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Exploring daylight and perceived spatial comfort through virtual reality in home environment

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ABSTRACT

This study examines how variations in room brightness simulated in virtual reality (VR), influence-perceived brightness, satisfaction, and spatial comfort in virtual home environment. While VR is increasingly used to simulate various built-environment conditions, its application to assessing spatial comfort in homes remains limited, despite the strong impact of residential spaces on physical and psychological well-being. A within-subjects experiment was conducted with 38 participants who experienced two VR-simulated bedrooms differing in window size. After each exposure, participants evaluated the environment in terms of brightness, satisfaction, and spatial comfort. Results showed that larger windows were consistently perceived as brighter, confirming VR's effectiveness in capturing daylight variation. However, this perceptual increase did not translate into higher satisfaction or comfort ratings, suggesting that daylight alone cannot fully account for affective and behavioral responses. This research underscores the need for architects to use VR not only as a visual representation of the design, but also as a tool for evaluating subjective comfort during early design decision-making, while highlighting the need to integrate environmental, psychological, and experiential dimensions to inform user-centered residential design.

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Virtual reality; immersive virtual environment; perceived spatial comfort; daylight simulation

1. Introduction

VR has emerged as a promising tool for simulating real-world environmental conditions in immersive, interactive formats, offering architects and designers a powerful means to present building design with an accurate, experiential preview of future living spaces (Azmi et al. 2022; Chen, Cui, and Hao 2019; Chiamulera et al. 2017; Juan, Chen, and Chi 2018). The atmosphere of a living environment simulated in VR has been proven to significantly affect future occupants' emotional and behavioral responses (Abd-Alhamid, Kent, and Wu 2024; Azmi et al. 2022; Ko et al. 2023). Atmosphere, in this context, is a holistic perception of the environment that includes key components such as daylighting visual comfort, a crucial part of the overall indoor environmental quality (IEQ) (Mayhoub and Rabboh 2022; Rockcastle, Chamilothori, and Andersen 2017; Sawyer 2021)

Daylight visual comfort refers to the subjective feeling of comfort or discomfort related to the amount, quality, and distribution of natural light within a space (Dahlan et al. 2009; Day et al. 2019; Ngarambe et al. 2022; Uddin et al. 2024). Daylight is a vital aspect of human well-being in built environments, especially in residential settings where we spend a substantial portion of our time (Carneiro, Aryal, and Becerik-Gerber 2021). Recent studies by Azmi et al. (2025) have highlighted that most VR-based daylight visual comfort research between 2020 and 2024 has concentrated on office environments, primarily to investigate the impact on worker productivity. They recommend a greater focus on residential spaces, advocating for VR as a valuable pre-occupancy design tool to ensure new homes prioritize human comfort, particularly daylight visual comfort (Azmi et al. 2025).

Although a growing number of VR-based daylight evaluation research has been conducted in the literature, most existing studies assess daylight visual comfort with task-oriented outcomes, with a predominant focus on office environments and productivity-related matrics (Azmi et al. 2025). There is a gap in research that investigates how daylight and room brightness are perceived and experienced in residential spaces, particularly bedrooms where physical and emotional comforts are the primary concerns. In addition, current literature mostly relies on post-occupancy assessments, leaving a gap in understanding how occupants perceive spatial comfort during design stage through immersive VR simulations.

Beyond addressing physical spatial needs, architects consider daylight access as a core design criterion (Bellazzi et al. 2022; Ngarambe et al. 2022). Daylight control is typically achieved by modifying building features, including shading devices, window openings, louver angle adjustments, and façade design (Abd-Alhamid, Kent, and Wu 2024; Azmi et al. 2025; Chan

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and Tzempelikos 2013; Ko et al. 2023; Mahmoud and Elghazi 2016; Ngarambe et al. 2022). This study moves beyond prevailing performance-oriented approaches to daylight evaluation by adopting a perception-based assessment on daylight visual comfort. Specifically, using immersive VR simulations, this study examined how variations in window size influence perceived brightness and how this perception in turn shapes occupants' subjective experience of spatial comfort in residential bedroom. By situating the investigation within a residential setting, this research extends VR-based studies of daylight in shaping spatial comfort in domestic spaces.

