EVALUATING DAYLIGHT LIGHTING APPEARANCES IN VIRTUAL REALITY ENVIRONMENTS

An Undergraduate Research Scholars Thesis

by

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Submitted to the LAUNCH: Undergraduate Research office at
Texas A&M University
in partial fulfillment of requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Faculty Research Advisor: Dr. John Keyser

May 2022

Major: Computer Science

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This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

TAMU IRB #: 2021-1416M Approval Date: 12/07/2021 Expiration Date: 12/06/2024

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ABSTRACT

Evaluating Daylight Lighting Appearances in Virtual Reality Environments

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This paper focuses on evaluating the displays of lighting in built environments within virtual reality systems. Two approaches for simulating daylighting in VR are presented: (1) a 360º panorama view of the space at a particular point and then generating renderings from multiple different locations in the scene vs (2) a free roam approach in which a texture is created for each polygon face in the scene. A user study is conducted to quantify user presence, perceptual impressions, and physical symptoms of users in the different daylighting display approaches being contrasted. The results from the user study indicate there is no significant difference in physical symptoms or in the usefulness of one approach over the other in terms of evaluating daylighting. One aspect of the study did find a stronger sense of spatial awareness in the free-roam environment. The presented results can lead to additional research in using virtual reality to simulate real environments when investigating the impacts of daylighting in spaces.

DEDICATION

This thesis is dedicated to my family, friends, instructors, and peers who supported me throughout the research process.

ACKNOWLEDGEMENTS

Contributors

I would like to thank my faculty advisor, Dr. Keyser for his knowledgeable guidance and hours of support throughout the course of this research process. Thanks also go to my colleagues and the Department of Computer Science and Engineering faculty and staff for making my time at Texas A&M University a great experience. Finally, a big thanks to my family and friends for their continuous love and encouragement.

Funding Sources

No funding was provided for this project. Undergraduate research was supported by and developed under the *Human Centric Daylighting based on circadian stimulus, view, visual comfort, and lighting needs* grant from the Texas A&M University Triad Program.

NOMENCLATURE

HDR	High Dynamic Range
VR	Virtual Reality
WSL	Windows Subsystem for Linux

1. INTRODUCTION

Daylighting has a substantial role in various aspects of architectural design, ranging from a user's overall wellbeing to energy efficiency and productivity. Most people spend the majority of their time indoors and many studies have shown the benefits of good daylighting in buildings; therefore, daylighting design aims to provide sufficient illuminance for improved user presence and help manufacturers develop technologies that satisfy customer needs [1]. However, daylighting faces limitations, and studies are conducted to evaluate design choices in determining what types of designs work well at meeting goals.

1.1 Daylighting Simulations

Daylighting is the process of the controlled use of natural light within buildings and is implemented by placing windows or other transparent mediums and reflective surfaces to provide effective illumination throughout the day. The goal is to optimize the amount of daylight in the room while minimizing glare and promoting the quality of light distribution to maintain a comfortable environment and pleasing atmosphere [2]. Illuminance quantifies the amount of light over a given surface area; luminance quantifies the amount of light passing through or reflected from a surface – how light is perceived by the human eye. While illuminance metrics are used to determine light sufficiency, luminance is the standard metric for quantifying glare.

The first methods for daylighting simulations involved miniature models, but technical advances allow for the current method for daylighting simulation which is to create virtual models of the building's complicated geometry typically with the aid of advanced CAD systems and input devices. Radiance, a physically based rendering system, is the standard tool used to stimulate daylighting. It uses a hybrid backward ray-tracing algorithm with extensions to handle directional-diffuse reflection at any level in any environment to create renderings which can then be viewed on a digital device [10]. Additionally, it gives users liberty during the simulation process to control the output for creating accurate results.

1.2 Daylighting in VR Simulations

With VR systems gaining popularity over the years and the advances in computing power and computer graphics, virtual simulations have become the standard for daylighting simulation. VR simulations allow for simpler and quicker methods of testing by allowing us to recreate and study in isolation and in a controlled way. However, common virtual reality displays can be problematic by inaccurately conveying glare to a user or being unable to contrast intensely dark from light areas. Fully addressing this would require a display format that can convey large differences in luminance.

