VRGlare: A Virtual Reality Lighting Performance Simulator for real-time Three-Dimensional Glare Simulation and Analysis

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Abstract -
Lighting performance simulators play an important role in the architectural design process, as it provides the means to address lighting design issues early within the design stage of a construction project life-cycle. Currently, several lighting performance simulators provide support for glare simulation and analysis; however, they are primarily limited to two-dimensional desktop displays and not capable of simulating glare in real-time. Furthermore, the quantitative data produced from these simulators consist of reports, complex numerical data-sets, two-dimensional graphs, and charts, which creates a divergence between the data produced and the three-dimensional context of the building. As a result, analysis of glare data generally requires specialists such as experienced architects who have an extensive background in interpreting these two-dimensional data-sets. In order to overcome the aforementioned issues, we present VRGlare: an immersive Virtual Reality lighting performance simulator capable of real-time glare simulation and analysis. In addition to semi-realistic lighting renderings, this research proposes four visualisation techniques to represent glare within an immersive three-dimensional context. We also present two multi-sensory approaches designed to re-create the physical discomfort that occurs when experiencing glare. This paper provides an overview of the developed simulator which includes the hardware, software, algorithms, visualisations, and multi-sensory representation of glare discomfort.

Keywords -
Virtual Reality; Lighting Performance Simulation; Immersive Glare Visualisation; Glare Analysis; Building Information Modelling

1 Introduction

Sufficient work-place lighting is an essential requirement for workers who spend multiple hours on a computer per day. Previous studies have demonstrated visual discomfort in the workplace has a negative impact on a worker's overall level of productivity, performance, and overall job satisfaction [1, 2]. The physical symptoms associated with visual discomfort include eye-strain, headaches, fatigue, red, sore, itchy, watering eyes, and lighting sensitivity. Visual discomfort can occur in workplaces due to various factors associated with lighting including uniformity, glare, veiling reflections, shadows, and flicker [3]. As a result, providing architects with the necessary tools to mitigate visual discomfort during their design process is required. With the continuous advancements of Lighting Performance Simulators (LPS) in recent years, LPS has become an increasingly used tool for architects to plan and design their ideal lighting layout. A LPS can be defined as a software system that provides the ability to simulate, analyze, and assess the performance of lighting through realistic simulations, algorithms, and large subsets of data. Currently, several LPS systems provide support for glare simulation and analysis, however, they are primarily limited to two-dimensional desktop displays and not capable of simulating glare in real-time. Furthermore, the quantitative data produced from these simulators consist of reports, complex numerical data-sets, two dimensional graphs, and charts, which creates a divergence between the data produced and the three-dimensional context of the building. These traditional methods of representing glare data were based on the limitation that computers lacked the hardware capability to simulate lighting data in real-time. However, as processing speed and power of computers rapidly advances [4], glare simulators will transition from requiring lengthy calculation processes to real-time simulation of data. As a result, new and improved methods for representing glare will be introduced over-time rendering previous methods obsolete. In order to overcome the aforementioned issues, we present VR-Glare: an immersive LPS capable of real-time simulation and visualisation of Glare for lighting design and analysis. The proposed system utilizes Virtual Reality (VR) to improve the spatial awareness, and presence [5] lacking in modern PC-based LPS. A set of five immersive visualisations were developed and presented in this paper to demonstrate the potential of using VR for real-time glare simulation and analysis. Due to the dynamic range of current head-mounted displays (HMDs), it is not possible to experience glare discomfort in VR. Therefore, we present two multi-sensory approaches to achieve recreation of glare discomfort in VR using haptic and audio interfaces.

The specific contributions of this paper are:

- A **real-time Virtual Reality Glare simulator** for immersive glare analysis and design.
- A set of **five visualisation techniques** to represent glare within a real-time immersive environment.
- Two methods for **representing glare discomfort through multi-sensory** approaches.