This exploration is crucial given the increasing importance of using digital visualization to inform user needs and comfort in architectural design. This study also analyzes the potential for VR to serve as a digital substitute for physical mock-ups, offering a significant advantage in communicating complex spatial and luminous qualities that are difficult to convey through traditional two-dimensional representations (Juan, Chen, and Chi 2018; Kreutzberg and Naboni 2019). Beyond mere visualization, VR technology provides an interactive and highly engaging platform for users to explore and even customize residential spaces (Azmi et al. 2022). The integration of immersive qualitative renderings in VR simulations enables a rigorous evaluation of daylighting conditions within the proposed designs. This approach supports evidence-based decision-making regarding window placement, glazing selection, and shading strategies, thereby optimizing natural light penetration and spatial distribution to enhance both visual comfort and energy efficiency (Chen, Cui, and Hao 2019; Keshavarzi, Caldas, and Santos 2021; Ko et al. 2023; Sawyer 2021). Taken together, this study contributes to the existing literature by demonstrating how VR can be applied not merely as a visualization tool, but as an evaluative medium for understanding daylight perception and spatial comfort in residential design.

This paper is structured as follows. It begins with a comprehensive literature review on the applications of VR in architectural visualization and daylight simulation, followed by exploration of perceived spatial comfort. Next, the research methodology adopted in this study is described, leading into the presentation and analysis of the results, along with a discussion of the key findings. Finally, the paper concludes by highlighting the novel contributions of the research and offering recommendations for future studies.

2. Literature review

2.1. VR in architectural visualization

VR has become an influential tool in architectural visualization, especially within the architecture industry. In the context of property development and real estate, VR has gained traction as an innovative marketing platform, offering immersive and globally accessible experiences for prospective buyers (Azmi et al. 2022; Azmi, Mashita, and Mohamad 2025). Immersive 3D walkthroughs create realistic spatial experiences that replicate actual environmental conditions and evoke genuine emotional responses, allowing users to better understand and engage with architectural designs (Bauer and Andringa 2020; Fernandes, Da Silva Moura, and Costa 2018; Hegazy, Yasufuku, and Abe 2020; Scorpio et al. 2021; Suh and Prophet 2018).

For architects, VR accelerates design exploration, supports iterative decision-making, and enables pre-occupancy evaluations that incorporate user-centered feedback on the IEQ of the spaces, including daylight (Azmi et al. 2025; Bellazzi et al. 2022; Du et al. 2023; Hegazy, Yasufuku, and Abe 2020; Y. Hong and Michalatos 2016; Salamone et al. 2020). Empirical studies also demonstrate that VR can influence user perception and experience, such as feelings of satisfaction and pleasure within virtual environments (Azmi et al. 2022; T. Hong et al. 2019; Kent and Schiavon 2020).

Nevertheless, several challenges continue to limit the full effectiveness of VR in architectural applications. Current systems do not provide complete sensory immersion, lacking tactile, olfactory, and realistic auditory feedback, which weakens the sense of presence (Azmi et al. 2022). Hardware constraints such as tethered head-mounted displays (HMDs), limited mobility, and narrower fields of view reduce navigation realism and spatial evaluation. Users may also struggle to accurately perceive scale, spatial proportions, and material details within virtual environments, which are essential for evaluating design quality and functionality.

Ongoing advancements in VR applications for architecture are essential to fully realize their potential. The incorporation of haptic feedback, advanced auditory systems, and wireless HMDs can significantly enhance immersion and interactivity, while higher-resolution hardware will improve the accuracy and realism of virtual experiences. Building on these technological developments, scholars have emphasized the need for future studies to focus on residential contexts and to involve more diverse participant groups, thereby producing findings that reflect a wider range of cultural, emotional, and behavioral perspectives in architectural design. Aligned with this direction, the present study contributes by examining the usability of VR in evaluating a key aspect of IEQ, which is daylight visual comfort and its influence on emotions and perceived spatial comfort in immersive virtual environments.

Collectively, while various literature in VR have shown that the technology has been extensively used for architectural visualization and marketing, less is known about its application in for emotional and spatial comfort assessments. This gap motivates the need for a framework that examines how VR can capture perceived spatial comfort influenced by daylight conditions in domestic environments.