High dynamic range images are rendered such that stored values spanning the whole tonal range of real-world scenes are mapped to each pixel, addressing this issue. Image-based lighting using HDR images accounts for information about the shape, color, and intensity of direct light sources as well as the distribution of indirect light from surfaces in the scene [4]. Compared to its predecessor, SDR, HDR images can more accurately simulate how objects and environments would look if they were illuminated by light from the real world.

Consumer VR systems do not support image-based lighting using HDR images and are converted into SDR for viewing daylighting in VR. As a result, the ability to convey contrasting dark areas from light areas is compromised.

1.2.1 Optimizing User Immersion in VR with Daylighting

Different virtual reality approaches for user immersion may produce different levels of user presence and overall experience. This study uses a new VR approach that allows users to walk around freely, but with limitations for viewing the daylight renderings. Its effectiveness is unknown. The systematic methodology of this study is to conduct a user study to evaluate the effectiveness of the free roam simulation approach to determine if the new approach can provide a better feeling of presence for the user without compromising the effects of daylighting in the simulation too much. The results can help find an effective way to change daylighting simulation and be important to future virtual reality advancements as virtual reality environments are comparatively more adjustable and easily changeable for daylighting.

1.3 Previous Work

Previous research around the perceptual accuracy of virtual reality environments has identified factors crucial for improving the feeling of presence and possible subjectiveness in human responses to virtual reality. Results from previous studies highlight key factors such as user interaction and immersion in creating virtual reality environments that are perceptually realistic and can provide an experience that is indistinguishable from normal reality [5,8]. Other studies relating to user presence in virtual reality environments, such as Bishop and Rohrmann's, investigate the experience of a rendered virtual reality model environment that is immersive and interactive juxtaposed to its real life, physical environment to identify crucial parameters in creating virtual environments [7,9]. The conclusions focused on the similarities of subjective cognitive and affective responses between the simulations and those when exposed to reality. The study conducted by Higuera-Trugillo, Maldonado, et. al focused on the psychological responses evoked by a simulated environment and contrasted the results to those from a physical environment setup to determine the most effective presentation mode for the best psychological and physical responses and sense of realism [3].

Although there are studies that research the experience of an immersive simulated environment, none have reached definitive conclusions regarding different user immersive methods and daylighting with simulated environments. Previous studies have used dim scenes in virtual reality environments whose luminances are much lower than its real-life counterpart and presented significant differences in scores. This raises the question of whether the free-roam approach - which could improve a user's sense of presence but compromises the quality of daylight renderings - is as effective for VR simulations as the current standard approach using high-quality rendering but with little movement. Key takeaways from these previous studies influenced the methodology of this study, specifically, that this user study should produce valid results and quantify criteria such as user presence, perceptual impressions, and physical symptoms of users.

2. METHODS

The goal of this thesis is to compare the effectiveness of two VR approaches: a 360º panorama view and a free roam approach. The methods followed in this study consist of the selection of VR simulations for both the 360º panorama and free roam approach and the experimental design for a user study.

2.1 Equipment

The VR headset used in this study is the Oculus Rift (DK2) which uses a 1920 × 1080 pixel low persistence display. In the development of this study, the software used was Oculus Runtime in combination with Godot Game Engine and the corresponding Godot Oculus VR Toolkit development package. The game engine allows the user to interact with the scene in VR once the FBX models of the scenes are imported; Godot was specifically used due to its compatibility with HDR files. A teleportation method requiring two hand-held controllers was used in the free-roam method to enable users to freely move around the scene.

2.2 Virtual Environment: 360º Panorama Simulation

Panoramas are a popular approach to create 3D projections in various VR applications such as situations where the background of an environment is static, allowing the user to look around in all directions. The 360º panorama simulation was generated by first implementing a cube map of a 360º space as different square images stitched together and then creating an equirectangular projection of the space. This approach produces a high-quality panorama around the user due to each texture being mapped to a corresponding HDR image. Using a custom 3D model of a room as a starting point, the test room was then exported to Radiance for rendering various lighting appearances. With Radiance, it is possible to produce multiple HDR textures for highly accurate visualizations throughout the scene preparation and simulation process. The rendering with Radiance resulted in an empty room environment which was then imported into the game engine Godot (Figure 2.1). The HDR texture files can be loaded into Godot and converted to a compatible .tres type as a PanoramaSky attribute within the virtual simulation.

