Perception of Indoor Lighting: A Comparative Study in Physical and Virtual Environments

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Abstract

Virtual reality (VR) is increasingly used in lighting research to explore human perception in a controlled visual environment. However, its ability to emulate real-world experiences remains uncertain due to technological limitations. This study examines VR's efficacy in evaluating responses to six indoor lighting scenarios within an office setting, varying in sky conditions, light Correlated Color Temperature (CCT), and blind position. The first phase involved 26 participants assessing office lighting in a physical environment; the second phase involved 15 participants evaluating virtual replicas. Assessments focused on attributes like “Brightness”, “Color”, “Monotonous”, “Vibrance”, and “Likability”. Statistical analysis revealed no significant differences in the perception of color, likability, and monotonousness between VR and real settings, though disparities in vibrancy and brightness were noted. Qualitative feedback highlighted challenges in distinguishing between lighting setups and identified issues regarding VR's ability to replicate the resolution and scale of real-world environments. This study underscores VR's potential and limitations in lighting research.

Keywords: Virtual Reality, Indoor Lighting, Human Perception, CCT, Brightness.

Introduction

In recent years, the convergence of VR, architectural design, and lighting has significantly changed our approach to the built environment [1]. VR environments, increasingly used in lighting research and design, facilitate the creation of adaptable settings [2], [3]. Researchers can adjust lighting parameters in real-time for rapid iteration and hypothesis testing. VR also offers a controlled experimental setting, reducing the challenges of dynamic real-world indoor and daylight lighting conditions [4].

Virtual environments are widely used in lighting studies focusing on human preferences, interactions with indoor lighting, and visual interest [4], [5]. Studies show that VR can effectively represent the physical world in terms of perceived presence, complexity, and view satisfaction [6]. One study comparing human responses to physical lighting versus digital photographs, video, and VR, found that VR most closely matches physical conditions [7]. However, VR faces challenges in replicating complex lighting phenomena due to factors like rendering and tone-mapping algorithms, display hardware, calibration, and software limitations [2], affecting the fidelity of VR simulations and human perceptions of light in virtual environments. For instance, one study found high fidelity for brightness in VR, but noted that dimly lit physical spaces appear brighter in VR [8]. Various VR creation methods, including real-time rendering with game engines, photogrammetry, and motion capture, are employed. Photogrammetric VR technology, popular in architecture and lighting design for its user-friendliness and efficiency, captures high-quality HDR images, processes, and stitches them into 3D models for VR integration [9].

Due to their widespread use, researchers have explored photogrammetric VR in lighting research and design focusing on attributes like brightness, color, and glare, identifying several benefits and limitations [8], [9], [10]. For example, Rockcastle et al. examined spatial lighting attributes in VR under diverse conditions, observing accurate representations in well-lit scenes but significant discrepancies in glare, contrast, and brightness in dimly lit and high-contrast spaces [8]. A later study by Rockcastle et al. also found that despite these limitations, the increased visual immersion provided by VR head-mounted displays lowered the number of significantly different ratings between real and virtual spaces compared to 2D or panoramic images presented on 2D displays [11]. Jafarifiroozabadi et al. assessed user satisfaction with daylight quality in office spaces using Matterport's web-based digital twins technology, comparing electrochromic windows with different blinds [10]. Their findings revealed higher satisfaction and reduced glare in VR than in physical settings, despite some inconsistencies.

As the reviewed work suggests, VR offers both potential and limitations for replicating physical spaces in lighting design and research. Critical factors like CCT and illuminance significantly affect task performance and visual perception [12], necessitating their precise inclusion in lighting simulations. Despite the increased use of VR, there remains a noticeable gap in empirical research on illuminance and CCT in visual perception within this domain, indicating an opportunity for further exploration.