2 Related Work

Despite the rapid hardware advancements of computers in the last decade, limited investigations have been conducted on real-time simulation of glare data for lighting analysis and design. Moreover, no prior research exists on exploring the use of immersive three-dimensional visualisation techniques to create a direct link between glare data produced and the three-dimensional context of the building. As a result, the related works discussed in this section consists mostly on previous research exploring the integration of immersive displays for lighting performance simulation and analysis. The specific research addressed includes the following areas associated with immersive lighting performance: artificial and natural lighting design, day-lighting analysis, and energy cost and consumption. We also provide a brief overview of the historical research developments for LPS, and describe a modern commercial LPS which supports glare simulation and analysis: DIALux.

2.1 Immersive Lighting Performance tools for Simulation and Analysis

In recent years, researchers have begun exploring the integration of Virtual and Augmented reality (AR) with Building Information Modelling (BIM) for lighting design and analysis. BIM is described as a process where building information related to a project's activities is directly linked with a corresponding three-dimensional virtual CAD model. BIM has the potential to be a valuable tool for improving the accuracy of future lighting simulations as non-geometrical factors such as material can have a considerable impact on lighting performance. One of the earliest works using immersive displays for lighting analysis was achieved by Sheng et al. [6] who built a multi-projector AR table-top visualisation system capable of simulating artificial and natural lighting of buildings. The developed prototype was capable of simulating the effects of day-lighting over a 24 hour day-time cycle. Similarly, Natephra et al. [7] developed a BIM-based lighting design feedback (BLDF) prototype targeted towards immersive visualisation using VR. The motivation for developing BLDF was to address flaws associated with previous LPS tools. The authors noted one of the key improvements of their prototype was the implementation of a built-in system to calculate and provide information relating to lighting energy cost and consumption. The results from a case-study conducted demonstrated BLDF was capable of providing stakeholders with an increased level of satisfaction and understanding for perceiving and optimizing lighting conditions to improve lighting design, and mitigate energy costs for future occupants. The authors discussed one of the future directions of their work is to incorporate support for glare simulation and analysis. More recently, Wong et al. [8] developed an immersive lighting visualisation tool incorporating VR and aspects of BIM. This was achieved by linking lighting simulation data obtained from DIALux with the Unity 3D Game Engine to handle VR visualisation and interaction. The results of this research concluded that the system was capable of producing realistic lighting rendering effects and provided the appropriate feedback for users to make informed lighting decisions. Immersive VR daylighting analysis and simulation tools such as RadVR [9] have also demonstrated VR as an effective medium to improve spatial understanding of tasks, improve navigation, and sun position analysis in comparison to PC oriented LPS tools. Representation of daylighting data using RadVR was achieved through two-dimensional heatmaps which incorporated a three colour gradient palette consisting of blue as the minimum value, yellow as the median, and red as the maximum. Birt et al. [10] performed a comparability study aimed at assessing the advantages and disadvantages of using VR for lighting simulation and analysis compared to AR. The results of this research showed VR was most efficient for lighting visualisation and provided a more realistic reconstruction of the real world, whereas AR improved the manipulability of the system, enhanced creativity, and improved participants confidence of the design.

2.2 Commercial Glare Simulation and Analysis applications

The history of lighting performance simulators dates back as early as 1970s when researchers begun developing algorithms to predict luminance and illuminance levels of natural, and artificial light sources [11]. Due to the limited computational power at this time, data was primarily represented numerically. By the 1990s, computer hardware became advanced enough to allow lighting simulators to produce semi-realistic rendered images of lighting. However, these simulators still primarily relied on representing data through numerical datasets, and two-dimensional images and drawings such as isolines. The 1990s also saw the introduction of Radiance: a LPS capable of simulating glare [12], luminance, and illuminance levels [13]. The lighting engine utilized a backwards ray-tracing approach to produce semi-realistic lighting simulations of CAD models. Among numerical datasets, Radiance also utilized semi-realistic static images to visualise lighting data. These images could be overlayed with different visualisations such as false-colour images or contour lines. Radiance was later open-sourced and is still widely utilized as both a lighting analysis tool and backend lighting engine to several LPS systems. Modern commercial LPS applications such as DIALux[1] provides support for calculation, and analysis of glare, daylighting, and artificial