In the 360º panorama simulation, users do not have the liberty to move freely around the environment. Users would have the VR headset on and could look around by moving their head like they would in real life.

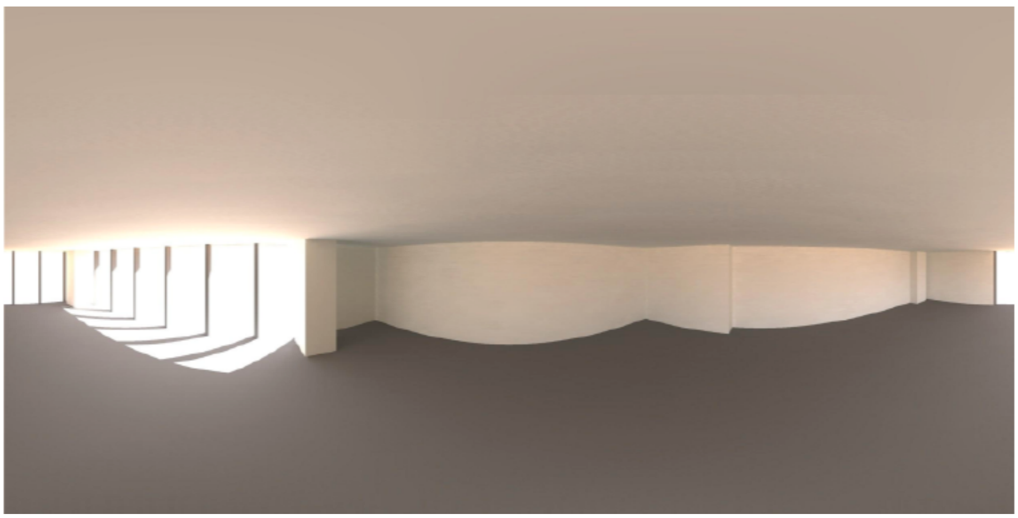

Figure 2.1: Virtual Environment of 360º Panorama View Approach

2.3 Virtual Environment: Free-Roam Simulation

In contrast to the previous 360º panorama approach, the free-roam simulation resembles the VR experience most users are accustomed to. Users have a strong sense of presence in the simulated environment by having the ability to move around and interact with the environment.

The free-roam environment was generated by first generating a parallel projection view for each face of a 3D object of the room, then rendering an HDR file again for each face using Radiance. Next, the 3D object and HDR files mapped to each face are imported to a 3D software tool to create a final FBX model file of the room which is compatible with a virtual reality game engine application, Godot (Figure 2.2).

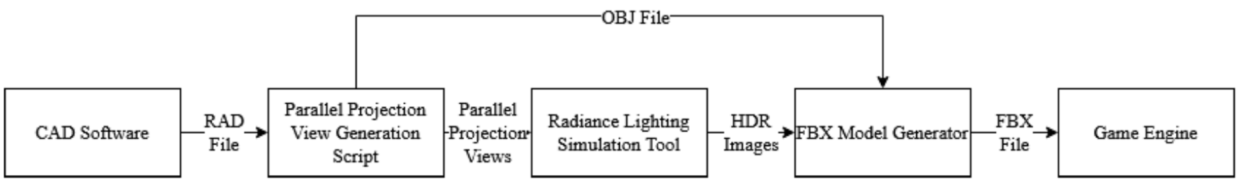

Figure 2.2: Pipeline for Generating Free-Roam VR Environment

An important feature of the free-roam application is the teleportation locomotion method to enable users to freely move around the room. With the VR headset on, users could move around the scene by holding down the controller's trigger, aiming the projection around the environment, and then releasing it at the spot they want to move to (Figure 2.3).

