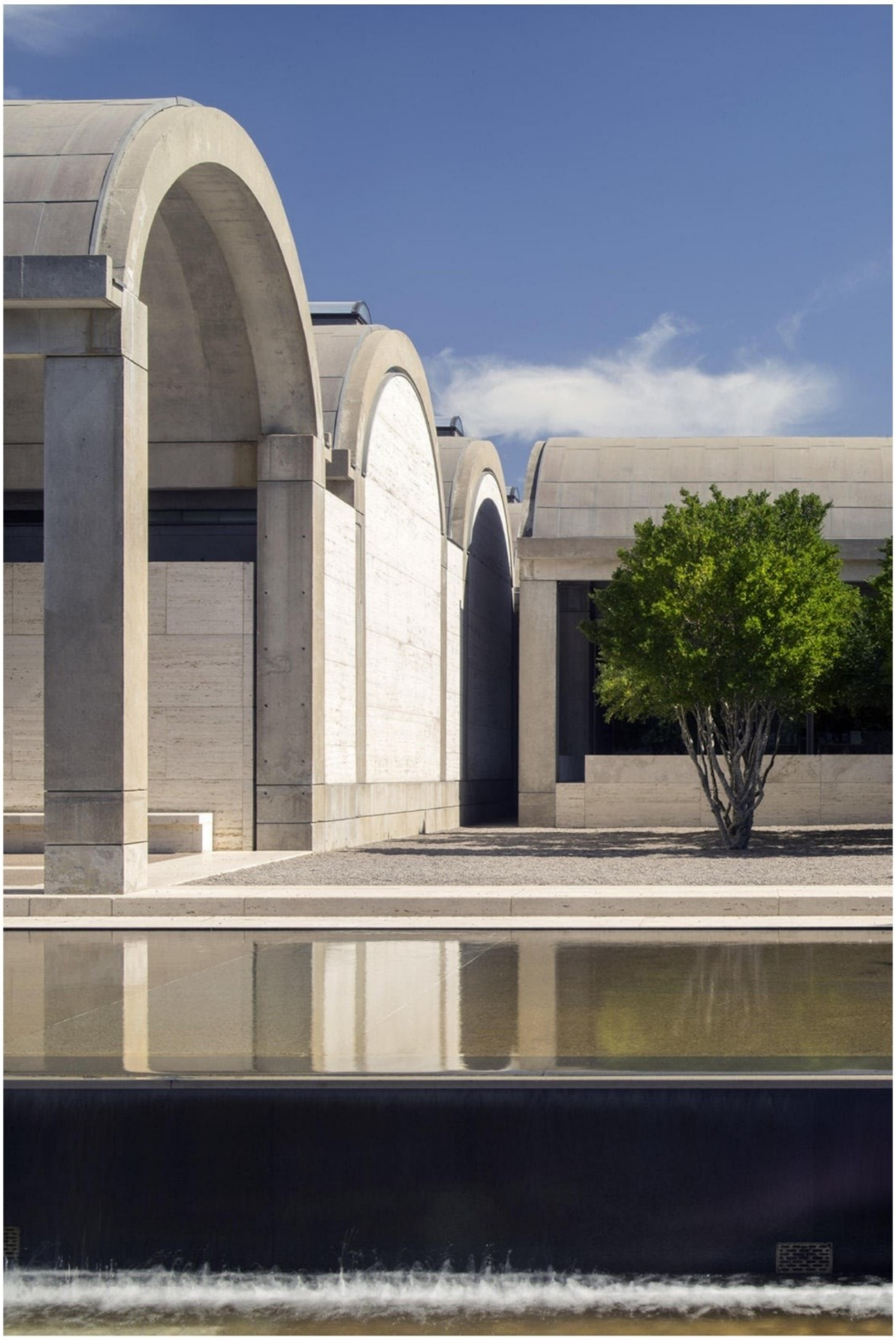
"The Kimbell Art Museum's original building, designed by Louis I. Kahn and opened to the public for the first time in 1972, has become a mecca of modern architecture. Kahn designed a building in which "light is the theme." Natural light enters through narrow plexiglass skylights along the top of cycloid barrel vaults and is diffused by wing-shaped pierced-aluminum reflectors that hang below, giving a silvery gleam to the smooth concrete of the vault surfaces and providing a perfect, subtly fluctuating illumination for the works of art."

公式サイトから博物館についてのこれらの抜粋をお読みください:

「キンベル美術館のオリジナルの建物は、ルイ・I・カーンによって設計されており、1972で初めて一般にオープンし、現代建築のメッカとなっています。カーンは「光がテーマである」建物を設計した。自然光は、サイクロイドバレルボールトの上部に沿って狭いプレキシガラスの天窓を通って入り、下にハングアップする翼型の穿孔アルミニウム反射板によって拡散され、ボールト表面の滑らかなコンクリートに銀色の輝きを与え、完璧を提供し、芸術作品のための微妙に変動する照明。

Aerial View of the Kimbell Art Museum/キンベル美術館の空中風景

Detailed shot of the arches at the main entrance/メインエントランスのアーチの詳細なショット



Architectural Drawings and Interior/建築図面とインテリア

The following is a collection of floor plans and images of the interior halls of the museum. Please have a look at them to grasp a better understanding of the building. Keep in mind to compare these real images with the virtual space you be in soon.
以下は、博物館の内部のホールの間取りやイメージのコレクションです。その建物についての理解を深めるためにそれらを見てください。あなたがすぐにある仮想空間でこれらの実際の画像を比較することを念頭に置いてください。

Floor Plan of the museum halls/ミュージアムホールの間取り図

A walk through inside the museum/博物館の中を歩く

http://youtube.com/watch?v=ZIyIOv541V8

Entrance Lobby

South Gallery/サウスギャラリー

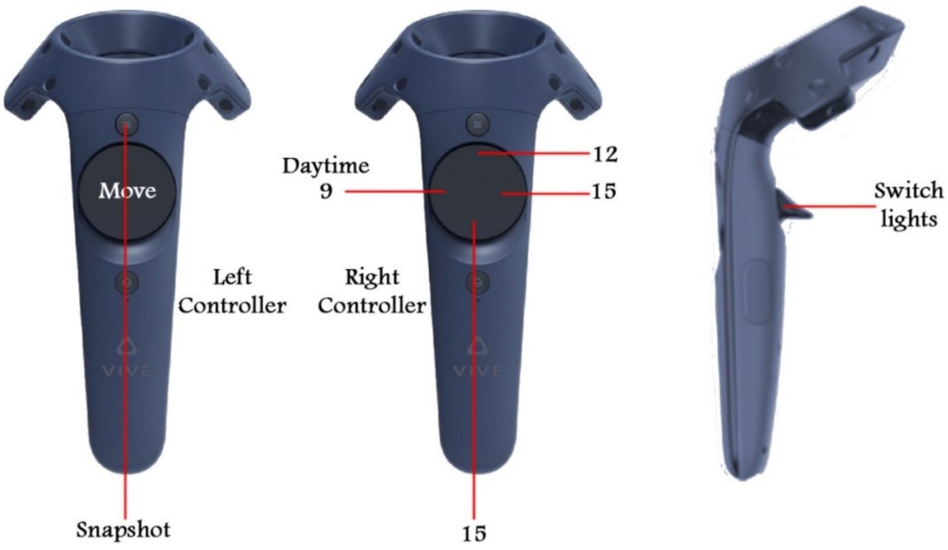
Barrel Vaults/バレルの金庫室

Experiment Instructions/実験手順

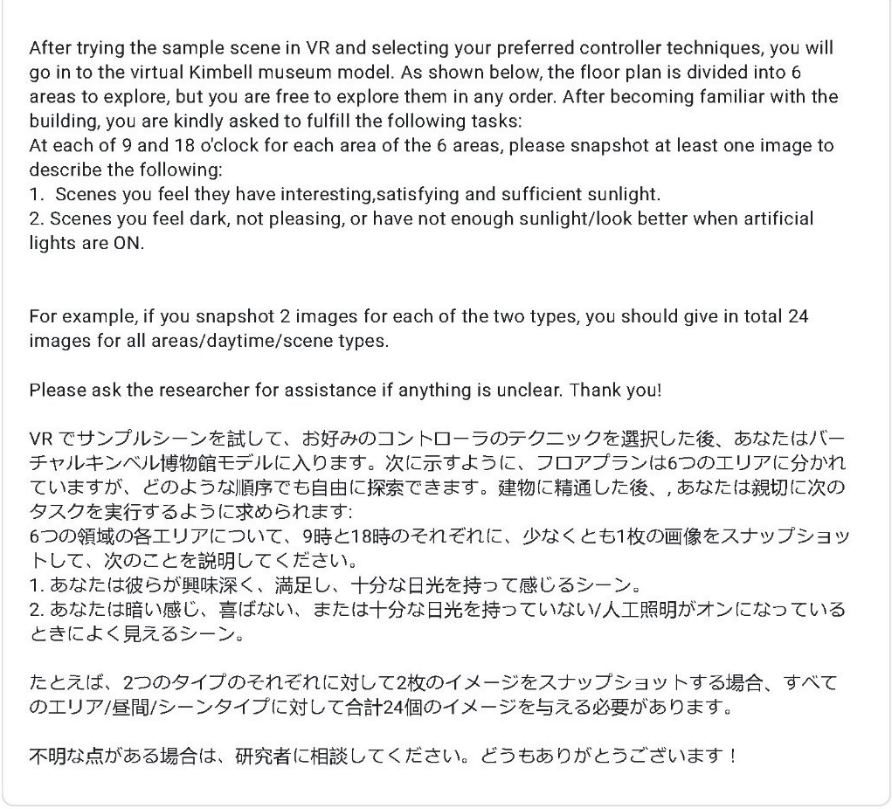
In this section, please try to memorize the control button for your movement and interaction in vr using keyboard/mouse or motion controllers. You will have a chance to try both controls on a sample scene before going to the full scene.
このセクションでは、キーボード/マウスまたはモーションコントローラを使用して vr であなたの動きと相互作用のためのコントロールボタンを暗記してみてください。シーン全体に移動する前に、サンプルシーンで両方のコントロールを試す機会があります。