[1]https://www.dialux.com/en-GB/

lighting analysis, energy consumption, among a variety of other features. The software integrates CAD support allowing users to design buildings directly through their software, or import CAD models and BIMs using the Industry Foundation Class. DIALux utilizes LUMSearch: a catalogue search engine to support the integration of a comprehensive range of lighting fixtures. However, despite the significant computational hardware advancements over-time, lighting visualisations in DIALux still primarily consist of traditional approaches for representing glare. These approaches include isolines, numerical data-sets, two-dimensional graphs and charts, static three-dimensional false-colour images and lighting renderings, and auto-generated reports. Although these traditional methods of representing glare data are still effective, users lack the in-situ awareness of the building which we believe can potentially lead to misinterpretation of data. Furthermore, calculation of glare data requires a lengthy calculation process and isn't capable of real-time. We believe real-time simulation of glare data is necessary to provide a more precise representation of glare data resulting in users making more informed lighting decisions.

3 System Overview

3.1 Hardware

The VR technology used to run VRGlare consisted of a standard HTC Vive[2] setup. We also experimented with the Pimax 5K Plus[3] HMD capable of producing a 170 degree field of view (FOV), and 2560x1440 resolution on each lens. However, due to the significantly higher performance demands of the Pimax we primarily used the Vive. A powerful PC was used to handle the high processing and memory demands of VRGlare. The specifications of the PC consisted of an Nvidia GeForce RTX 2080 Graphics Card with an Intel(R) Core(TM) i7-9700 CPU @ 3.00GHz processor and 16GB RAM. Two standard HTC Vive controllers with 6DOF tracking were used as the input devices.

3.2 Lighting Performance Simulator: VRGlare

In order to develop our own glare visualisation techniques, we designed and built our own custom LPS which we called VRGlare. VRGlare was developed using the Unity 3D game engine, and the software was programmed entirely in C#. The lighting rendering system was based off Unity's High Definition Rendering Pipeline described in Section 3.5.1, and initial lumen calculations were based off Unity 3D's built-in lighting integration. The SteamVR library was incorporated to provide VR support, and the 3D User Interaction Toolkit [14] to provide basic VR interaction. The specific motivation for building our own custom LPS was due to other open-source solutions not providing real-time simulation capability, lacked VR support, or did not provide access to their rendering system to build custom visualisation techniques.

[2]https://www.vive.com/
[3]https://www.pimax.com/pages/5k-plus-bundle

3.3 Glare Calculations

3.3.1 Real-time calculation Algorithm

The following four-step algorithmic approach is utilized in VRGlare to achieve a real-time simulation of glare data.

1. At run-time, all objects within the Virtual Environment (VE) are broken down into smaller submeshes. **(Re-calculated once every 500ms)**
2. Lux is calculated for each submesh by casting a ray from each light source to all submeshes within the light sources range.
3. Retrieve all active submeshes within the user's view frustum.
4. Re-calculate glare for each sub-mesh using the UGR equations shown below.

3.3.2 Unified Glare Rating

The Unified Glare Rating (UGR) [15] illustrated in equation 1 is utilized in our LPS to calculate glare discomfort. The UGR equation is used to determine the likelihood of a luminaire causing glare discomfort to surrounding objects. UGR outputs values generally range from < 10 being imperceptible, to > 28 being uncomfortable (see Table 1).

$$UGR = 8log[0.25/Lb \sum (L^2\omega/p^2)] \tag{1}$$

Where Lb is the background luminance, L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye, ω is the solid angle of the luminous parts of each luminaire at the observer's eye, and p is the Guth position index for each luminaire.

Table 1. This table demonstrates the range of values outputted by the UGR equation and its associated description. The corresponding RGB values used in the heat-map visualisation described in Section 3.5.2 are shown on the right-most column (The RGB colours in the table may differ from the generated colours in the system).