This study evaluates the reliability of VR technology in replicating physical lighting conditions in virtual environments. It investigates human responses to six indoor lighting scenarios in an office, varying by sky conditions, light CCT, and blind positions. This research is part of a broader investigation into how indoor lighting influences human perception of space. It is conducted in two phases: 1) a physical space, and 2) VR representations of that space. Detailed results from the first phase, which assessed the effects of variables such as sky condition, blind position, and CCT on human perception, have been published [13]. Significant effects from blind position and CCT, as well as interactions between these variables, were found. This paper compares light perception under identical conditions in both physical and VR environments, evaluating VR's reliability in lighting studies.

Methods

The study was conducted in a university office/ meeting room (13 x 10 x 9.5 ft), featuring an east-facing window, a glass wall facing the hallway, a desk, chairs, TV, whiteboard, gray carpeting, and mostly white walls with a dark blue northern wall (Figure 1). Used regularly for meetings and work-related tasks, it was chosen to replicate typical workspace lighting conditions.

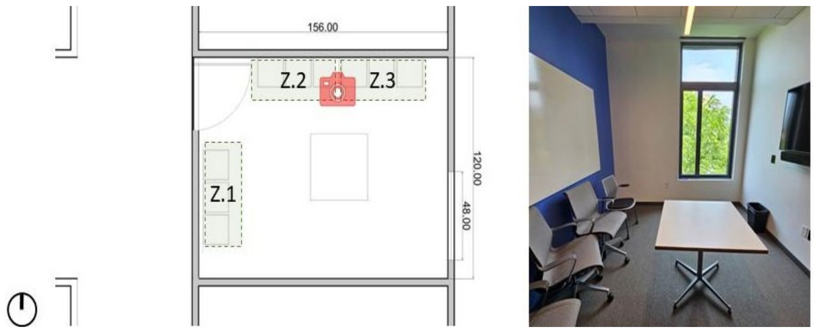

Figure 1: Left: experiment room plan. Right: photo of experiment room.

Lighting Setup and conditions

A customized lighting setup was created for this experiment by attaching LEDs to the existing fixtures with cable straps, due to building management restrictions on altering the room's lighting, providing both direct and indirect lighting. The experiment tested 16 lighting scenarios under various conditions, including sunny and overcast skies, with lights on or off, and blinds open or closed. Three color temperatures were assessed: 2700 K, 4000 K, and 6500 K (Figure 2). CCT and illuminance levels were measured at the center of the room, horizontally at desk level (77 cm/30 inches), and vertically at eye level (1.2 m/4 ft), for someone seated facing the southern wall (Table 1). Ev measurements spanned a 180-degree range at 0, 45, 90, 135, and 180 degrees.

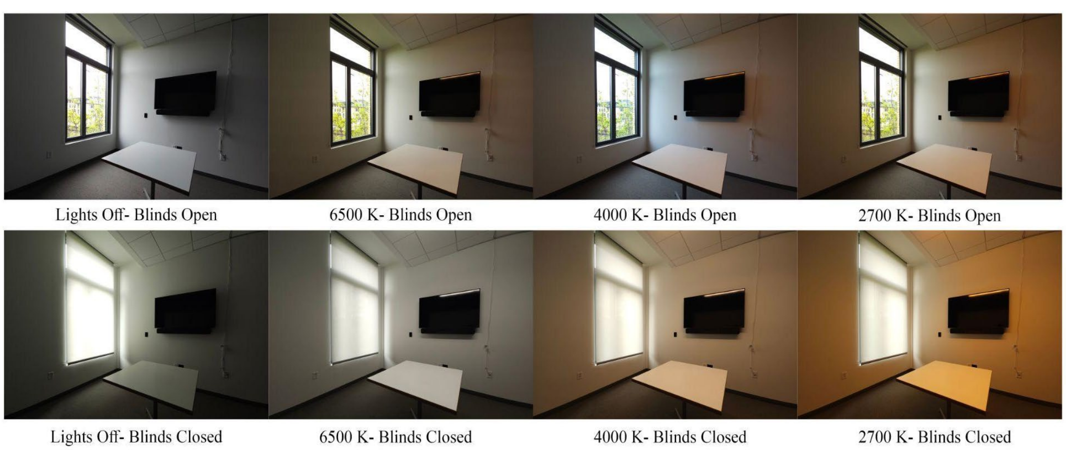

Figure 2: Eight lighting conditions varying in CCT and blind positions were tested under each sky condition (sunny vs. overcast) in phase 1.