2.2. VR to simulate daylight

Recent research increasingly demonstrates the value of VR in assessing daylight and visual comfort. Daylight-related factors including window-to-wall ratio, orientation, time of day, and daylight color have been shown to affect user satisfaction, spatial perception, and emotional responses (Azmi et al. 2025). For instance, shading preferences vary across the day (Carneiro, Aryal, and Becerik-Gerber 2021), larger glazing areas enhance daylight availability and satisfaction (Yeom et al. 2020), and daylight color can alter thermal perception (Chamilothori et al. 2019). VR-based studies confirm that immersive simulations can reliably capture these effects: enhanced daylight conditions improve mood (Kayhan, Şahin, and Erkan 2021), while façade geometry influences emotions, such as excitement and pleasantness (Chamilothori et al. 2022b).

In addition, existing VR-based studies highlight the importance of window design in supporting occupants' psychological and physiological well-being. Using immersive VR simulations, Abd-Alhamid, Kent, and Wu (2024) demonstrated that window size and layout influence view perception related to occupant health, while Ko et al. (Ko et al. 2023) showed that glazing area, window distance, and viewing direction significantly affect occupant satisfaction, recommending minimum window-to-wall ratios above 25% and horizontal view angles exceeding 35°. Together, these findings emphasize the need to integrate window size, layout, and view access considerations early in the design process to enhance occupants' visual experience and overall well-being.

These findings establish VR as a promising pre-occupancy tool for daylight comfort assessment, offering architects the ability to test lighting conditions in realistic environments while preserving experiential qualities. VR demonstrates its capacity to replicate spatial qualities, evokes genuine emotional responses, and provides evidence-based insights to inform design decisions (Azmi et al. 2025; Bellazzi et al. 2022; Salamone et al. 2020)

Despite the evidence in existing literature that VR can simulate daylight, most studies focus on offices or classrooms, with limited attention to bedrooms and other private residential spaces (Bellazzi et al. 2022). There is also a lack of studies that explicitly link window design, perceived brightness, and spatial comfort within immersive residential VR environments, highlighting a clear avenue for investigation.

2.3. Perceived spatial comfort

Perceived spatial comfort can be understood as an individual's subjective sense of ease or unease in relation to the spatial characteristics of a given environment (Alfirević and Simonović-Alfirević 2020). This concept is multidimensional, extending beyond physical attributes to encompass psychological and emotional responses shaped by scale, layout, proportion, and environmental qualities, such as light and openness. Perceived spatial comfort is not limited to physical parameters but emerges from a complex combination of sensations, many of which operate subconsciously.

This multidimensionality explains why comfort is often difficult to define or measure precisely, as it transcends objective criteria and is instead rooted in the subtle interplay of perceptual, psychological, and cultural factors (Alfirević and Simonović-Alfirević 2020). The achievement of comfort in space is therefore relative, varying across individuals, and more challenging to analyze than environmental parameters that fall within measurable ranges. This subjectivity reflects the way people interpret space not only through physical measures but also through psychological and emotional filters, making spatial comfort a nuanced and multifaceted phenomenon. Given these complexities, the potential for evaluating spatial comfort through VR is particularly important, as VR provides an immersive medium to capture perceptions of space and enables designers to assess user comfort before construction or physical implementation.

Juhani Pallasmaa (2012) views architecture as a multisensory encounter, where comfort stems from the interplay of sight, sound, touch, and even smell, resulting in what he describes as an "essential feeling of intimate warmth." Peter Zumthor (2006) extends this idea by linking comfort to architectural atmosphere, defined through sensory qualities that evoke mood, well-being, and harmony. Recent research in VR environments further supports this phenomenological framing. Azarby and Rice (2022) demonstrated that immersive VR provides more accurate spatial awareness than traditional desktop displays, influencing how participants perceive comfort and spaciousness.