UGR Rating	UGR Description	Heat Map RGB	
<10	Imperceptible	0, 34, 255	
>10 <15	Just perceptible	0, 255, 255	
>15 <18	Perceptible	0, 255, 125	
>18 <21	Just acceptable	0, 255, 0	
>21 <24	Unacceptable	0.35, 0.72, 0.188	
>24 <28	Just uncomfortable	0.7, 0.72, 0.188	
>28	Uncomfortable	1, 0, 0.188	

3.4 Bench-markings: Performance Analysis

The capability and performance of VRGlare was measured through a series of stress-tests designed to determine how many glare calculations points the system was capable of handling in real-time. The structure of these tests consisted of spawning an increasing amount of light sources, and virtual objects within the users FOV. To maintain a consistent amount of submeshes, we re-used the same object for each trial. The heatmap visualisation later described in Section 3.5.2 was used as the primary glare visualisation technique throughout the tests. The hardware specifications used in these tests are described in Section 3.1, with the exception of the Pimax 5K which was substituted with a standard HTC Vive HMD. The overall results demonstrated VRGlare performed reasonably well (45 FPS) with 5 light sources, and 50 objects (1300 submeshes) within the user's FOV. A full breakdown of the bench-marking results are described in Table 2.

Table 2. Benchmarking results for heatmap visualisation

Objects In FOV	Light Source	Sub-Meshes	Rays Casted	Frames per second
1	1	26	27	90
10	2	260	552	85
10	5	260	1305	50
20	5	520	2605	48
20	10	520	5210	46
50	5	1300	6505	45
50	10	1300	13010	27
75	10	1950	19510	15
100	10	2600	26010	10
100	20	2600	52020	<5

3.5 Glare Visualisation Techniques

In this section we provide an overview of the visualisations and multi-sensory approaches used in VRGlare to represent glare within an immersive three-dimensional environment. The visualisations described consist of a standard semi-realistic lighting rendering, real-time heatmaps, three new visualisations, and two multi-sensory glare discomfort techniques. Each section provides an overview of each technique which includes the design motivations, partial implementation details, advantages, disadvantages, and potential uses.

3.5.1 Semi-realistic Lighting Visualisation

The semi-realistic lighting visualisation is designed to present a standard semi-realistic rendering of the generated lighting, and glare present within the VE. This is achieved through Unity's built-in High Definition Rendering Pipeline (HDRP) which handles the backend rendering calculations. A number of variables such as the intensity, position, and orientation of natural, and artificial light sources within the VE are used to calculate lighting. Additional object parameters such as materials are also considered to generate semi-realistic glare rendering. Furthermore, the HDRP combines semi-realistic shaders, and global illumination algorithms to simulate direct and indirect lighting phenomenons such as glare, shadows, reflectiveness, and light ray bouncing.

Figure 1. This image presents the standard HDRP Lighting Visualisation: which is a realistic representation of Glare within the scene. Lights are set to 800 lumens and a 3 meter range.

The motivation for utilizing the HDRP as our default visualisation is to present a semi-realistic recreation of the expected lighting produced based on a given lighting design. Additional four-dimensional support has been integrated into the system allowing users to simulate the lighting at specific times throughout the day. The combined use of Unity's HDRP with VR also allows users to experience the interior lighting of a building from a first-person perspective. VR locomotion techniques such as teleportation has also been implemented in VRGlare to provide a non-disorienting approach to navigate throughout the building. We believe this visualisation could be particularly useful for architects to gather lighting feedback from client(s) and other stakeholders associated with the development of the building. The disadvantages of using a default lighting visualisation mainly stems from the user's inability to accurately determine whether the intensity of glare present inside the VE is acceptable or not. As a result, we present our implementation of four visualisations, and two multi-sensory approaches to overcome this specific problem. Furthermore, the HDRP utilizes separate algorithms for glare calculation as opposed to the UGR standards described in section 3.3. This results in less-accurate representation of glare depicted in the rendering as opposed to our other propose visualisations which utilize the standardized UGR equations to calculate glare.