Table 1: Lighting measurements for the selected physical and VR spaces

	Physical Spaces (average measurement across experiment days)			VR Spaces		
Lighting Conditions	**Eh (lux)**	**Ev (lux)**	**CCT (K)**	**Eh (lux)**	**Ev (lux)**	**CCT (K)**
Sunny- 2700 K - No Blinds	896	424	3954	871	394	3910
Sunny- 6500 K - No Blinds	906	418	5863	875	402	5910
Sunny-4000 K-No Blinds	878	410	4975	853	388	4995
Sunny-4000 K- Blinds	606	197	4211	588	174	4162
Overcast-4000 K-No Blinds	602	310	4325	620	326	4300
Overcast-4000 K- Blinds	469	109	3753	493	128	3775

All lighting conditions were scanned using Matterport technology to create VR spaces. Positioned 2 ft from the northern wall at 1.2 meters high, the camera captured these setups. Based on participant feedback and to minimize survey fatigue, six lighting conditions were selected for the second phase from scenarios where lights were on (Figure 3). This selection used statistical analysis with the Wilcoxon signed-rank test and Bonferroni correction, focusing on 'Color' perception. No significant differences appeared in spaces with identical CCT at 2700 K and 6500 K. However, notable differences were seen in the 4000 K conditions. Thus, the final VR experiment included one space from both 2700 K and 6500 K settings (under sunny skies without blinds) and all four 4000 K settings (with and without blinds, under sunny and overcast skies).

Equipment

A Quest 3 VR headset with 2064 x 2208 resolution and 90/120 Hz refresh rate was used, featuring a 110-degree horizontal and 96-degree vertical field of view [14]. The study employed the Matterport Pro2 camera for 3D interior scans, capturing images at 134 megapixels with 4K lenses [15]. This infrared camera has a 360-degree horizontal and 300-degree vertical field of view, includes features like high dynamic range exposures, automatic white balancing, and 3D data registration. Operated via Matterport's app, it performs automated 360-degree scans on a tripod. The custom lighting used 36 ft of Paltix CCT COP LED strip lights, powered by a 24V 1.5 A adapter, with frosted film to diffuse light. Light levels were measured using an LI-180 Licor spectrometer.

Figure 3: Evaluated VR environments.

Experiment Procedure and Participants

The VR spaces were created in May 2023, and the first phase of the experiment in the physical space ran from mid-May to mid-June 2023. The second phase occurred in February 2024. Participation was unpaid and voluntary, with participants recruited randomly through university mailing lists, social media platforms, and class announcements. This study was approved by the Carnegie Mellon University Institutional Review Board (IRB) in May 2023. Before the experiment, participants received a consent form and an overview indicating the study's focus on indoor lighting, without disclosing specific lighting conditions. The first phase involved 26 participants—11 females, 15 males, and one undisclosed—aged 18 to 50. The first phase spanned four days and included sessions from 11 AM to noon under both sunny and overcast conditions, with each participant evaluating the lighting on one sunny and one overcast day.

Participants, grouped in clusters of 5-8, were seated in one of the three locations and maintained the same seats across sessions. Each used a QR code to access and complete a questionnaire on their phone evaluating lighting. Fifteen of the initial participants (eight males and seven females, aged 18 to 50) were available and willing to continue into the second phase, where they evaluated six lighting conditions in VR in a randomized order, with the researcher reading questions and recording responses. The questionnaire in both phases assessed perceptions of “Likability”, “Monotony”, “Vibrancy”, “Brightness”, and “Color” (Table 2). The first phase also included detailed assessments of room ambiance, previously published by the authors. In the second phase, participants provided verbal and written feedback on the VR experience via an online form. Each session lasted about 20 minutes in both phases.

Table2: Study questionnaire and tested light perceptions.