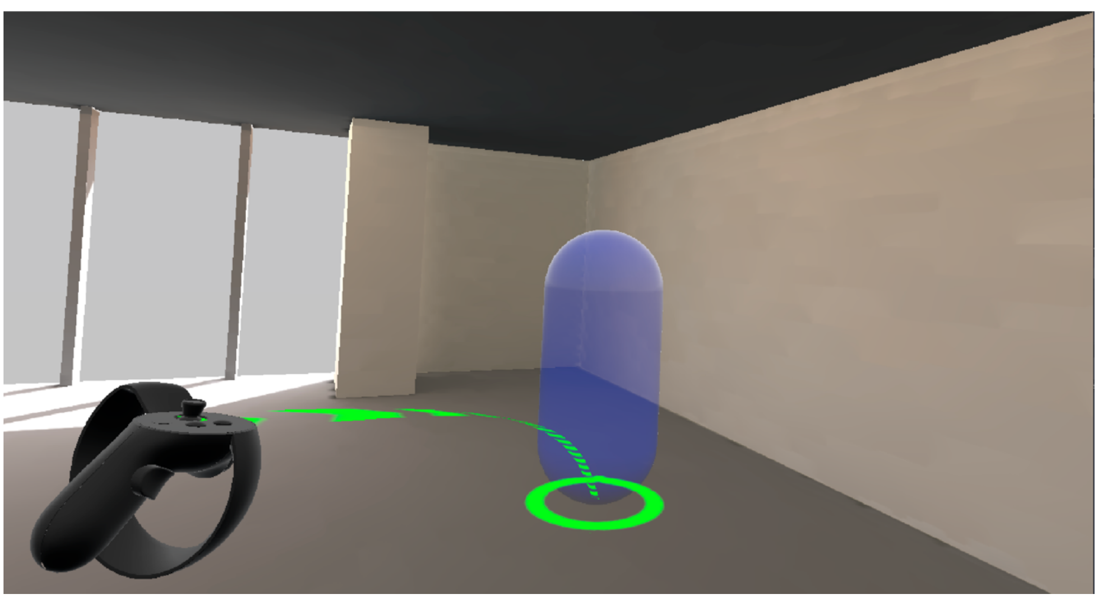

Figure 2.3: Users can use the hand controllers to move around the room.

2.4 Experimental Design

In this study, due to the room simulation not being modeled after a real environment, the experiment was designed to best quantify how a user perceives presence based on the daylighting of an arbitrary room. The methodology consisted of collecting experimental data questionnaire items using a Likert scale. Questions were grouped in three sections relating to user presence, perceptual impressions, and physical symptoms of the users. The questions were based on those of previous studies such as Chamilothori, Wienold, and Anderson [5]. The participants would be immersed in both virtual simulations and asked to evaluate the two VR approaches, the 360º panorama and free roam simulations, one at a time. Half of the participants would start in the 360º panorama simulation while the other half would start in the free-roam simulation to minimize variation between their answers. While participants were immersed in the virtual reality environment, they would be asked to complete three tasks relating to daylighting appearances within the simulation. The first task is to ask the participant where they think the best location would be to place a table, desk, and mirror in the empty virtual environment and why. The second task would be to render the same environment at different times of the day. Radiance can render the lighting of a specific location at a specific time. The goal is to determine which time of day's lighting appearance the participant found most comfortable. Lastly, the third task aimed to compare the perceived spatial accuracy of the two environments by placing two objects in the virtual room and asking the participants to determine the location of the objects on a 2D blueprint of the room. After each simulation, participants would fill out a post-simulation questionnaire which was chosen to have a thorough assessment of the users' sense of presence within the VR environment (Table 2.2). In the questionnaire, participants would be asked about their experience with VR systems prior to this user study to ensure that the sample population encompassed a range of VR users from novice to frequent, experienced users.

Table 2.2: Questionnaire

Questionnaire Items	
Reported Presence	
RP. 1	I feel like I was just perceiving pictures. [a]
RP. 2	I felt present in the virtual space. [a]
RP. 3	I was unaware of my real environment. [a]
Perceptual Impressions	
PI. 1	How pleasant was the space? [b]
PI. 2	How interesting was the space? [b]
PI. 3	How exciting was the space? [b]
Physical Symptoms	
PS. 1	How sore do your eyes feel? [b]
PS. 2	How fresh does your head feel? [b]
PS. 3	How fatigued do you feel? [b]
	How much experience do you have with VR systems?