The application of VR as a methodological tool provides significant advantages in examining these perceptual dynamics. Unlike static renderings, VR immerses participants in an experiential setting where they can realistically perceive depth, brightness gradients, and the atmospheric qualities of space (Heydarian et al. 2015). This immersion enhances ecological validity, allowing researchers to systematically manipulate window and façade configurations for different daylight penetrations to measure the resulting comfort perceptions in controlled conditions. By leveraging VR to investigate these relationships, researchers and practitioners can integrate user-centered feedback

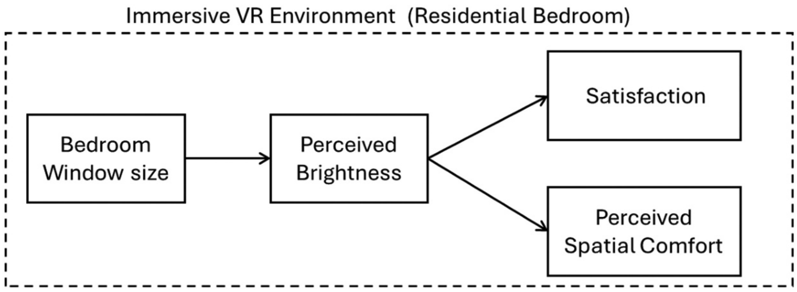

Figure 1. Conceptual framework for evaluating perceived brightness, satisfaction and spatial comfort in VR (source: authors own work).

into the design process, ensuring that residential environments support both functional and psychological needs. This reinforces the value of VR as not only a visualization tool but also a rigorous research instrument for advancing evidence-based design practices in architecture.

Based on the literature analysis above, Figure 1 illustrates the conceptual framework guiding this study that integrates VR-based simulation for daylight variation from different window properties, and subjective comfort assessment.

Variations in bedroom window size serve as an independent variable, influencing occupants' perceived brightness within an immersive VR-simulated residential bedroom. Perceived brightness is conceptualized as a mediating factor that shapes experiential outcomes, namely occupants' satisfaction and perceived spatial comfort. This framework guides the experimental design and data analysis, focusing on perceptual rather than purely performance-based daylight evaluation. Building on this framework, the study was conducted in a fully immersive VR environment simulating a residential bedroom. The VR setting, participant inclusion and exclusion criteria, sampling methods, and experimental procedures are described in detail in the following section.

3. Methodology

This study employed a within-subjects experimental design in which each participant selected for this study experienced both conditions in VR - (1) a bedroom with one window panel facing west (WWR = 10%), (2) a bedroom with four window panels facing west (WWR = 30%). The study was conducted in a fully immersive VR environment where participants were required to wear the VR HMD, simulating standard residential bedroom design in Malaysia for an apartment (typical size approximately 10 m^2 or 3 m × 3.5 m × 2.7 m ceiling height).

In this experiment, the two bedrooms were modeled in 3D using SketchUp Pro and the Enscape software plugin, with VIVEPORT and SteamVR Engine to run the HTC Vive. To ensure that variations in perceived brightness, satisfaction, and perceived spatial comfort were attributable solely to window size, all other architectural variables, such as window orientation, bedroom wall colour, surface reflectants, and bedroom layout, were controlled across the two IVE conditions. Daylight conditions were standardized by fixing the solar altitude and azimuth to those corresponding to Sunday, 15 December 2024 at 1:30 pm in Kuala Lumpur (altitude ≈64.5°, azimuth ≈180°, due south). The selected time reflects an average daytime occupancy period and follows established experimental protocols in daylight perception research by Yeom et al. (2020). As part of the experimental control, the Visual Settings in Enscape were standardized across all IVEs. These settings included exposure level, color temperature, illumination, and cloud conditions to ensure consistency in the VR simulation viewed by participants. Figure 2 illustrates the two VR conditions used for this study.

HTC Vive was utilized as the VR equipment in this experiment, operating through VIVEPORT and SteamVR. To enable position and orientation tracking, the setup included two base stations along with a set of controllers for navigation. The HTC Vive features a head-mounted display (HMD) equipped with dual 3.6-inch AMOLED screens, offering a resolution of 1200 × 1800 pixels, with a refresh rate of 90 Hz. The same tool was used in various VR daylight visual comfort studies (Azmi et al. 2022; Nolé Fajardo, Higuera-Trujillo, and Llinares 2023; Yeom et al. 2020). Figure 3 illustrates the HTC Vive used by the participants during the experiment.

3.1. Sampling

Forty participants were initially recruited through a purposive sampling method to target individuals most likely to provide relevant information, thereby optimizing data collection efficiency and reducing associated costs (Memon et al. 2024; Stratton 2024).