Keyboard and mouse controllers/キーボードとマウスのコントローラ

Motion Controllers/モーションコントローラ



Experiment Tasks/実験タスク



After trying the sample scene in VR and selecting your preferred controller techniques, you will go in to the virtual Kimbell museum model. As shown below, the floor plan is divided into 6 areas to explore, but you are free to explore them in any order. After becoming familiar with the building, you are kindly asked to fulfill the following tasks:
At each of 9 and 18 o'clock for each area of the 6 areas, please snapshot at least one image to describe the following:
1. Scenes you feel they have interesting,satisfying and sufficient sunlight.
2. Scenes you feel dark, not pleasing, or have not enough sunlight/look better when artificial lights are ON.

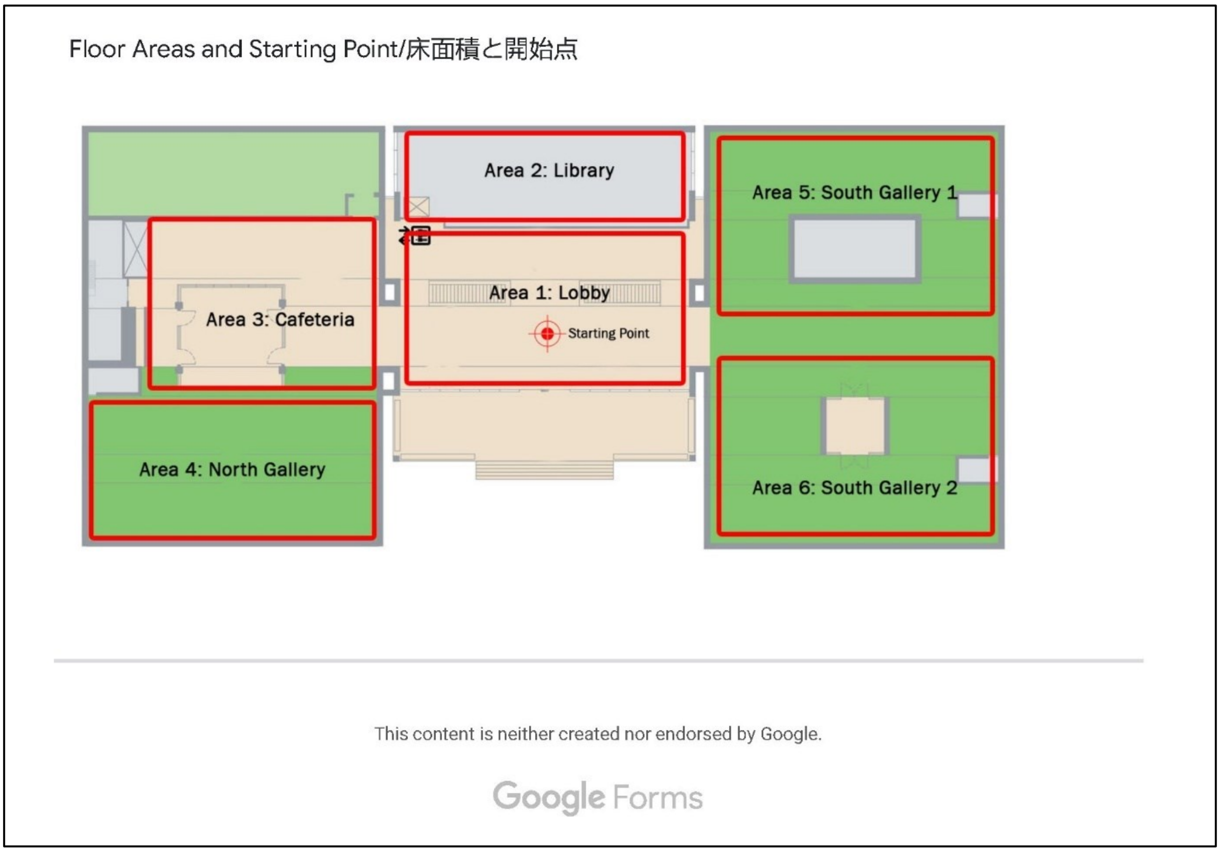
For example, if you snapshot 2 images for each of the two types, you should give in total 24 images for all areas/daytime/scene types.

Please ask the researcher for assistance if anything is unclear. Thank you!

VR でサンプルシーンを試して、お好みのコントローラのテクニックを選択した後、あなたはバーチャルキンベル博物館モデルに入ります。次に示すように、フロアプランは6つのエリアに分かれていますが、どのような順序でも自由に探索できます。建物に精通した後、, あなたは親切に次のタスクを実行するように求められます:
6つの領域の各エリアについて、9時と18時のそれぞれに、少なくとも1枚の画像をスナップショットして、次のことを説明してください。
1. あなたは彼らが興味深く、満足し、十分な日光を持って感じるシーン。
2. あなたは暗い感じ、喜ばない、または十分な日光を持っていない/人工照明がオンになっているときによく見えるシーン。

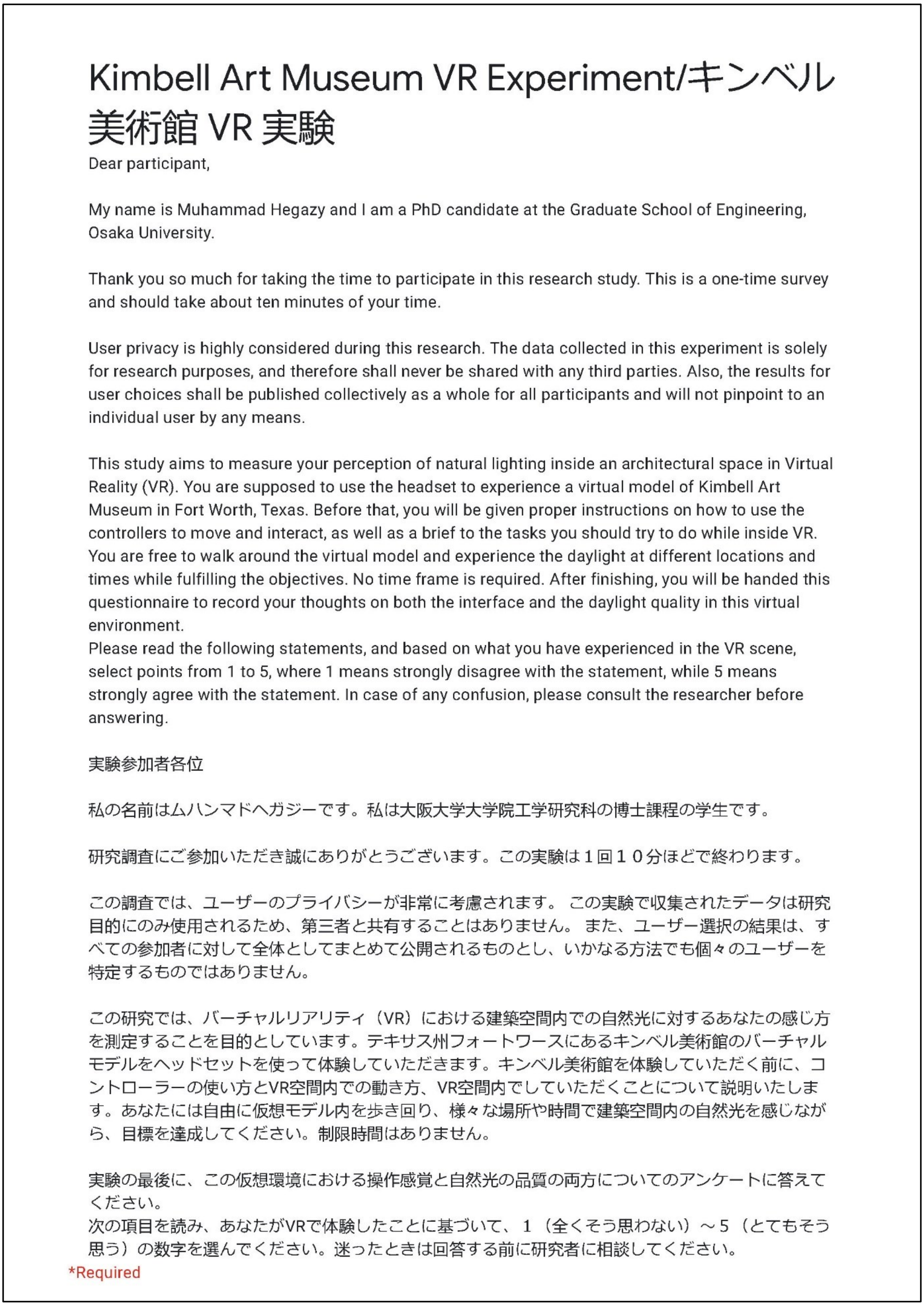
たとえば、2つのタイプのそれぞれに対して2枚のイメージをスナップショットする場合、すべてのエリア/昼間/シーンタイプに対して合計24個のイメージを与える必要があります。

不明な点がある場合は、研究者に相談してください。どうもありがとうございます！



Floor Areas and Starting Point/床面積と開始点

Figure 70: Kimbell Art Museum VR Experience questionnaire



Kimbell Art Museum VR Experiment/キンベル美術館 VR 実験

Dear participant,

My name is Muhammad Hegazy and I am a PhD candidate at the Graduate School of Engineering, Osaka University.