Question	Scale (1 to 7)
On the scale of 1 to 7 how do you rank the brightness of this space?	Extremely dark –extremely bright
On a scale of 1 to 7, how would you rate the color of light in this space?	Extremely cool–extremely warm
On a scale of 1 to 7, how much do you like the overall lighting in this space?	Strongly disliked–strongly liked
Does the lighting feel monotonous to you?	Not at all monotonous–incredibly monotonous
On a scale of 1 to 7, how vibrant does the lighting in this space feel to you?	Not at all vibrant–incredibly vibrant

Statistical Analysis

The Wilcoxon signed-rank test—a non-parametric rank test—was conducted to compare the perceptions between VR and physical spaces. The null hypothesis states that the difference in the median differences of two paired samples is zero. Thematic qualitative methods were used to analyze participants' comments and feedback at the end of the study.

Results

This section presents findings from statistical tests and qualitative analyses. Table 3 shows data distribution for lighting impressions in VR and physical spaces. VR was perceived as more "likable" (mean: 4.61, median: 5) than physical spaces (mean: 4.1, median: 4) and less "Monotonous" (mean: 3.5, median: 3 vs. mean and median: 3.9 and 4). VR also appeared more "Vibrant" (mean: 5, median: 4.7) and "Brighter" (mean: 5.2, median: 5) compared to physical settings (means: 4.8 and 4.7, medians: 4.8 and 5, respectively). VR spaces were cooler (mean: 4.3, median: 4 vs. mean: 4.4, median: 4.5). The Boxplots in Figure 4 indicate more variability in perceptions of "Vibrant", "Brightness", and "Color" in physical spaces, suggesting a broader range of opinions, while "Likability" and "Monotonous" responses were more consistent across environments.

Table 3: Wilcoxon signed-rank test results.

Perception	W_Statistic	P-value	Effect Size
Likability (N=15)	67	1.39×10^{-1}	1.03×10^{-1}
Monotonous (N=15)	41	4.83×10^{-1}	2.79×10^{-1}
Vibrant (N=15)	57.5	3.17×10^{-2}	3.67×10^{-2}
Brightness (N=15)	64.5	4.71×10^{-2}	6.6×10^{-2}
Color (N=15)	26	1.81×10^{-1}	4.99×10^{-1}

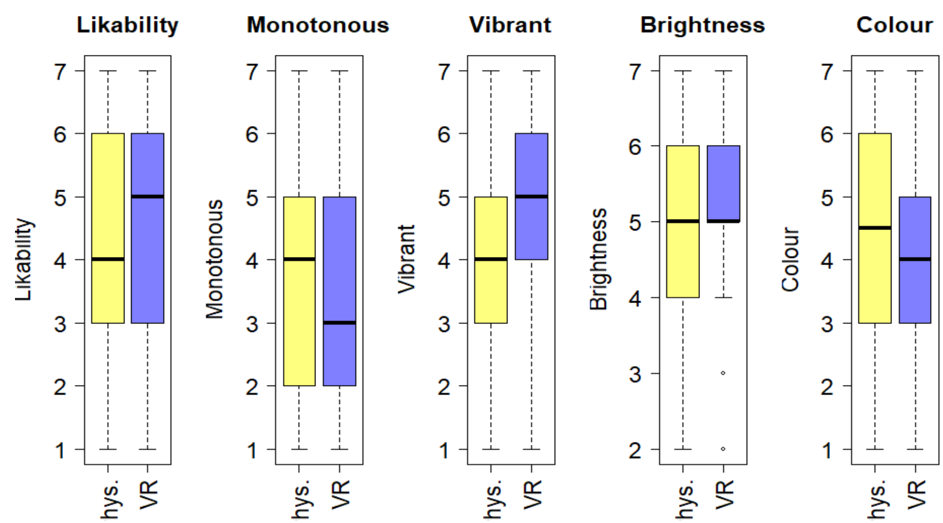

Figure 4: Box Plots comparing light perception across physical spaces and VR environments.