Figure 2. The two-bedroom conditions simulated in VR (source: authors own work).

Figure 3. VR equipment (HTC Vive) used in the experiment. (source: authors own work).

Recruitment was conducted through social media posts and physical posters on the university bulletin board, outlining the eligibility criteria and honoraria offered to selected participants. Applications were screened by the researchers to ensure that participants were at least 18 years old and had no vision impairments, such as color blindness, that could affect experimental outcomes. These criteria were based on previous studies (Ma, Lee, and Cha 2022; Nolé Fajardo, Higuera-Trujillo, and Llinares 2023; Nuria Castilla et al. 2023a)

The selected participants comprised both undergraduate and postgraduate students enrolled at a university in Selangor, Malaysia. Of these, two participants withdrew before completing all the experimental sessions, resulting in a final sample size of 38 participants whose data were included in the analysis. The age range spanned the early twenties to early thirties, reflecting a young adult demographic typical of higher education settings. This research was approved by the Institutional Review Board at Universiti Putra Malaysia Ethics Committee for Research Involving Human Subjects (Approval No. JKEUPM-2024–897). Informed consent was obtained from each participant prior to participation.

A sensitivity power analysis was conducted using G*Power version 3.1.9.7 to determine whether the sample size was adequate for the analysis. For a within-subjects Wilcoxon signed-rank test with a sample of 38 participants, a significance level of $\alpha = 0.05$, and an assumed medium effect size (d_z = 0.50), the achieved statistical power was calculated at 0.905. This value exceeds the conventional threshold of 0.80 (Cohen 1988), indicating that the sample size was sufficient to detect medium effects with high confidence. Accordingly, the analysis presented in this study can be considered adequately powered to yield reliable results.

3.2. *Verbal questionnaire*

To capture participants' responses, a verbal questionnaire using a 5-point Likert scale (0 = lowest, 5 = highest) was administered after each VR condition. This approach follows protocols from previous studies which allow participants to provide simple, intuitive verbal responses while wearing the HMD (Carneiro, Aryal, and Becerik-Gerber 2021; Chinazzo et al. 2020; Ma, Lee, and Cha 2022; Mirdamadi, Zomorodian, and Tahsildoost 2023).

Three constructs were measured – perceived room brightness, satisfaction, and perceived spatial comfort. The questionnaire items were adapted from previous studies (Chamilothori et al. 2022a, 2022b; Kong et al. 2022; Mirdamadi, Zomorodian, and Tahsildoost 2023; Moscoso et al. 2021), including the attributes of spatial comfort as described by Alfirević and Simonović-Alfirević (2020). Table 1 shows the verbal questionnaire items employed in this study.

3.3. *Experiment procedure*

For within-subjects design, it is vital for the researcher to control order and time-related factors, which could threaten the internal validity of the experiment. First, the time-related factors such as participant fatigue, order effects, and carryover effects in this study were controlled by the counterbalancing procedure. Counterbalancing is a procedure in which all possible order sequences in which participants receive different treatments or participate in different groups are balanced in an experiment (Privitera 2024). In this experiment, participants were randomly assigned to one of the two groups ($n = 19$ for each group), each of which viewed the simulations in a different sequence. The similar counterbalancing procedure was also conducted by a similar experimental studies that compares participants' response in variuos virtual environment conditions (Azmi et al. 2022; Castilla et al. 2023b; Heydarian et al. 2015; T. Hong et al. 2019; Nolé Fajardo, Higuera-Trujillo, and Llinares 2023).

Participants completed the experiment individually in a controlled setting. Upon arrival, they received a briefing on the procedure and were fitted with the HTC Vive headset. After familiarization with the VR environment, participants were exposed to two bedroom simulations according to their assigned counterbalanced sequence. In each condition, they were allowed sufficient time to observe the space, focusing particularly on daylight conditions, before providing verbal ratings on the questionnaire items. Short breaks were given between conditions to minimize fatigue. The experiment procedure is illustrated in Figure 4.

Prior to hypothesis testing, the dataset was examined for normality using the Kolmogorov – Smirnov test. Results indicated that the data do not follow a normal distribution across the measured variables, confirming the need to apply non-

Table 1. Verbal questionnaire items.