Thank you so much for taking the time to participate in this research study. This is a one-time survey and should take about ten minutes of your time.

User privacy is highly considered during this research. The data collected in this experiment is solely for research purposes, and therefore shall never be shared with any third parties. Also, the results for user choices shall be published collectively as a whole for all participants and will not pinpoint to an individual user by any means.

This study aims to measure your perception of natural lighting inside an architectural space in Virtual Reality (VR). You are supposed to use the headset to experience a virtual model of Kimbell Art Museum in Fort Worth, Texas. Before that, you will be given proper instructions on how to use the controllers to move and interact, as well as a brief to the tasks you should try to do while inside VR. You are free to walk around the virtual model and experience the daylight at different locations and times while fulfilling the objectives. No time frame is required. After finishing, you will be handed this questionnaire to record your thoughts on both the interface and the daylight quality in this virtual environment.
Please read the following statements, and based on what you have experienced in the VR scene, select points from 1 to 5, where 1 means strongly disagree with the statement, while 5 means strongly agree with the statement. In case of any confusion, please consult the researcher before answering.

実験参加者各位

私の名前はムハンマドヘガジーです。私は大阪大学大学院工学研究科の博士課程の学生です。

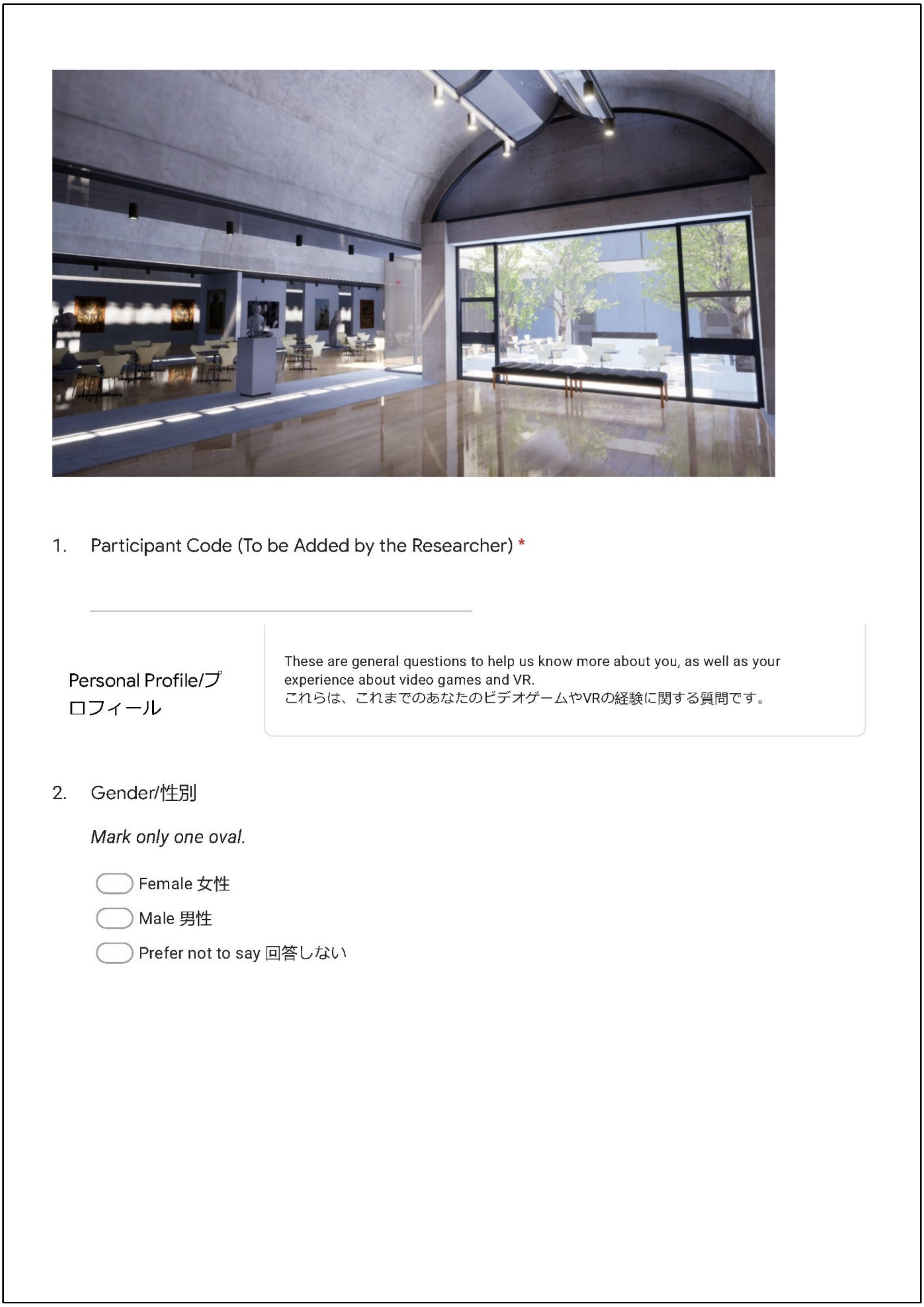
研究調査にご参加いただき誠にありがとうございます。この実験は１回１０分ほどで終わります。

この調査では、ユーザーのプライバシーが非常に考慮されます。 この実験で収集されたデータは研究目的にのみ使用されるため、第三者と共有することはありません。 また、ユーザー選択の結果は、すべての参加者に対して全体としてまとめて公開されるものとし、いかなる方法でも個々のユーザーを特定するものではありません。

この研究では、バーチャルリアリティ（VR）における建築空間内での自然光に対するあなたの感じ方を測定することを目的としています。テキサス州フォートワースにあるキンベル美術館のバーチャルモデルをヘッドセットを使って体験していただきます。キンベル美術館を体験していただく前に、コントローラーの使い方とVR空間内での動き方、VR空間内でしていただくことについて説明いたします。あなたには自由に仮想モデル内を歩き回り、様々な場所や時間で建築空間内の自然光を感じながら、目標を達成してください。制限時間はありません。

実験の最後に、この仮想環境における操作感覚と自然光の品質の両方についてのアンケートに答えてください。
次の項目を読み、あなたがVRで体験したことに基づいて、１（全くそう思わない）～５（とてもそう思う）の数字を選んでください。迷ったときは回答する前に研究者に相談してください。