The Wilcoxon signed-rank test comparing lighting perceptions between VR and physical spaces showed no significant statistical differences in "Likability" and "Monotonous" perceptions ($p > 0.05$). This indicates no evidence of differences in how participants perceived monotony, likability, or color. Despite a large effect size (4.99×10^{-1}) suggesting a notable difference in color perception between VR and physical spaces, the p-value above 0.05 means this difference could be due to chance in this sample. Significant differences were found in perceptions of "Vibrant" ($W = 57.5$, $p = 3.17 \times 10^{-2}$) and "Brightness" ($W = 64.5$, $p = 4.71 \times 10^{-2}$), yet the small effect sizes of 6.6×10^{-2} and 3.67×10^{-2} suggest these differences might not be practically meaningful.

A comparative analysis of average vote differences based on lighting condition between VR and physical spaces is presented in Figure 5. VR lighting conditions are generally perceived as "Brighter" and more "Vibrant" across all settings, except for the space with a CCT value of 6500 K, where the physical space is perceived as both "Brighter" and more "Vibrant". Notably, the 6500 K setting also shows the largest discrepancy in the perception of "Monotony" between VR and physical spaces. Furthermore, spaces without blinds tend to show the least difference in perceptions of “Brightness” and “Vibrancy” between VR and physical environments, suggesting that natural lighting may result in a closer alignment of how these attributes appears in both VR and the physical world. The perception of “Color” varies across different lighting settings; VR is perceived as warmer in conditions with blinds. In contrast, light color is perceived as cooler in all other spaces across CCT levels when there are no blinds and daylight is present, indicating that the presence of daylight may cause colors to appear warmer in VR compared to physical spaces.

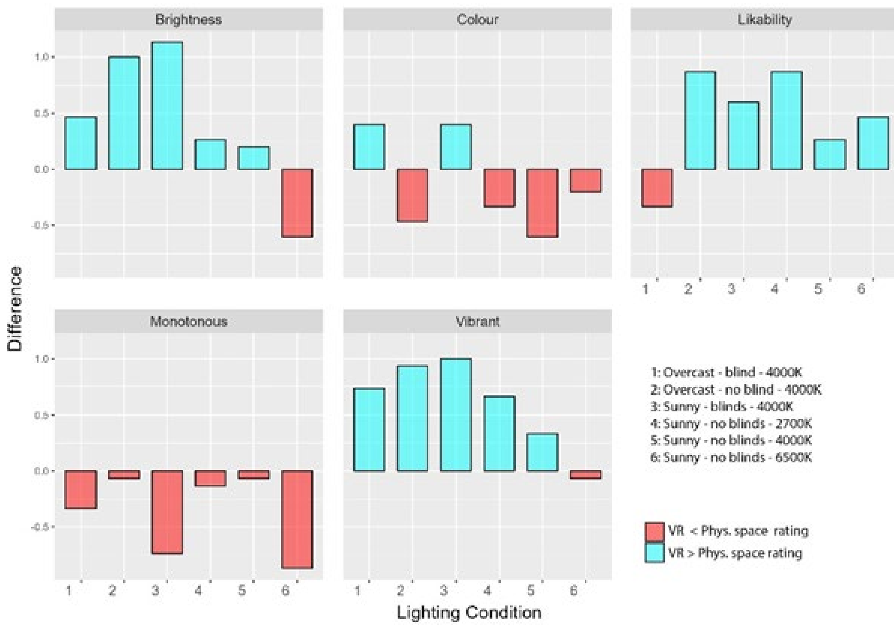

Figure 5: Comparative Analysis of Perception Differences Between Virtual and Physical Environments Under Varied Lighting Conditions

The effect of participant location on perception

The Kruskal-Wallis analysis revealed no significant impact of seat location on any of the evaluated perceptions of ($p = 0.6608$, $\chi2= 0.82861$), Color ($p = 0.06655$, $\chi2 = 5.4196$), Vibrant ($p =0.4588$, $\chi2 = 1.5584$), Monotonous ($p = 0.9524$, $\chi2 = 0.097447$), and Likability ($p = 0.2326$, $\chi2 = 2.9172$) during the first phase of the experiment.