Variables	Question	Likert Scale (Participants answer their rating verbally)
Perceived room brightness	How bright is this room?	0 to 5, with 0 corresponding represents "Not bright at all" and 5 represents "Extremely bright"
Satisfaction	How satisfied are you with the brightness of this room?	0 to 5, with 0 represents "Not satisfied at all" and 5 represents "Extremely satisfied"
	Do you think this room satisfies your needs and requirements?	
	Will you be satisfied if this is your room?	
Perceived spatial comfort	How cozy is the room for you to stay in currently?	0 to 5, with 0 corresponding represents "Not cosy at all" and 5 represents "Extremely cosy"
	Do you think the bedroom is suitable for you to use at this time of the day?	0 to 5, with 0 corresponding represents "Not suitable at all" and 5 represents "Extremely Suitable"

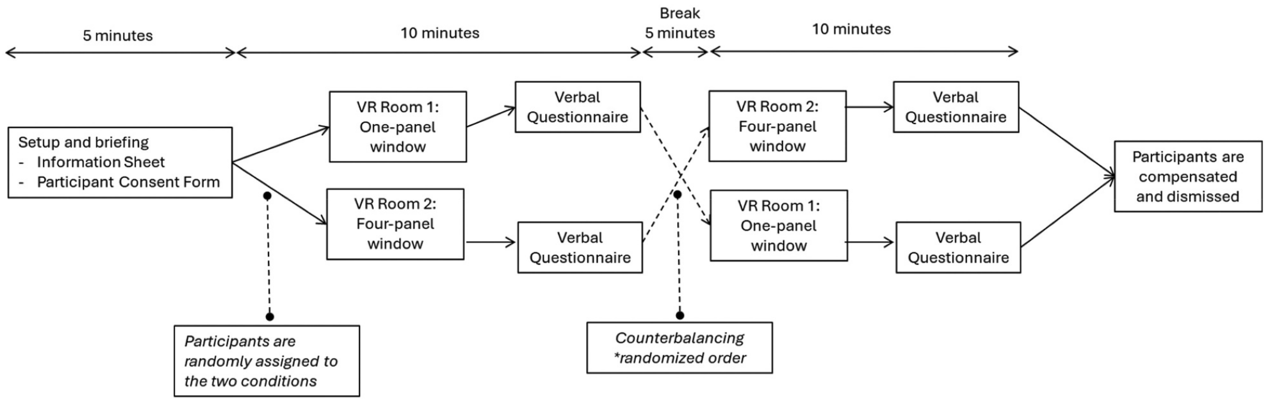

Figure 4. Within-subjects experiment design for VR evaluation of bedroom design with counterbalancing procedure. (source: authors own work).

parametric statistical techniques. Accordingly, the Wilcoxon Signed-Rank test was selected as the primary method of analysis. This test is a non-parametric alternative to the paired-sample t-test and is particularly suited for within-subjects designs where two related samples are compared but assumptions of normality are not met. For all the analyses, statistical significance was established at $p \leq 0.05$.

4. Results

4.1. Homogeneity of the participants

To examine the robustness and validity of the collected data, potential group-level differences were assessed by comparing responses across demographic categories. Specifically, participants were divided into groups based on gender (male vs. female) and educational background (architecture vs. non-architecture). The Mann – Whitney U-test was employed to evaluate whether these demographic factors influenced perceptions of brightness, satisfaction, and perceived spatial comfort across two different VR simulation conditions. The results suggest that participant demographics had minimal influence on the outcomes, supporting the homogeneity of the sample and the validity of subsequent analyses.

4.2. Mann–Whitney test: gender

When comparing the gender groups between male and female participants, the Mann – Whitney U-test revealed no statistically significant difference in satisfaction ratings ($U = 123.00$, $Z = -0.26$, $p = 0.796$, $r = 0.04$) and no significant difference in perceived spatial comfort ($U = 119.00$, $Z = -0.40$, $p = 0.692$, $r = 0.06$). Both results indicate negligible effect sizes, suggesting that male and female participants responded in a highly comparable manner to the simulated daylight conditions. These findings provide evidence that gender was not a determining factor in shaping either the perceived satisfaction with daylight quality or the likelihood of expressing spatial comfort in this study.