*Required



1. Participant Code (To be Added by the Researcher) *

____

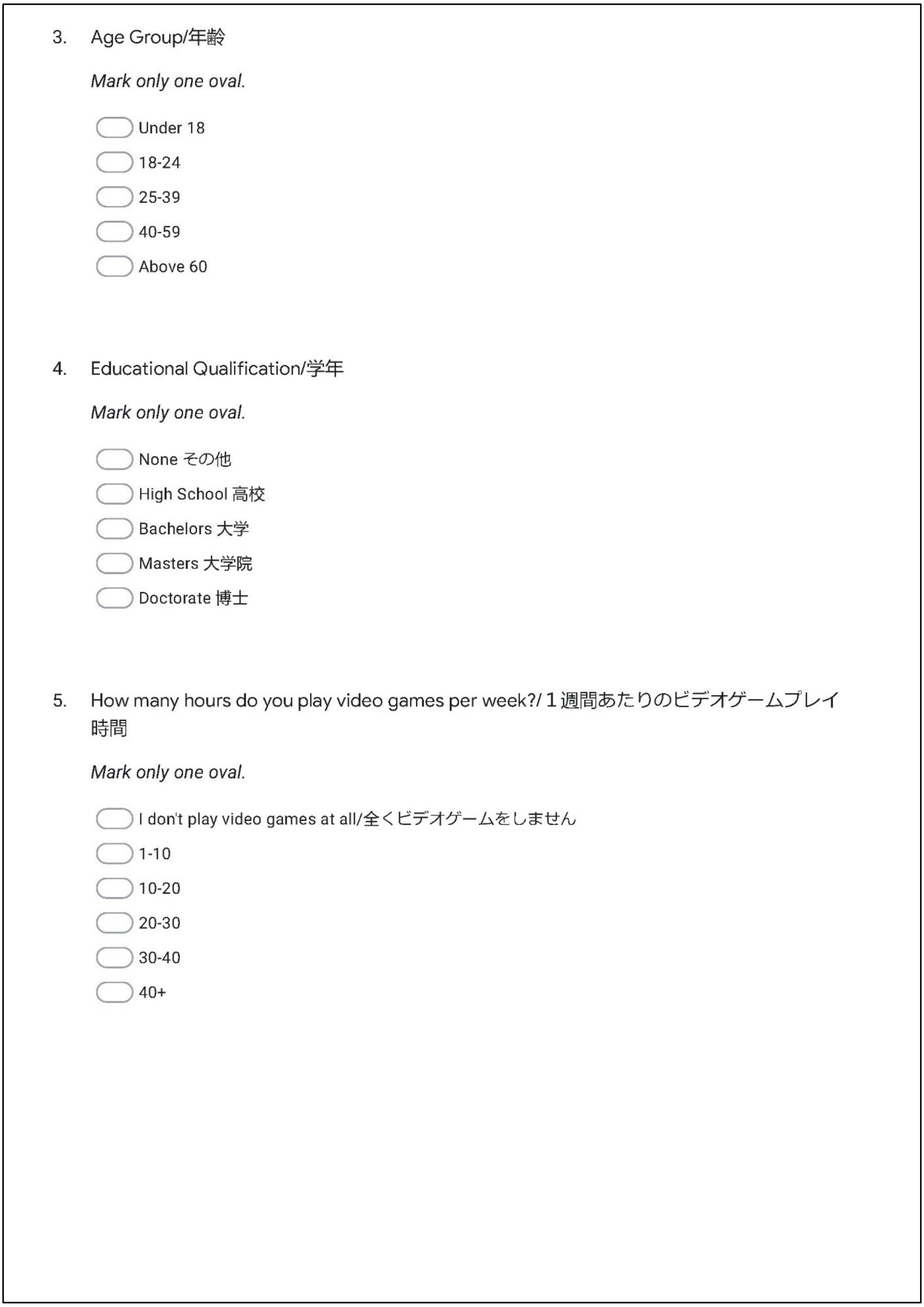
Personal Profile/プロフィール

These are general questions to help us know more about you, as well as your experience about video games and VR.
これらは、これまでのあなたのビデオゲームやVRの経験に関する質問です。

2. Gender/性別

Mark only one oval.

○ Female 女性
○ Male 男性
○ Prefer not to say 回答しない



3. Age Group/年齢

Mark only one oval.

○ Under 18
○ 18-24
○ 25-39
○ 40-59
○ Above 60

4. Educational Qualification/学年

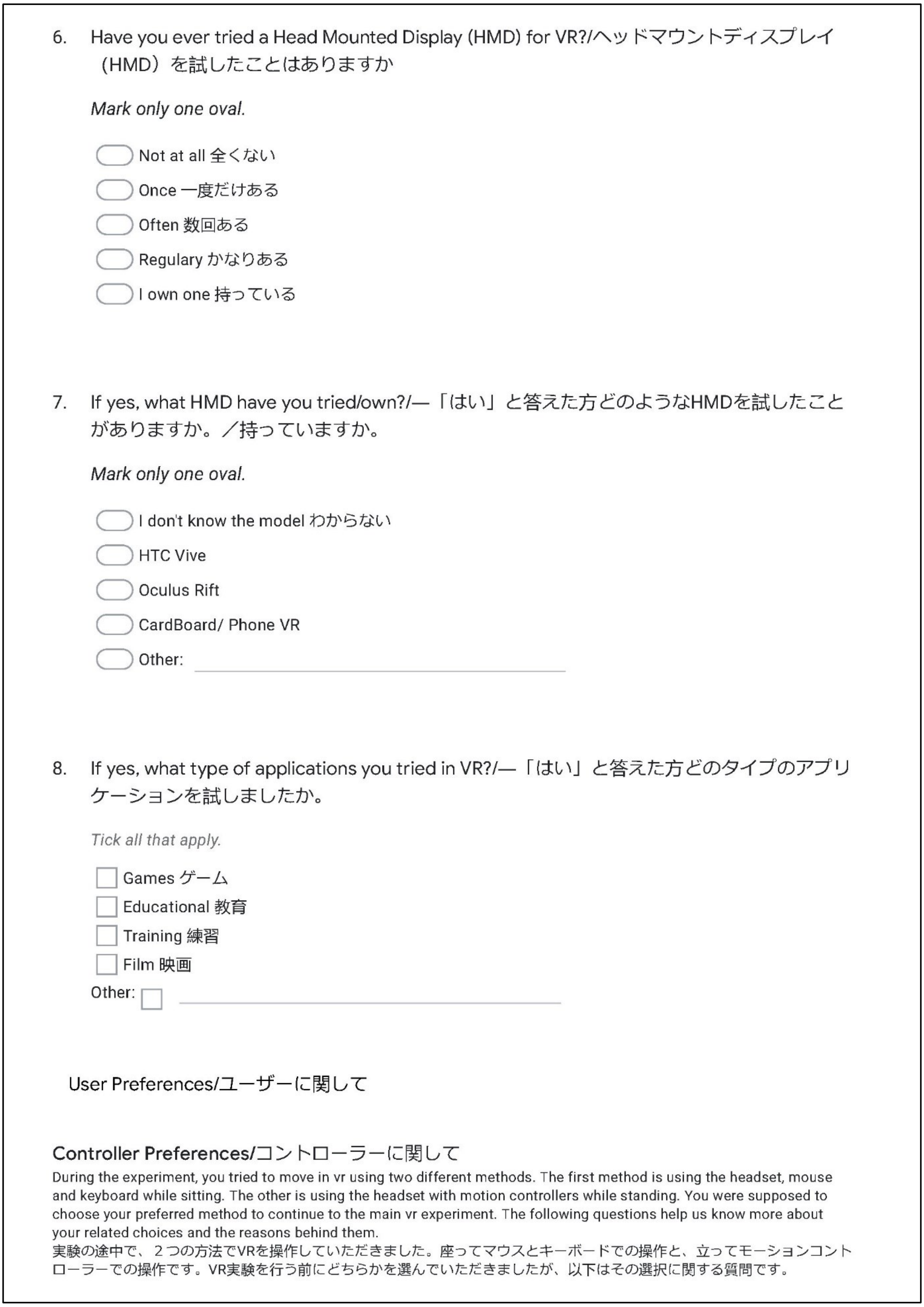
Mark only one oval.

○ None その他
○ High School 高校
○ Bachelors 大学
○ Masters 大学院
○ Doctorate 博士

5. How many hours do you play video games per week?/１週間あたりのビデオゲームプレイ時間

Mark only one oval.

○ I don't play video games at all/全くビデオゲームをしません
○ 1-10
○ 10-20
○ 20-30
○ 30-40
○ 40+



6. Have you ever tried a Head Mounted Display (HMD) for VR?/ヘッドマウントディスプレイ（HMD）を試したことはありますか

Mark only one oval.

○ Not at all 全くない
○ Once 一度だけある
○ Often 数回ある
○ Regulary かなりある
○ I own one 持っている

7. If yes, what HMD have you tried/own?/—「はい」と答えた方どのようなHMDを試したことがありますか。／持っていますか。

Mark only one oval.

○ I don't know the model わからない
○ HTC Vive
○ Oculus Rift
○ CardBoard/ Phone VR
○ Other: ____________________

8. If yes, what type of applications you tried in VR?/—「はい」と答えた方どのタイプのアプリケーションを試しましたか。

Tick all that apply.

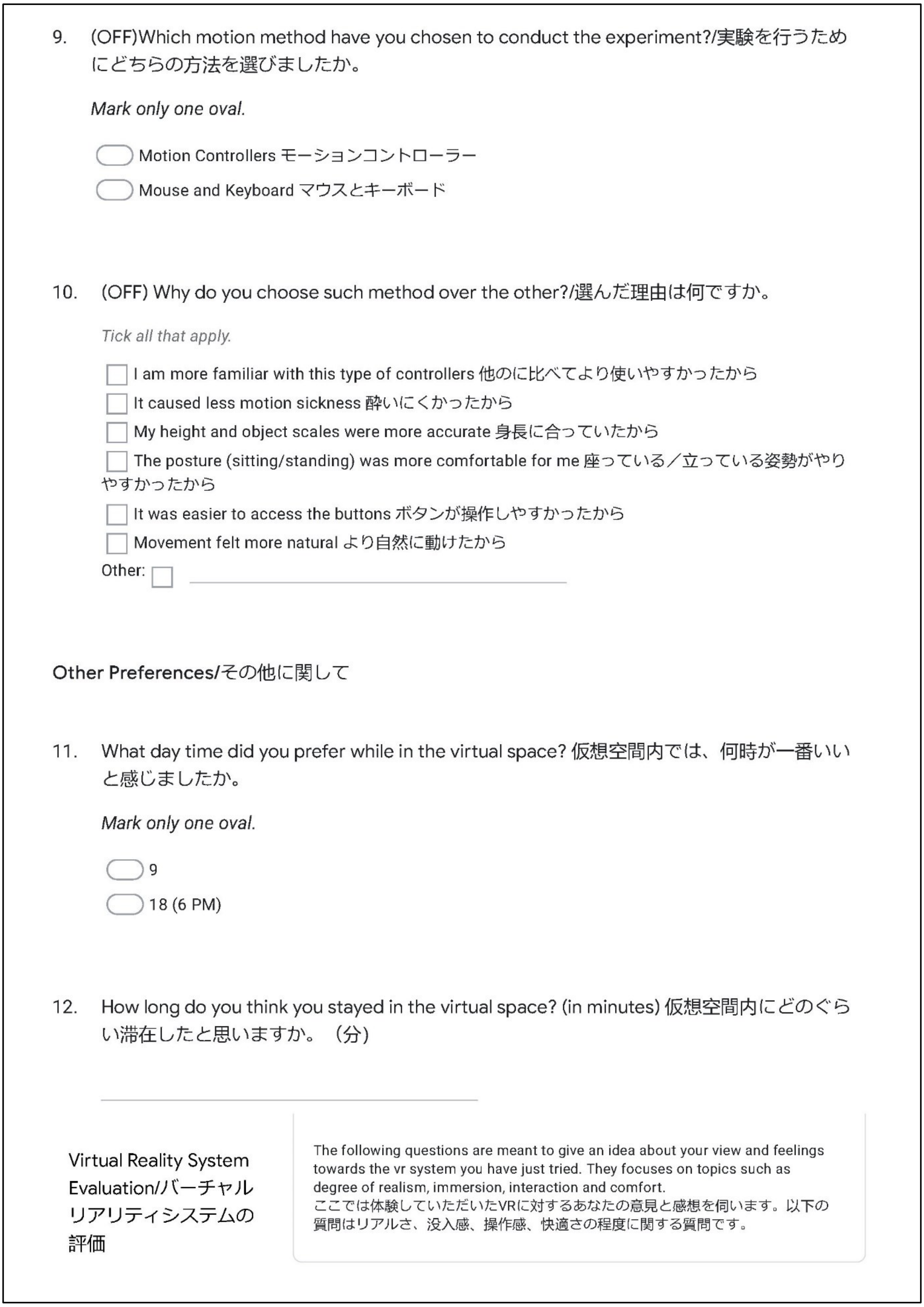
☐ Games ゲーム
☐ Educational 教育
☐ Training 練習
☐ Film 映画
Other: ☐ ____________________