[a]A scale from 1 to 5, 1 corresponding to *fully disagree* and 5 corresponding to *fully agree*
[b]A scale from 1 to 5, 1 corresponding to *not at all* and 5 corresponding to *very much*

3. RESULTS

The results of the experimental study are presented in five subsections including the experimental protocol, followed by the results from each of the tasks as well as the participant's reported experience from the post-survey questionnaire including perceptual accuracy, physical symptoms, and the perceived presence.

3.1 Experimental Protocol

The experimental study was conducted with 18 participants, aged between 21 and 50. Originally, we expected to enroll about 35 people in this research for more valid and accurate results. Due to hardware issues negatively impacting the VR environment quality and overall quality of the user study, only 18 studies were completed successfully. The duration of the experiment was 25 minutes per participant, conducted in scheduled appointments. Each followed the same process; at the start of each session, subjects were guided through an informed consent document containing information about the experiment and its associated risks. After, they had to acknowledge and sign the form to proceed. The participants were then given a basic tutorial for using the VR equipment and navigating around a VR environment. With the VR headset adjusted correctly and controllers in hand, assisted by research personnel, the participants were able to interact and move around within the VR environment. The participants were randomly assigned to evaluate the free-roam or 360º panorama simulation first, counterbalancing the order of stimuli between subjects; the participants were not told which environment they were in.

Once familiar with the VR room and navigating in VR, participants were instructed to perform the following tasks: (1) Locating the best spot in the VR environment to place a bed, a table, and a mirror followed by providing a verbal explanation for the reasoning behind each decision. Their oral responses were recorded by research personnel. (2) Participants could explore the room under various lighting conditions and then rate how pleasant they found the environment on a scale of 1 to 10. Their oral responses were recorded by research personnel. (3) Objects were placed in the environment for the participants to locate. When the participants felt they had a good idea of where the object's location was in the room, they would remove the headset and determine the object's location by marking it on a 2D floorplan of the room. Ideally, having experimental data for all three tasks would provide more insight. However, due to technical issues when rendering 360º panoramas for multiple daylighting appearances, only tasks 1 and 3 were asked to be performed for this user study.

After the participant conducted both tasks (1) and (3), they were asked to take off the headset and given a post-simulation questionnaire (Table 2.4). The participants would put on the headset again, and the process was repeated for a second VR environment. A tutorial for navigation was given, followed by the participant performing two tasks, and then a post-simulation questionnaire, after which the study was complete.

3.2 Questionnaire Results

For each environment, each participant evaluated both the free-roam approach as well as the 360º panorama approach and answered the post-simulation questionnaire. We then evaluated and compared the perceptual accuracy and sense of presence of both VR approaches by calculating the overall average for each question as well as category and observing if there is a significant difference in the results. Table 3.1 shows the average distribution within the sample size, indicating similar experiences for both free-roam and 360º panorama simulation. Perceptual impressions and physical symptoms show almost no difference between the two VR approaches. In contrast, the responses regarding reported presence show a slightly larger difference.

Table 3.1: Questionnaire Results

	Free-Roam Average	Panorama Average
Reported Presence		
I feel like I was just perceiving pictures.	2.5	2.3
I felt present in the virtual space.	4	3.9
I was unaware of my real environment.	3.7	3.4
Perceived Impressions		
How pleasant was the space?	3.8	3.9
How interesting was the space?	3.2	3.3
How exciting was the space?	2.8	2.8
Physical Symptoms		
How sore do your eyes feel?	1.2	1.2
How fresh does your head feel?	3.6	3.5
How fatigued do you feel?	1.1	1.1

3.2.1 Statistical Analysis

The original hypotheses were as follows:

H_1: Higher presence will be reported from the free roam simulation.

H_2: Higher perceived impressions will be reported from the 360º panorama simulation.

H_3: Worse physical symptoms will be reported from the free roam simulation.

Previous studies investigating virtual reality environments use tests of analysis of variance to determine whether the null hypothesis of no significant difference between the compared environments can be proved true or rejected.