Thematic Analysis

The qualitative analysis identified three main themes from participants' experiences in the VR experiment: 1) Immersive Experience Quality, 2) Perceptual Variability and Bias, and 3) Sensory and Affective Impact. Participants reported varied immersion quality, often citing inadequate resolution and scale as immersion barriers. One participant noted a mismatch in VR settings: “The eyesight range through the VR is set a little higher than my own height”. Another observed spatial discrepancy: “The VR space felt very much like the room itself except that the table seemed a little bigger as if it were taking up more of the space”. Another comment highlighted visual fidelity: “The resolution wasn't that high, and the pixels were distinguishable”.

Several participants noted perceptual variability and bias. About 70% reported a discrepancy in light perception between VR and physical spaces, emphasizing challenges in distinguishing lighting conditions in VR: “It was more difficult to differentiate between the different lightings compared to when I was physically in the room”. Participants also mentioned that light reflection from surfaces like the TV helped them identify light colors: “The reflection of the light on the TV influenced color choices instead of the room rendering quality”.

Participants' responses highlighted the preservation and enhancement of ambiance and lighting in VR, positively affecting sensory and affective experiences. One participant noted, “I think the blinds being open is an automatic +1 for my enjoyment of the space regardless of brightness. Even the warmth of the lighting was less important to me once the window shades were open”. Another commented, “The experience feels more vivid with the VR set-up”.

Discussions and Conclusions

This pilot study assessed the reliability of VR technology, using the Matterport camera, to replicate physical spaces for lighting research and design. The objective was to determine if VR could accurately analyze lighting effects as perceived in real environments. The findings indicated both potentials and limitations of VR in lighting studies. Statistically, lighting perceptions in VR closely matched those in physical spaces, underscoring VR’s capability to simulate real-world lighting scenarios. VR environments were generally perceived as brighter, consistent with previous research. While there were statistically significant differences in “Vibrant” and “Brightness”, the small effect sizes imply minimal practical impact. The absence of significant differences in “Likability” and “Monotonous” supports VR’s reliability. For “Color”, the large effect size suggests practical differences, though the p-value was not significant; a larger sample might reveal statistical significance. VR spaces received more positive ratings, seen as brighter, more vibrant, less monotonous, and more likable. This positivity could arise from the engaging or pleasing nature of VR environments, and novelty of the VR experience, potentially leading to higher ratings. Moreover, the controlled lighting conditions in VR, unlike physical spaces affected by natural light and environmental factors, likely improved perceptions of vibrancy and brightness.

The statistical outcomes are promising, supporting the use of VR to replicate emotional and aesthetic responses similar to those in physical spaces. However, qualitative feedback pointed out challenges, especially in differentiating between lighting conditions in VR. This difficulty likely arises from the Matterport camera’s automatic white balancing, which cannot be manually adjusted. The camera automatically adjusts light color balance to maintain consistency under varying lighting conditions and compensates for CCT variability, representing a significant limitation in VR’s sensory fidelity compared to real-world experiences. Issues with resolution and accurate lighting rendering were also noted, potentially affecting the VR experience. The study's findings are relevant to researchers and professionals in lighting research and design, architecture, and VR development. The study shows that VR can effectively replicate real-world lighting conditions, making it a valuable tool for preliminary lighting evaluations in design and research. However, discrepancies in rendering complex lighting attributes highlight the need for continued advancements in VR technology to ensure its reliable use in lighting research and studies of human perception.

Limitations and Future Work

The study was conducted with a small number of participants in an office/academic setting. Future research should include more participants and diverse environments such as residential, healthcare, and educational spaces. This study utilized common VR hardware and software, and findings might not generalize across all VR technologies. The Matterport technology used here does not offer adjustable camera settings like white balancing and exposure, limiting the ability to refine the visual output. Future studies should explore different VR technologies for lighting research**.**

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