User Preferences/ユーザーに関して

Controller Preferences/コントローラーに関して

During the experiment, you tried to move in vr using two different methods. The first method is using the headset, mouse and keyboard while sitting. The other is using the headset with motion controllers while standing. You were supposed to choose your preferred method to continue to the main vr experiment. The following questions help us know more about your related choices and the reasons behind them.

実験の途中で、２つの方法でVRを操作していただきました。座ってマウスとキーボードでの操作と、立ってモーションコントローラーでの操作です。VR実験を行う前にどちらかを選んでいただきましたが、以下はその選択に関する質問です。



9. (OFF)Which motion method have you chosen to conduct the experiment?/実験を行うためにどちらの方法を選びましたか。

Mark only one oval.

○ Motion Controllers モーションコントローラー
○ Mouse and Keyboard マウスとキーボード

10. (OFF) Why do you choose such method over the other?/選んだ理由は何ですか。

Tick all that apply.

☐ I am more familiar with this type of controllers 他のに比べてより使いやすかったから
☐ It caused less motion sickness 酔いにくかったから
☐ My height and object scales were more accurate 身長に合っていたから
☐ The posture (sitting/standing) was more comfortable for me 座っている／立っている姿勢がやりやすかったから
☐ It was easier to access the buttons ボタンが操作しやすかったから
☐ Movement felt more natural より自然に動けたから
Other: ☐ ____________________________

Other Preferences/その他に関して

11. What day time did you prefer while in the virtual space? 仮想空間内では、何時が一番いいと感じましたか。

Mark only one oval.

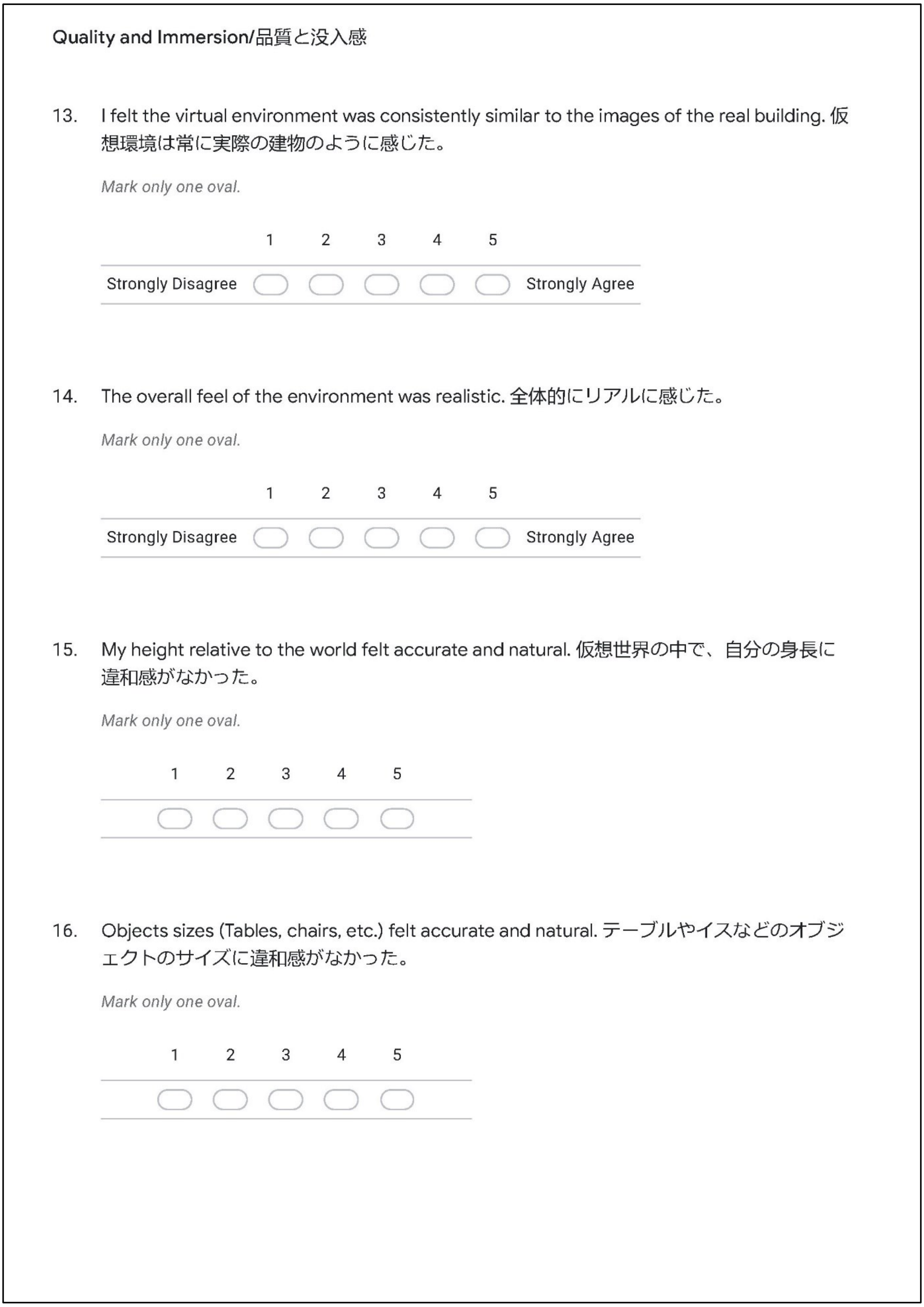
○ 9
○ 18 (6 PM)

12. How long do you think you stayed in the virtual space? (in minutes) 仮想空間内にどのぐらい滞在したと思いますか。（分）

____

Virtual Reality System Evaluation/バーチャルリアリティシステムの評価

The following questions are meant to give an idea about your view and feelings towards the vr system you have just tried. They focuses on topics such as degree of realism, immersion, interaction and comfort.
ここでは体験していただいたVRに対するあなたの意見と感想を伺います。以下の質問はリアルさ、没入感、操作感、快適さの程度に関する質問です。