For this user study, each environment was tested against three metrics: reported presence, perceptual impressions, and physical symptoms. Higher values for the reported presence and perceptual impressions category are considered positive, while lower values for physical symptoms are considered positive. The sample size, n, for this study is 18 individuals meaning a t-test will be used because $n < 30$. An independent samples one-tailed t-test was conducted to compare the means of two sets of data because they are independent. It is essential to use this for small samples due to their distributions having a possibility of being non-normal.

$$df = n_A + n_B - 2 \tag{1}$$

An alpha value of $\alpha = 0.05$ and Equation 1 for degrees of freedom was used, corresponding to $t_{\alpha,df} = 1.697$ on the t-table.

$$T = \frac{\bar{x}_A - \bar{x}_B}{s_p * \sqrt{\frac{1}{n_A} + \frac{1}{n_B}}} \tag{2}$$

Using Equation 2 for the test statistic, with *A* representing the free-roam environment and *B* representing the 360º panorama environment, the following were calculated (Table 3.2, 3.3, 3.4).

Table 3.2: Overview of the participants and their reported presence.

	$\bar{x}_A$	$\bar{x}_B$	T
I feel like I was just perceiving pictures.	2.555	2.333	0.596
I felt present in the virtual space.	4.058	3.941	0.461
I was unaware of my real environment.	3.733	3.466	0.667

Table 3.3: Overview of studied attributes and their perceptual accuracy.

	$\bar{x}_A$	$\bar{x}_B$	T
How pleasant was the space?	3.80	3.933	0.636
How interesting was the space?	3.266	3.333	0.211
How exciting was the space?	2.80	2.866	0.194

Table 3.4: Overview of the participants and their reported physical symptoms.

	$\bar{x}_A$	$\bar{x}_B$	T
How sore do your eyes feel?	1.20	1.20	0
How fresh does your head feel?	3.60	3.533	0.133
How fatigued do you feel?	1.133	1.133	0

Based on the results shown above, since the calculated test statistic $T,$ is less than $\mathrm{t}-$ table value $t_{\alpha,df}$, we fail to reject the null hypotheses and **cannot conclude from this that there is a significant difference** between the means for all three metrics: reported presence, perceptual impressions, and physical symptoms. Regarding physical symptoms, two of the three questionnaire items resulted in the same overall average.

3.3 Coding Process for Qualitative Research

For task 1, participants were asked to decide the best location to place a bed, a table, and a mirror within the empty VR environment. A verbal reasoning was provided and recorded by research personnel. The goal of this task was to determine whether one VR approach would prompt users to address the lighting of the room or rather, whether users were more aware of the lighting in one environment compared to the other from their verbal responses.

The experiment data from task 1 resulted in qualitative data. We used qualitative coding to systematically categorize excerpts in the qualitative data to search and identify concepts and find relations or patterns between data items. An initial close reading of the recorded text was performed to familiarize research personnel with the content and gain an understanding of the themes covered in the raw data [9]. After a first-round pass of reading the data, generic codes were assigned to certain excerpts such as descriptive keywords or phrases with strong positive or negative connotations or counting the frequency that “light” or “lighting” was addressed (Table 3.5). The initial codes functioned as a category name and description. Then, to reduce overlap and redundancy, the initial codes were grouped into categories based on whether they pertained to the same topic or general concept. For example, initial codes relating to the user’s impression of comfort were grouped together resulting in three subcategories: (1) comfort – positive, (2) discomfort - negative, and (3) no mention of comfort – indifferent.

Because the participants were asked to perform Task 1 in both the free roam and 360º panorama simulation, it is useful to see whether there is a change in opinion for where they believe is the most appropriate placement for the furniture. If the participant changed their placement in the second environment, the research personnel followed up by asking for their reasoning. If the participant decided to keep the placement the same as the previous environment, the research personnel followed by asking whether their reasoning was consistent with the prior.