Figure 2. This image presents the heatmap Lighting Visualisation: which generates a three-dimensional heatmap to represent the amount of Glare within the scene. Lights are set to 800 lumens and a 4 meter range.

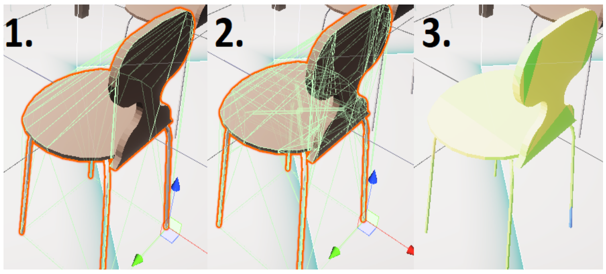

Figure 3. This diagram shows the process of superimposing heatmaps onto virtual objects. *1)* A standard object with a mesh collider is placed into the VE, *2)* The object is sliced into twenty-three submeshes, *3)* Calculations are performed and the generated heatmap is superimposed over the object.

3.5.2 Realtime Heatmap Visualisation

The real-time heatmap visualisation utilizes false-colour images to represent the intensity of glare within the user's FOV. The corresponding RGB colours used in the heatmaps to represent glare intensity follow a four colour gradient palette illustrated in Table 1. At run-time, all objects within the VE are broken down into sub-meshes, these sub-meshes are then used to calculate glare for multiple surface points of an objects. Once these calculations have taken place, the generated heatmaps are superimposed over objects within the VE providing glare feedback to the user (See Figure 3). Unlike previous LPS which require lengthy re-calculation processes whenever a change occurs to the building design, VRGlare is capable of producing calculations in real-time. This means when an object or light source properties are manipulated within the VE, the heatmaps will automatically and simultaneously update in real-time. Prior use of heat-map or false-colour visualisations to represent data on surfaces has been demonstrated as an effective approach to convey feedback due to its high-level of detail, and simplistic readability [16]. Heatmap visualisations provide a simple yet in-depth representation of glare data by revealing the glare intensities for all possible surfaces within the user's FOV using a colour-coded visualisation. The simplistic nature of heatmaps allows interpretation of glare data to be achieved without necessarily requiring an architect or interior designer to analyze data. The trade-off associated with using real-time heatmap visualisations results in users losing the semi-realistic aspects for both the lighting rendering and graphics within the scene. This is due to the visualisation technique superimposing RGB colour-coded heatmaps over the virtual objects thus obstructing the natural material of the objects, and as a result creating an inaccurate representation of how the expected lighting would appear within the building.

Heatmap Visualisation Extension: MirrorViz
MirrorViz is a tool developed as an extension to the real-time heatmap visualisations. The motivation for MirrorViz is that it allows users to overcome the trade-off limitation associated with being unable to experience the realistic-lighting rendering effects when using heatmaps. MirrorViz overcomes this limitation by attaching a 'mirror' to the user's hand which acts as a gateway between the heatmap and semi-realistic lighting rendering effects of the VE.

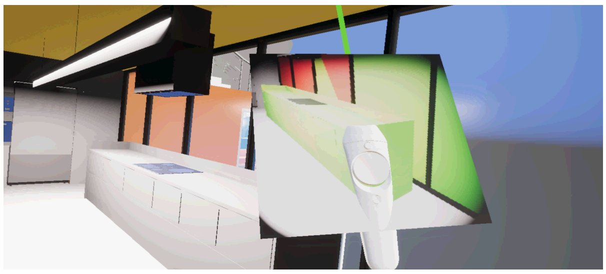

Figure 4. This image presents MirrorViz: an extension to the heatmap visualisation technique

3.5.3 Bendrays Visualisation

The Bendrays visualisation technique is loosely based off the previously developed interaction technique Bendcast[17]. Bendrays represents glare by casting multiple rays from the user's hand to objects within the user's FOV. The rays bend towards object surfaces that produce a UGR value greater than the glare discomfort threshold set by the user. The casted rays are represented as red bezier curves which bends towards objects based on the angle between the user's hand and the given object. This process provides a natural way of casting multiple rays from the user's hand without obstructing the user's perspective.