Quality and Immersion/品質と没入感

13. I felt the virtual environment was consistently similar to the images of the real building. 仮想環境は常に実際の建物のように感じた。

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

14. The overall feel of the environment was realistic. 全体的にリアルに感じた。

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

15. My height relative to the world felt accurate and natural. 仮想世界の中で、自分の身長に違和感がなかった。

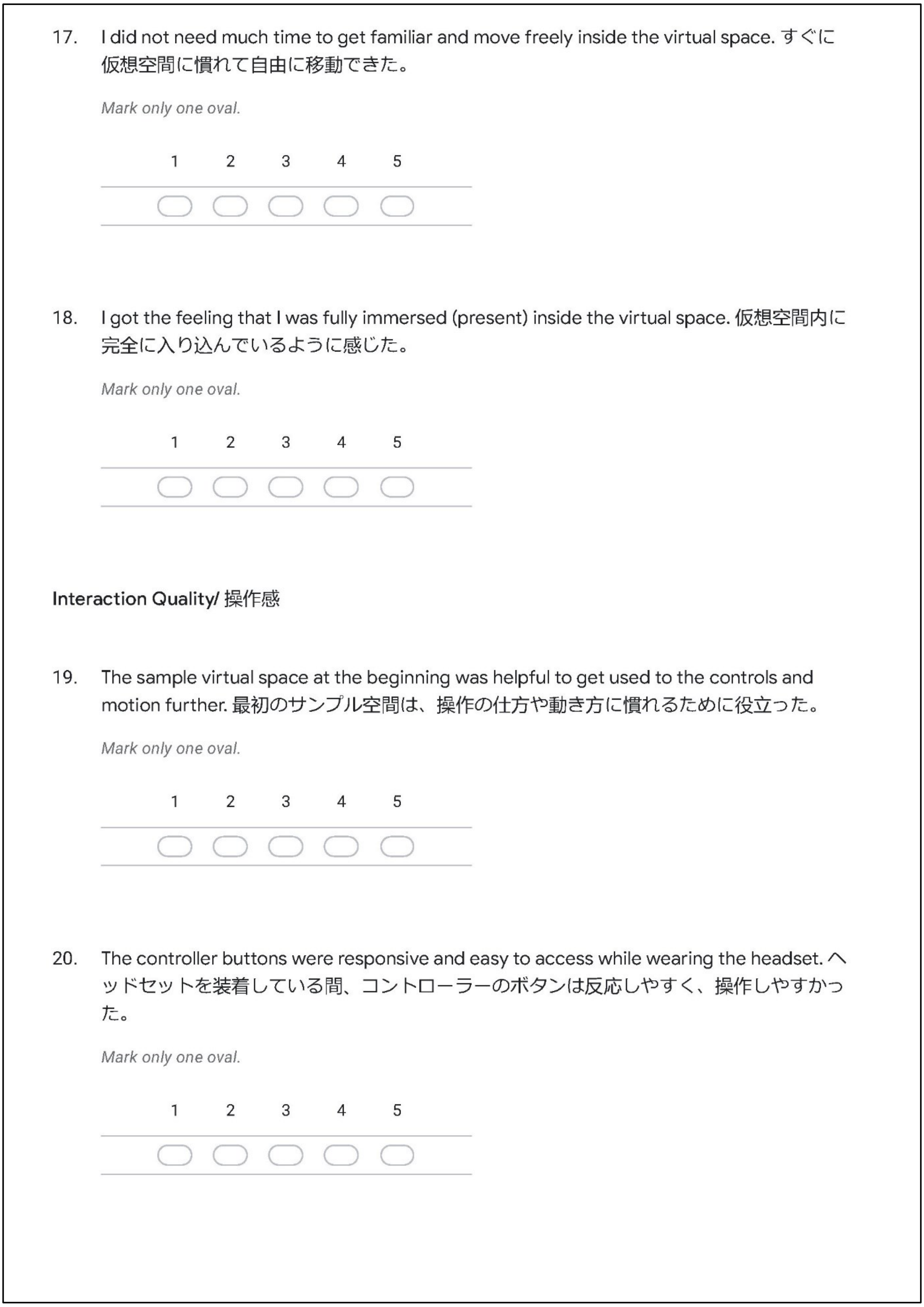
Mark only one oval.

1	2	3	4	5
○	○	○	○	○

16. Objects sizes (Tables, chairs, etc.) felt accurate and natural. テーブルやイスなどのオブジェクトのサイズに違和感がなかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○



17. I did not need much time to get familiar and move freely inside the virtual space. すぐに仮想空間に慣れて自由に移動できた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

18. I got the feeling that I was fully immersed (present) inside the virtual space. 仮想空間内に完全に入り込んでいるように感じた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Interaction Quality/ 操作感

19. The sample virtual space at the beginning was helpful to get used to the controls and motion further. 最初のサンプル空間は、操作の仕方や動き方に慣れるために役立った。

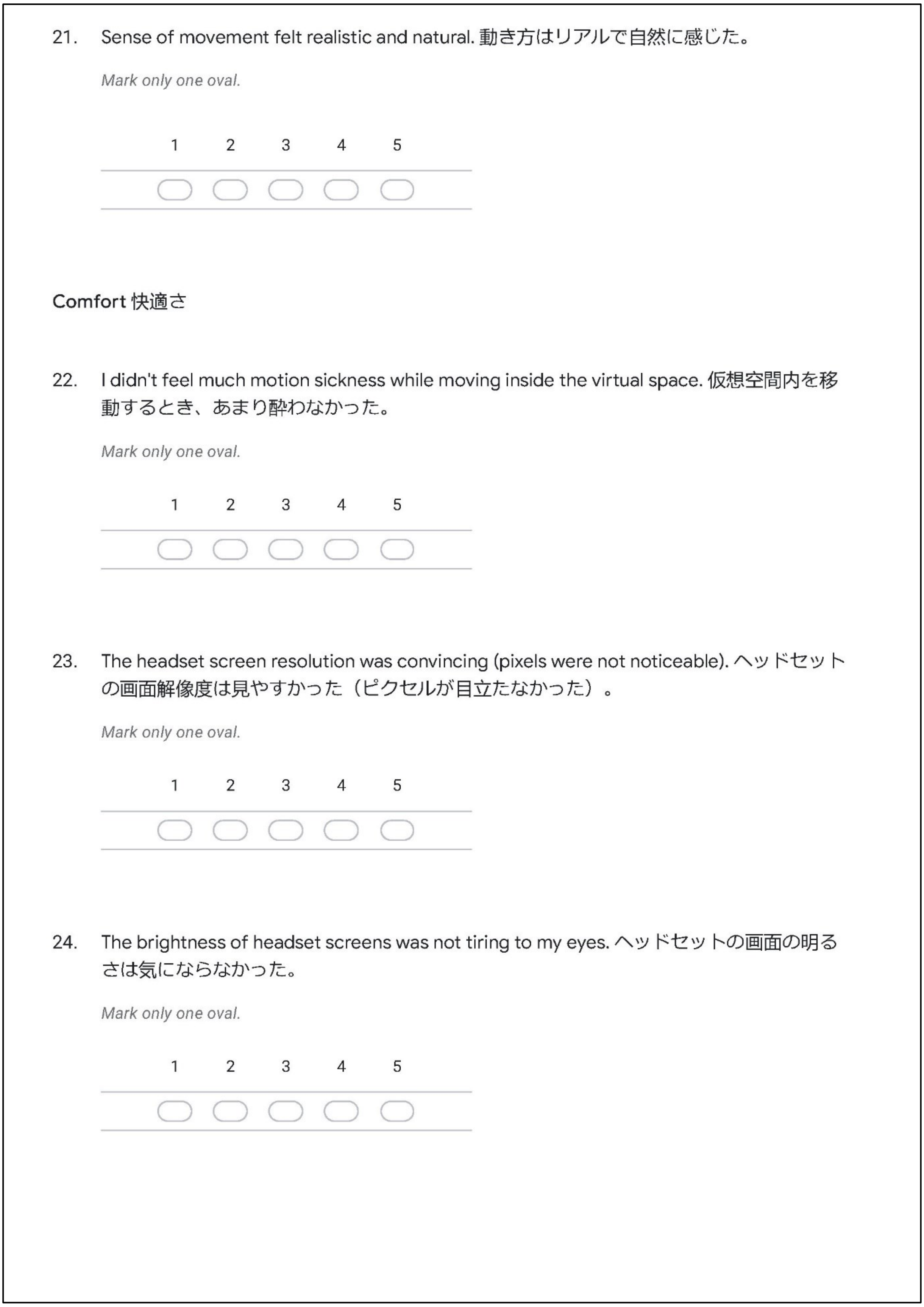
Mark only one oval.

1	2	3	4	5
○	○	○	○	○

20. The controller buttons were responsive and easy to access while wearing the headset. ヘッドセットを装着している間、コントローラーのボタンは反応しやすく、操作しやすかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○



21. Sense of movement felt realistic and natural. 動き方はリアルで自然に感じた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Comfort 快適さ

22. I didn't feel much motion sickness while moving inside the virtual space. 仮想空間内を移動するとき、あまり酔わなかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