Table 3.5: Coding Scheme Table for Qualitative Data from Task 1

Code	Primary Themes
Priority of Light	Does not mention lighting
	Mentions lighting in the room
	Mentions lighting multiple times and includes "natural lighting"
General Impressions	No mention of descriptive words
	Positive words
Change in Opinion Between Environments	Same placement for both environments
	Some furniture pieces were moved
	Due to lighting
	No mention of lighting
	Completely different placement

A total of 18 participants provided verbal responses for each of the three possible furniture pieces; therefore, an overall total of 54 responses were reviewed to determine the number of times each primary theme was mentioned with each occurrence being one point. If the participants mentioned a primary theme multiple times in their verbal response, only one point was recorded for that individual response. The theme "Change in Opinion Between Environments", which relates to whether participants choose a different placement for furniture between environments, had no variation between participants who experienced the free roam environment vs. the 360º panorama environment first. The frequency for each primary category was summed up and shown as percentages in Table 3.6.

Table 3.6: Resulting Frequency of Certain Themes

Primary Themes	**Frequency (%)**	
	Free-Roam	**Panorama**
Does not mention lighting	27.77%	27.77%
Mentions lighting in the room	72.22%	72.22%
Mentions lighting multiple times and includes "natural lighting"	44.44%	38.88%
No mention of descriptive words	94.44%	83.33%
Positive words	5.55%	16.66%
Same placement for both environments	33.33%	
Some furniture pieces were moved		
due to the lighting	33.33%	
no mention of lighting	16.67%	
Completely different placement	16.67%	

Participants addressed the lighting the same number of times between environments, indicating that one environment does not prompt participants to observe the daylighting more than the other. Or rather, participants are equally aware of the daylighting of the virtual reality environment between the free-roam and panorama. Though no significant differences were observed between perceived impressions in the free-roam and 360º panorama environments through the questionnaire method, the second method using the verbal responses of the participants indicated more positive perceived impressions of *cozy, comfortable, motivating* feelings from the 360º panorama environment resulting in a higher frequency of words with positive connotations when describing the environment. Lastly, the third theme addressed changes in the placement of furniture and whether participants used daylighting as a factor in their decision. Amongst all the participants, approximately $\frac{1}{3}$ changed their opinion partially due to lighting while $\frac{1}{3}$ kept their decisions the same. Of the $\frac{1}{3}$ participants whose placements remained the same, $\frac{2}{3}$ of the participants' original reasoning behind their placement factored in the lighting of the environment.

3.4 Perceived Presence in the Virtual Reality Environment

The third task asked participants to determine the position of two objects within the 3D space by marking it on a 2D floorplan of the room. The x-coordinate and y-coordinate of the objects were chosen by research personnel. To display the objects, they were rendered as a separate environment used specifically for this task. Using two objects allowed for more opportunities to compare a user's sense of presence and their (perceived?) spatial accuracy within the virtual environment. Participants marked the location with an "X" symbol to help with more precise measuring.

To create an accurate 2D blueprint of the floorplan, X server (software used to view images and graphics from within the Windows Subsystem for Linux) was used to view the floor of the 3d room (obtained from an OBJ file) as an HDR image which was then saved as a PNG file. Additionally, labels such as "window", and "column" were added to the 2D blueprint to help the user understand the orientation of the room. The coordinates of the objects were recorded and visible through X server using the 'ximage' command.

The floorplan was scaled to a 13.3 cm x 10.2 cm size. The difference in distance (cm) from the participant's indicated perceived location to the actual location was measured (Table 3.7). A larger number indicates that the user's perceived location of the object is farther away from the actual location of the object in the room.

Table 3.7: The distance in cm of how far away the participants perceived location of the object was from the actual location.

	Free-Roam		**Panorama**	
	Object 1	**Object 2**	**Object 1**	**Object 2**
Average	1.187 cm	1.075 cm	1.662 cm	1.60 cm
Variance	6.938 cm	3.412 cm	8.135 cm	8.135 cm

3.4.1 Statistical Analysis

The variance for the free-roam environment was smaller than the variance for the panorama environment. A two-tailed F-test was conducted to compare the variances of one object in the two environments.