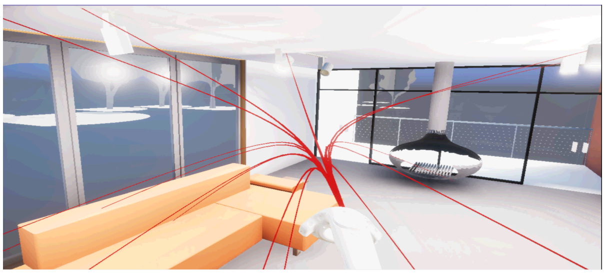

Figure 5. This image presents the Bendrays Lighting Visualisation: (Settings Lights 800 Lumens, 3 meter range in the scene. Rays bend to spots with > 30 UGR

The design motivations which led to the development of the Bendrays visualisation stems from addressing the fundamental limitation of heatmaps which results in users being unable to experience the semi-realistic lighting rendering and graphics provided by Unity's HDRP. Due to the high memory usage of the Bendrays algorithm, Bendrays can negatively impact the performance of the real-time simulator when a large number of objects exceeding the glare threshold are present within the user's FOV. Additionally, in this scenario, the large number of rays produced can potentially obstruct the user's perspective and reduce the readability levels of the visualisation. Lastly, based on our informal observations we believe Bendrays is unable to provide the level of detail compared to the heatmap visualisation and as a result interpretation of data is not as intuitive.

3.5.4 Animated Arrows Visualisation

Animated arrows is a volumetric glare visualisation designed to represent glare discomfort through virtual arrow cues. The generated arrows are omitted from a given light source to any light ray hit surfaces within the user's FOV that exceeds the glare threshold set by the user. The trajectory for the animated arrows is achieved by casting rays from the light source to all submeshes within the users FOV. Using this trajectory, the arrow follows the path of the casted ray until it hits the surface of the mesh. Once the animated arrow collides with the mesh, the object's material is momentarily replaced with a generated heatmap. Finally, the animation will reset after a specified amount of time set by the user and repeat the animation cycle over. Additional parameters can be modified by the user such as the speed of the animation, or the amount of arrows produced by modifying the glare threshold. Animated Arrows provides a unique approach to represent glare data as it allows the user to visualise the entire process of a light-ray being cast from the origin light source to the surface it hits. Due to the additional background information provided, we believe this visualisation not only allows users to visualise glare data, but also provides an approach for users to gain a more detailed understanding of the entire process that's causing the glare to occur. As a result, we believe animated arrows can be a particularly useful tool for re-designing artificial light sources to mitigate glare, especially for users who may not have an extensive background in lighting design. Our current implementation of animated arrows utilizes a performance heavy-algorithmic approach. This can specifically becomes an issue if a large amount of objects exceeding the glare threshold are present in the users FOV. The outcome in this scenario would result in the visualisation producing potentially hundreds of animated arrows causing the applications frame rate to drop. Similarly to the Bendrays visualisation, the large amount of arrows produced may result in the visualisation becoming distracting to the users, and partially obstruct the user's FOV resulting in decreased readability levels as depicted by Figure 6. Lastly, based on our informal observations we believe representation of glare data is not as intuitive as the heatmap visualisation. This is primarily due to the user being required to wait for the animation to complete its cycle in order to interpret the glare data from the generated heatmap.

Figure 6. Animated Arrows visualisation. Top image shows the visualisation with a UGR > 24 whereas the bottom image contains a UGR threshold of > 0

3.6 Multi-sensory Glare Discomfort Representations

Currently, LCD and other related displays do not provide the required dynamic range for reproducing the visual discomfort phenomena that occurs when a user experiences glare in VR. Therefore, in order to recreate the physical discomfort associated with experiencing glare we propose two multi-sensory approach of representing glare discomfort.