23. The headset screen resolution was convincing (pixels were not noticeable). ヘッドセットの画面解像度は見やすかった（ピクセルが目立たなかった）。

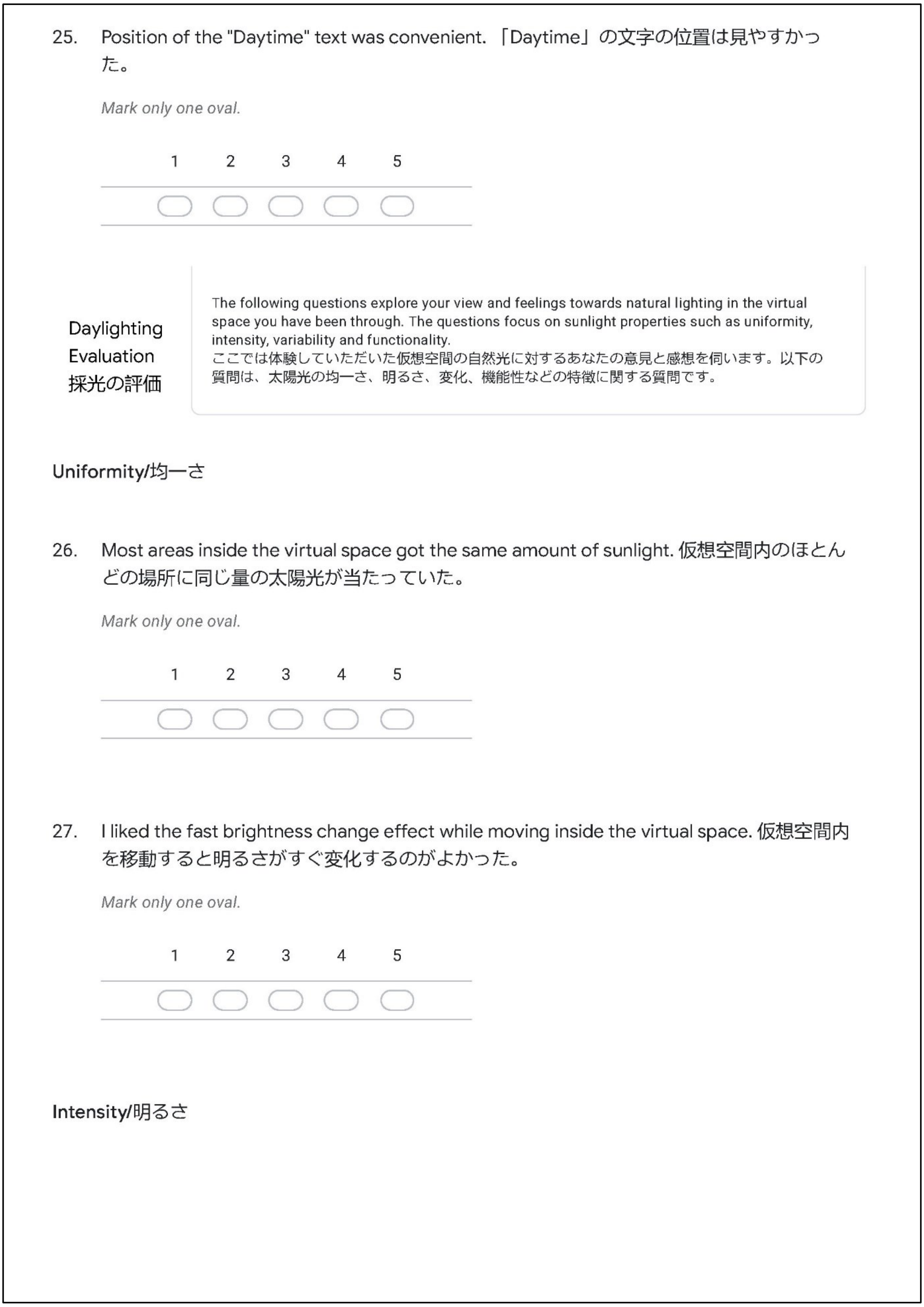
Mark only one oval.

1	2	3	4	5
○	○	○	○	○

24. The brightness of headset screens was not tiring to my eyes. ヘッドセットの画面の明るさは気にならなかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○



25. Position of the "Daytime" text was convenient. 「Daytime」の文字の位置は見やすかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Daylighting Evaluation 採光の評価

The following questions explore your view and feelings towards natural lighting in the virtual space you have been through. The questions focus on sunlight properties such as uniformity, intensity, variability and functionality.
ここでは体験していただいた仮想空間の自然光に対するあなたの意見と感想を伺います。以下の質問は、太陽光の均一さ、明るさ、変化、機能性などの特徴に関する質問です。

Uniformity/均一さ

26. Most areas inside the virtual space got the same amount of sunlight. 仮想空間内のほとんどの場所に同じ量の太陽光が当たっていた。

Mark only one oval.

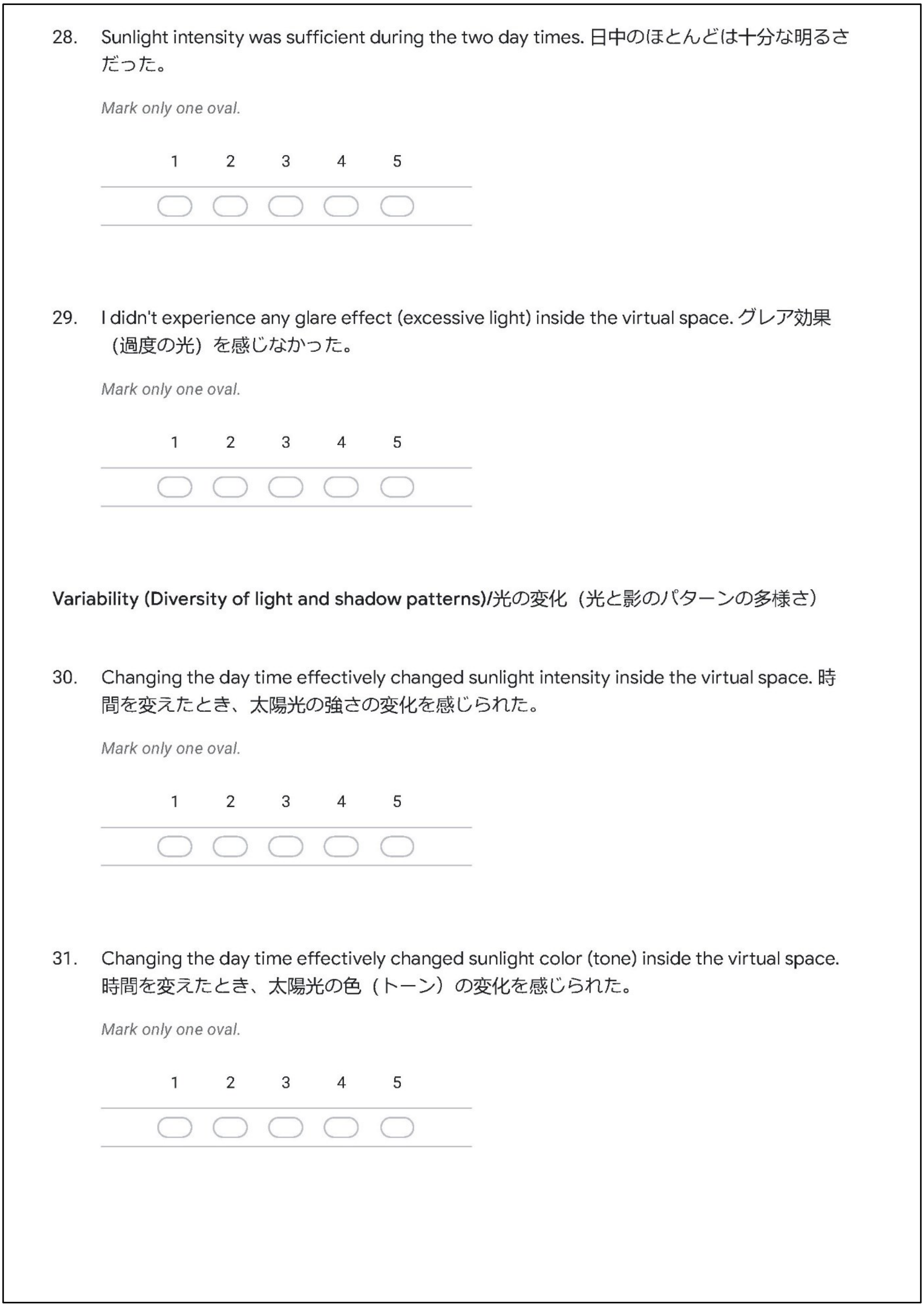
1	2	3	4	5
○	○	○	○	○

27. I liked the fast brightness change effect while moving inside the virtual space. 仮想空間内を移動すると明るさがすぐ変化するのがよかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Intensity/明るさ



28. Sunlight intensity was sufficient during the two day times. 日中のほとんどは十分な明るさだった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

29. I didn't experience any glare effect (excessive light) inside the virtual space. グレア効果（過度の光）を感じなかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Variability (Diversity of light and shadow patterns)/光の変化（光と影のパターンの多様さ）

30. Changing the day time effectively changed sunlight intensity inside the virtual space. 時間を変えたとき、太陽光の強さの変化を感じられた。

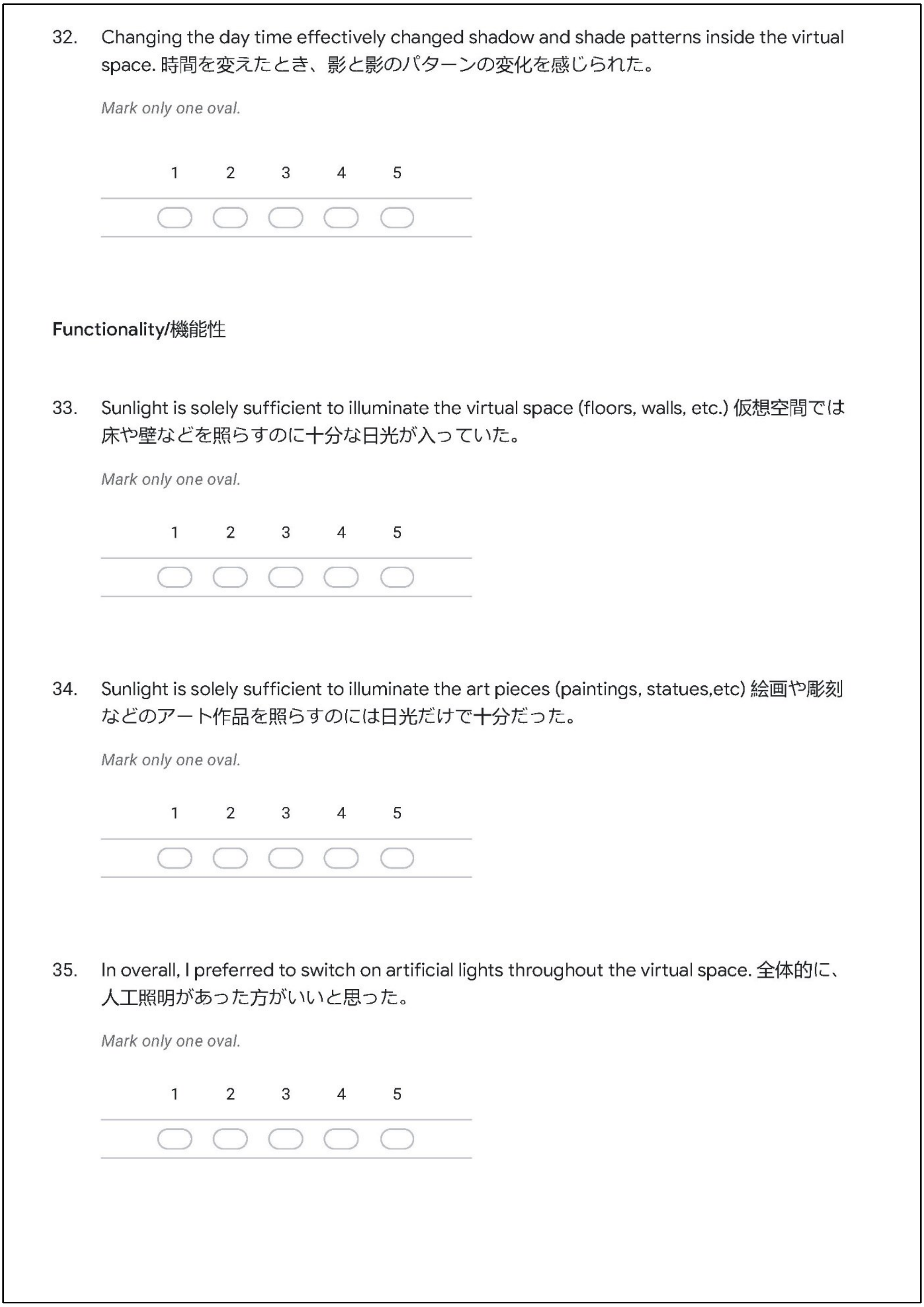
Mark only one oval.