The hypotheses tested are:

H_0: $\sigma_1^2 = \sigma_2^2$
H_1: $\sigma_1^2 \neq \sigma_2^2$

Let ${\sigma_1}^2$ and ${\sigma_2}^2$ be the unknown population variances, ${s_1}^2$and ${s_2}^2$ be the sample variances, and $n_1$and n_2 be the sample sizes. The F ratio, or test statistic, can be calculated by using Equation 3.

$$F = \frac{\left[\frac{{s_1}^2}{{\sigma_1}^2}\right]}{\left[\frac{{s_2}^2}{{\sigma_2}^2}\right]}. \tag{3}$$

Since the null hypothesis is ${\sigma_1}^2 = {\sigma_2}^2$, then the test statistic becomes $F = \frac{{s_1}^2}{{s_1}^2}$. For a two-tailed test, the critical values corresponding to this user study are 0.42 and 2.4034. The H_0 can be rejected if $F < 0.42$ or $F > 2.4034$. With F_1 and F_2 corresponding to object 1 and object 2 respectively, $F_1 = 0.7273$ and $T_2 = 0.1759$. Because $T_2 < 0.42$, we can reject the null hypothesis and conclude there is a significant difference between the two variances.

4. CONCLUSION

4.1 Discussion

This study aimed to determine whether one VR approach was more effective than another by using three different methods: (1) questionnaires to evaluate the participants' reported sense of presence, symptoms, and perceptual impressions, (2) asking participants to place furniture (in a virtual environment) to determine how much of an influence or role lighting plays in people's decision making, and (3) having the participants locate objects from a 3D virtual reality space to a 2D space to quantify people's spatial perception between the free-roam and 360º panorama environments.

While there were small differences between the averages of various questions asked in the questionnaire, specifically the "reported presence" category, there is no evidence to conclude a significant difference between the free-roam and 360º panorama environment. Based on the three metrics: reported presence, perceptual impressions, and physical symptoms, the participants showed similar results. The results appear reasonable since the room layout for both environments was very similar, and each participant was only exposed to each environment for a short period of time before taking the questionnaire. This may have contributed to the similar results.

The second testing method indicated there were no significant differences observed between perceived impressions in both environments. Based on the participants' verbal responses, neither environment prompted users to be more aware of the daylighting of the environment. Regarding whether users changed the placement of furniture, approximately $\frac{1}{3}$ of the participants changed their opinion partially due to lighting while $\frac{1}{3}$ kept their decisions the same. Of the $\frac{1}{3}$ participants whose placements remained the same, $\frac{2}{3}$ of the participants' original reasoning behind their placement factored in the lighting of the environment. While this is not conclusive as to why one environment's lighting prompts users to change their opinion, it can illustrate that daylighting plays a role in people's opinion of the room enough to change their room layout.

The third testing method in this study did not address the effects of daylighting within virtual reality environments; however, it did show whether users have a higher sense of presence in one environment than the other. Results of the average distance of participants' perceived location from the actual location indicated better performance in the free-roam environment and an overall lower variance in results. It can be noted that the variance reported for object 1 and object 2 in the panorama view is the same.

4.2 Conclusion

In this study, a new, novel free-roam approach for generating a more immersive virtual reality environment was introduced, and its effectiveness was tested as an alternative approach to the previous standard. Both quantitative and qualitative data were analyzed to compare the participants' responses to the different virtual reality environments. Based on the three different methods to investigate the effectiveness according to the metrics: reported presence, perceived impressions, and physical symptoms, it can be concluded that both approaches result in similar responses from users. There were no significant differences observed, and neither approach was found to be more effective than the other in displaying daylighting within the virtual space.

The data did support that the free roam environment gives a stronger sense of spatial presence. The lower differences and smaller variance indicate stronger performance from users in understanding location. While this does not mean the free-roam method will be better for evaluating daylighting, the free roam approach may be a better option to be used as a surrogate to real spaces for empirical research.

4.3 Future Works

The experimental testing of the proposed methods demonstrated possible differences in the three metrics: reported presence, perceived impressions, and physical symptoms. Additional user studies with a much larger population sample as well as investigating differences between real daylit spaces and the corresponding virtual reality modeled after the real space could provide more insight from a different perspective on whether there is a significant difference between users' perceptions between the two virtual reality environment approaches. Participants were immersed in the virtual simulation for a short period of time for each environment. Longer exposure may result in different responses than those presented in this thesis. Future work is encouraged to investigate the effectiveness of both methods on other aspects of subjective perception and experience.

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