Table 3. Audio and Haptic feedback table

UGR Rating	UGR Description	Mean Pitch Frequency (Sine)	Mean Pitch Frequency (Triangle)	Vibration Freq
<10	Imperceptible	97.8 Hz	151.8 Hz	20 Hz
>10 <15	Just perceptible	127 Hz	224.8 Hz	30 Hz
>15 <18	Perceptible	154.2 Hz	270 Hz	50 Hz
>18 <21	Just acceptable	191.2 Hz	502 Hz	70 Hz
>21 <24	Unacceptable	313.4 Hz	899.2 Hz	100 Hz
>24 <28	Just uncomfortable	494.2 Hz	1152.2 Hz	150 Hz
>28	Uncomfortable	1057 Hz	1794.4 Hz	255 Hz

3.6.1 Audio-based Discomfort Representation

Our first approach utilizes an audio-based interface designed to re-create glare discomfort by stressing the user through audio cues. This is achieved by producing varying pitches of three-dimensional frequencies based on the amount of glare visible within the user's FOV. The algorithm is described as followed: firstly, the UGR calculation is performed to determine the amount of glare associated with each object present in the user's FOV. Next, a three-dimensional audio source is placed at the position of the produced glare sources. Finally, the audio source outputs a three-dimensional sound at a specific frequency based on the amount of glare produced by a given object. The frequencies obtained as illustrated in Table 3 were collected by running a pilot study where participants (n=5) were instructed to change the Hertz frequency to match the description described in the UGR discomfort-scale. The mean pitch was then calculated from the data-set and used to determine the frequencies of the sounds produced by the simulator. Another design motivation for developing this technique was to provide users with an approach to represent discomfort levels of glare in the VE without having to visually the experience the glare. One particular scenario where this technique could be used is to provide 360 degree glare feedback, this would allow a user to gain an understanding of objects producing glare behind or outside the users FOV. The disadvantages with using an audio-based interface to represent glare is primarily associated with the difficulty required to accurately interpret data and locate the origin of a glare source. To resolve this issue, we propose using the audio interface concurrently with a visualisation technique.

3.6.2 Haptic-based Discomfort Representation

In addition to an audio-based glare discomfort technique, we also experimented with an alternative multi-sensory approach which utilizes haptic feedback to convey glare discomfort through vibrations. This is achieved by outputting vibrations ranging in intensity values based on the amount of glare present within the user's FOV. The hardware to achieve this consisted of two HTC Vive Controllers, each capable of producing vibrations ranging between 0-255 Hertz. The motivation for developing this technique was strictly to experiment with alternative multi-sensory approaches to represent glare. Based on our initial informal observations we believe vibrations are not as an effective sensory modality for reproducing the physical discomfort of glare in comparison to an audio-based interface. However, we believe this proof of concept could be potentially used to capture glare discomfort feedback in a less physically distressing manner. The hardware used to output haptic-feedback also plays a key role in how effective the technique will perform. In our case, we used the HTC Vive Controllers which was limited to producing a maximum of 255 Hertz on each hand.

4 Future Directions

The immersive glare-based simulation and visualisations presented in this paper is one aspect of a more compact immersive LPS prototype we built. The future directions of this work aims to conduct a formal user study to evaluate all aspects of our immersive lighting simulator which includes interior/exterior lighting design and simulation, daylight analysis, energy consumption, and cost analysis. We also aim to explore the advantages and disadvantages of using immersive displays and six degrees of freedom input devices compared to a standard PC-mouse desktop setup for lighting analysis, and design. Current implementations of our system is limited to a uni-directional exchange of data between Revit and Unity using the Industry Foundation Class. A future direction could be to develop a workflow that creates a real-time bi-directional exchange of BIM data between Revit and Unity. Finally, using the ZED Mini depth-sensor we aim to incorporate Mixed Reality support into our system. This will allow users to navigate between AR and VR perspectives which has previously been identified as a potentially valuable tool for lighting analysis, and design[10].