4.3. Mann–Whitney test: educational background

Further analysis was undertaken to explore whether an architectural background might shape the way participants perceive and assess the built environment when experienced in a VR setting. The Mann – Whitney U-test showed no significant difference in satisfaction ratings between participants with architecture and non-architecture educational background ($U = 150.00$, $Z = -0.88$, $p = 0.378$, $r = 0.14$). However, a significant difference emerged in perceived spatial comfort ($U = 111.50$, $Z = -2.01$, $p = 0.044$, $r = 0.33$), with participants from non-architecture backgrounds reporting higher perceived spatial comfort than their architecture-trained counterparts. The effect size ($r = 0.33$) suggests a moderate influence, indicating that architectural expertise may shape spatial comfort perceptions based on daylight conditions, even when satisfaction levels remain similar.

Table 2 summarizes the statistical analyses of the Mann – Whitney U-test employed to evaluate whether demographic factors, such as gender and educational background influenced satisfaction, and perceived spatial comfort across the two different VR simulation conditions.

4.4. Wilcoxon signed-rank test: perceived room brightness

The Wilcoxon Signed-Rank test was used to evaluate whether participants perceived differences in daylight brightness across the two window size conditions. The analysis revealed a significant difference in perceived brightness ratings between the bedroom with one

Table 2. Summary of statistical analyses results based on demographic differences.

Variables	Test Statistics	Z-value	*p*-value	Effect Size	Cliff's Delta, δ	Interpretation
Gender Differences						
Satisfaction Male ($n = 9$) vs Female ($n = 29$)	$U = 123.00$	$Z = -0.26$	0.796	$r = 0.04$	$\delta = -0.057$	Male and female participants responded similarly to the simulated daylight conditions, with no significant differences and negligible effect size.
Perceived Spatial Comfort Male ($n = 9$) vs Female ($n = 29$)	$U = 119.00$	$Z = -0.40$	0.692	$r = 0.06$	$\delta = -0.088$	
Education Background						
Satisfaction Architecture ($n = 18$) vs non-architecture ($n = 20$)	$U = 150.00$	$Z = -0.88$	0.378	$r = 0.14$	$\delta = -0.167$	Architectural and non- architectural background respondents rated similar satisfaction evaluation.
Perceived Spatial Comfort Architecture ($n = 18$) vs non-architecture ($n = 20$)	$U = 111.50$	$Z = -2.01$	0.044*	$r = 0.33$	$\delta = -0.380$	Respondents with architecture education background tended to score lower in perceived spatial comfort than the non-architecture group.

window panel and the bedroom with four window panels. Specifically, the test statistic was 444.500 (SE = 50.631), yielding a standardized value of $Z = 3.881$, $p < 0.001$.

This result indicates that participants consistently rated the four-panel window configuration as brighter than the one-panel window configuration when viewed in immersive VR. Importantly, the direction and magnitude of the differences confirm that window size exerts a substantial influence on users' perceptual evaluation of daylight quality.

4.5. Kendall's tau correlation analysis: perceived brightness and satisfaction

To further investigate the relationships among the assessed attributes, Kendall's tau-b correlation was applied. This non-parametric measure of association was selected because the variables under study were ordinal in nature and the dataset contained several tied ranks. Specifically, the analysis examined the extent to which perceived brightness ratings correlated with satisfaction scores and perceived spatial comfort across different window configurations.

The correlation analysis revealed a weak positive association between the four-panel window configuration and satisfaction ratings ($\tau = 0.140$, $p = 0.260$, $N = 38$). While the coefficient indicates a slight tendency for participants to report higher satisfaction when exposed to the larger window size, the relationship did not reach statistical significance. This suggests that, although the four-panel configuration clearly enhanced brightness perception (as confirmed by the Wilcoxon test), this improvement did not translate into a consistent increase in satisfaction scores across participants. Similarly, when analyzing the one-panel window configuration, a very weak positive correlation with satisfaction was observed ($\tau = 0.073$, $p = 0.548$, $N = 38$). This association was even smaller than that of the four-panel condition and likewise not statistically significant. The result indicates that satisfaction ratings remained relatively stable and were not systematically influenced by exposure to the one-panel window configuration.