1	2	3	4	5
○	○	○	○	○

31. Changing the day time effectively changed sunlight color (tone) inside the virtual space. 時間を変えたとき、太陽光の色（トーン）の変化を感じられた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○



32. Changing the day time effectively changed shadow and shade patterns inside the virtual space. 時間を変えたとき、影と影のパターンの変化を感じられた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Functionality/機能性

33. Sunlight is solely sufficient to illuminate the virtual space (floors, walls, etc.) 仮想空間では床や壁などを照らすのに十分な日光が入っていた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

34. Sunlight is solely sufficient to illuminate the art pieces (paintings, statues,etc) 絵画や彫刻などのアート作品を照らすのには日光だけで十分だった。

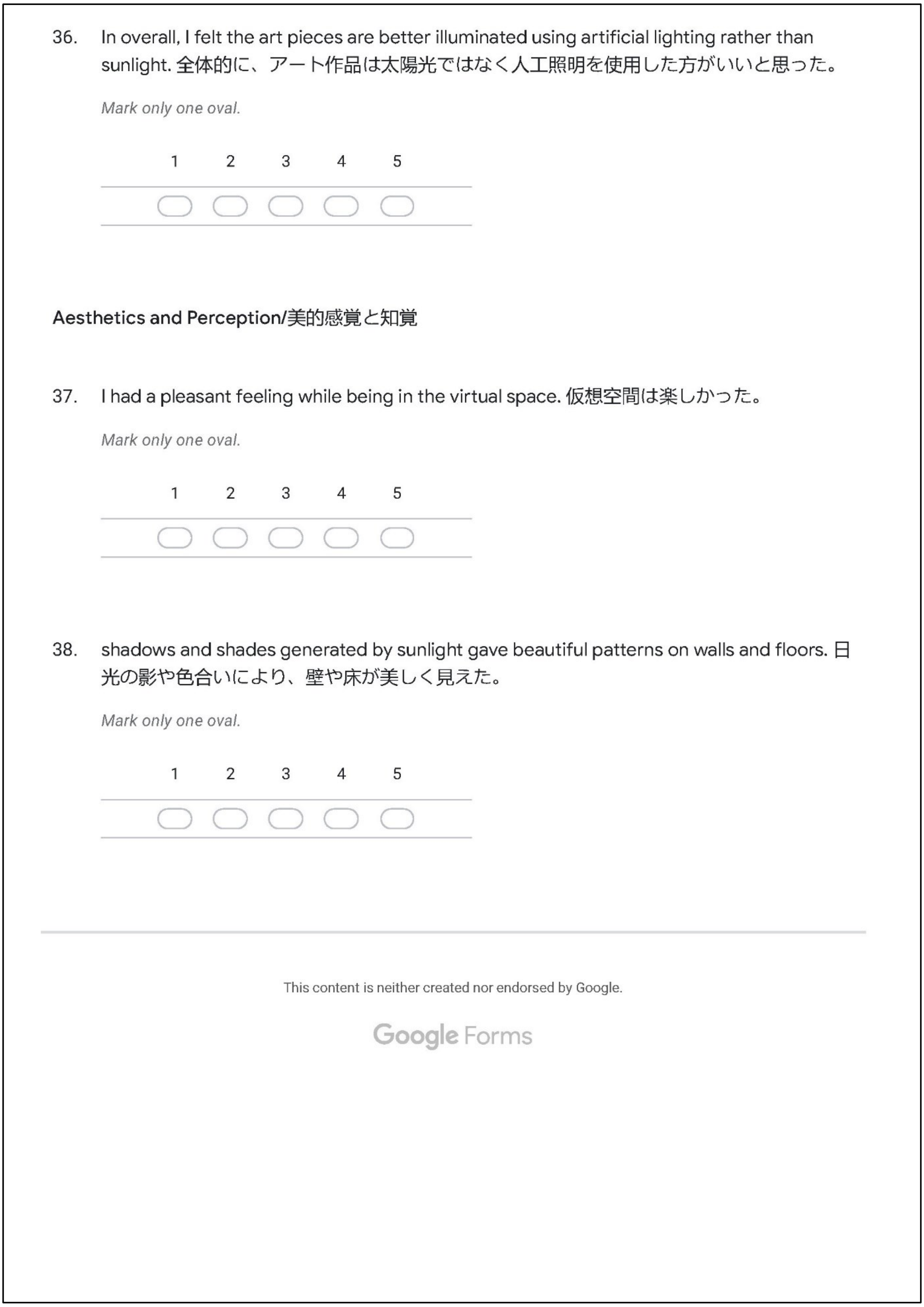
Mark only one oval.

1	2	3	4	5
○	○	○	○	○

35. In overall, I preferred to switch on artificial lights throughout the virtual space. 全体的に、人工照明があった方がいいと思った。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○



36. In overall, I felt the art pieces are better illuminated using artificial lighting rather than sunlight. 全体的に、アート作品は太陽光ではなく人工照明を使用した方がいいと思った。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Aesthetics and Perception/美的感覚と知覚

37. I had a pleasant feeling while being in the virtual space. 仮想空間は楽しかった。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

38. shadows and shades generated by sunlight gave beautiful patterns on walls and floors. 日光の影や色合いにより、壁や床が美しく見えた。

Mark only one oval.

1	2	3	4	5
○	○	○	○	○

Publications

Journal Articles

1) Hegazy, M., Yasufuku, K., Abe, H. “An interactive approach to investigate brightness perception of daylighting in Immersive Virtual Environments: Comparing subjective responses and quantitative metrics” Building Simulation. doi.org/10.1007/s12273-021-0798-3
2) Hegazy, M., Yasufuku, K., Abe, H. “Evaluating and Visualizing Perceptual Impressions of Daylighting in Immersive Virtual Environments.” Journal of Asian Architecture and Building Engineering 0(0):1–17. doi.org/10.1080/13467581.2020.1800477

International Conferences

1) Hegazy, M., Yasufuku, K., Abe, H. “Validating Game Engines as a Quantitative Daylighting Simulation Tool” in Proceedings of the 26th International Conference on Computer-Aided Architectural Design Research in Asia CAADRIA 2021. Hong Kong.
2) Hegazy, M., Yasufuku, K., Abe, H. “Multi-Objective Optimization Objectives for Building Envelopes: A Review Study” in Proceedings of the 54th International Conference of the Architectural Science Association 2020. Auckland, New Zealand.
3) Hegazy, M., Yasufuku, K., Abe, H. “Visualizing User Perception of Daylighting: A Comparison between VR and Reality” in Proceedings of BuildSim Nordic Conference. Oslo, Norway: SINTEF Proceedings.
4) Hegazy, M., Yasufuku, K., Abe, H. “Crowd-Based Illuminance Maps: Comparing Daylight Perception in Virtual Reality to Empirical Metrics” Velux Daylight Symposium. Paris, France. (2 Pages Abstract + Oral Presentation)
5) Hegazy, M., Yasufuku, K., Abe, H. “An Experiment to Evaluate Daylight Perception in Gamified Virtual Environments” In Proceedings of 12th Asian Forum on Graphic Science (AFGS 2019), 9-12 August 2019, Kunming, China.
6) Hegazy, M., Yasufuku, K., Abe, H. “Immersive Gamified Environments (IGE) as an Approach to Assess Subjective Qualities of Daylighting in Architectural Spaces” In Proceedings of IEEEVR, 23-27 March 2019, Osaka, Japan. doi.org/10.1109/VR.2019.8798086