5 Conclusion

This paper presented VRGlare: An immersive Lighting Performance Simulator supporting real-time glare simulation and analysis through the integration of Virtual Reality. In summary, we discussed the hardware, algorithms, equations, visualisations, and multi-sensory representations of glare in respect to the simulator. Five visualisation techniques were presented capable of representing glare and providing feedback to the user in a simplified, and effective manner. We also presented two multi-sensory glare discomfort techniques using an audio and haptic-based interfaces designed to simulate the physical discomfort caused when experiencing glare. Lastly, we discussed the limitations associated with our simulator, future directions, and goals. Our hope is that this work will act as a stepping stone towards the future research and development of using three-dimensional visualisation techniques for real-time lighting performance simulation.

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References

[1] GV Hultgren and B Knave. Discomfort glare and disturbances from light reflections in an office landscape with crt display terminals. Applied Ergonomics, 5 (1):2–8, 1974.

[2] Jeffrey Anshel. Visual ergonomics in the workplace: How to use a computer and save your eyesight. Performance+ Instruction, 33(5):20–22, 1994.

[3] Peter Robert Boyce. Human factors in lighting. Crc Press, 2014.

[4] Charles E Leiserson, Neil C Thompson, Joel S Emer, Bradley C Kuszmaul, Butler W Lampson, Daniel Sanchez, and Tao B Schardl. There's plenty of room at the top: What will drive computer performance after moore's law? Science, 368(6495), 2020.

[5] Yu Shu, Yen-Zhang Huang, Shu-Hsuan Chang, and Mu-Yen Chen. Do virtual reality head-mounted displays make a difference? a comparison of presence and self-efficacy between head-mounted displays and desktop computer-facilitated virtual environments. Virtual Reality, 23(4):437–446, 2019.

[6] Y. Sheng, T. C. Yapo, C. Young, and B. Cutler. A spatially augmented reality sketching interface for architectural daylighting design. IEEE Transactions on Visualization and Computer Graphics, 17(1):38–50, 2011.

[7] Worawan Natephra, Ali Motamedi, Tomohiro Fukuda, and Nobuyoshi Yabuki. Integrating building information modeling and virtual reality development engines for building indoor lighting design. Visualization in Engineering, 5(1):1–21, 2017.

[8] MO Wong, J Du, ZQ Zhang, YQ Liu, SM Chen, and SH Lee. An experience-based interactive lighting design approach using bim and vr: a case study. In IOP Conference Series: Earth and Environmental Science, volume 238, page 012006. IOP Publishing, 2019.

[9] Mohammad Keshavarzi, Luisa Caldas, and Luis Santos. Radvr: A 6dof virtual reality daylighting analysis tool. arXiv preprint arXiv:1907.01652, 2019.

[10] James Birt, Patricia Manyuru, and Jonathan Nelson. Using virtual and augmented reality to study architectural lighting. In International Conference on Innovation, Practice and Research in the Use of Educational Technologies in Tertiary Education, pages 17–21, 2017.

[11] CGH Plant and DW Archer. A computer model for lighting prediction. Building Science, 8(4):351–361, 1973.

[12] Gregory Ward. Radiance visual comfort calculation. volume 6, 1992.

[13] Gregory J Ward. The radiance lighting simulation and rendering system. In Proceedings of the 21st annual conference on Computer graphics and interactive techniques, pages 459–472, 1994.

[14] Kieran May, Ian Hanan, Andrew Cunningham, and Bruce Thomas. 3duitk: An opensource toolkit for thirty years of three-dimensional interaction research. In 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), pages 175–180. IEEE, 2019.

[15] Commission Internationale de L'Eclairage. Cie 117-1995 discomfort glare in interior lighting, 1995.

[16] Leland Wilkinson and Michael Friendly. The history of the cluster heat map. The American Statistician, 63(2):179–184, 2009.

[17] Kai Riege, Thorsten Holtkamper, Gerold Wesche, and Bernd Frohlich. The bent pick ray: An extended pointing technique for multi-user interaction. In 3D User Interfaces (3DUI'06), pages 62–65. IEEE, 2006.

[4]Gerhard Kimenkowski and Stephen Walton, Project Managers for CADwalk Global - https://www.cadwalk.global/