Taken together, Kendall's tau analysis indicates that while participants clearly distinguished differences in perceived brightness between window configurations, these perceptual variations did not strongly or consistently predict their satisfaction with space in VR. This highlights the importance of examining other mediating or moderating variables such as perceived spatial quality, personal preferences, or prior experiences when linking virtual environmental stimuli to affective and behavioral responses in residential design contexts.

4.6. Kendall's tau correlation: perceived brightness and perceived spatial comfort

To explore whether perceived brightness influenced behavioral intentions, Kendall's tau-b correlations were conducted between brightness ratings and perceived spatial comfort across the two window size conditions. This analysis tested the assumption that stronger daylight perceptions would elicit higher perceived spatial comfort evaluation.

For the one-panel window condition, the analysis indicated a weak and non-significant association between perceived brightness ratings and perceived spatial comfort ($\tau = 0.092$, $p = 0.444$, $N = 38$). Although the coefficient suggests a slight positive trend, the lack of statistical significance indicates that perceived brightness did not meaningfully predict participants' perceived spatial comfort. This suggests that in the case of smaller window configurations, brightness alone was not a decisive factor influencing participants' spatial comfort assessment. Instead, other aspects of the space, such as aesthetics, may have carried greater weight in shaping spatial comfort when viewed in VR.

In contrast, the four-panel window condition yielded virtually no relationship between perceived brightness ratings and perceived spatial comfort ($\tau = 0.006$, $p = 0.959$, $N = 38$). The near-zero coefficient and non-significant results suggest that brightness perceptions in the larger window conditions did not translate into increased interest in the perceived spatial comfort of the room. Although the four-panel design was perceived as significantly brighter, this perceptual advantage did not directly extend to the experience of spatial comfort within the VR environment. Table 3 presents Kendall's tau-b correlation coefficients between perceived room brightness and the evaluative measures of

Table 3. Kendall's tau-b correlation matrix.

Window Configuration	Variable Pair	N	Correlation (τb)	*p*-value	Interpretation
1-Panel	Perceived Brightness × Satisfaction	38	0.073	0.548	Non-significant; very weak association
	Perceived Brightness × Perceived Spatial Comfort	38	0.092	0.444	Non-significant; weak positive trend
4-Panel	Perceived Brightness × Satisfaction	38	0.140	0.260	Non-significant; weak positive association
	Perceived Brightness × Perceived Spatial Comfort	38	0.006	0.959	Non-significant; no observable relationship

satisfaction and perceived spatial comfort for both window configurations.

Overall, the findings reveal a disconnect between perceptual outcomes (perceived brightness) and behavioral intentions (perceived spatial comfort) across both window configurations. Although window size significantly influenced brightness perceptions, these differences did not consistently predict participants' willingness to adopt the designs.

5. Discussion

The results presented in this study provide a nuanced understanding of how window configurations in a virtual environment influence user perception and psychological response. Although participants were able to differentiate daylighting conditions based on room brightness in the virtual environment, their psychological and behavioral responses, such as satisfaction and perceived spatial comfort demonstrated a non-linear pattern.

Examining these factors within a VR environment is particularly important because VR provides an immersive and controllable platform that allows researchers to manipulate architectural variables, such as window size, orientation, and daylighting conditions without the cost and limitations of physical prototypes. Understanding how users perceive daylight comfort, satisfaction, and spatial comfort in VR is valuable for architects and designers, as it informs user-centered design strategies that improve indoor environmental quality, support well-being, and guide decision-making early in the design process.

The findings presented in this paper partly confirmed these objectives: participants perceived larger windows as brighter, but this perceptual difference did not consistently predict emotional or behavioral responses. The Wilcoxon Signed-Rank test confirmed that participants clearly perceived the four-panel window to be brighter ($p < 0.001$). However, Kendall's tau analysis revealed that this increased brightness did not translate into statistically significant increases in satisfaction or spatial comfort. This suggests that while window size is a strong determinant of brightness, it may not independently drive satisfaction or comfort, aligning with the literature that highlights the multifactorial nature of residential well-being (Aries, Beute, and Fischl 2020).

These findings align with previous VR studies demonstrating that environmental stimuli, such as daylight and façade geometry, influence perceptual responses (Chamilothori et al. 2019). However, unlike office-based research where brighter conditions were consistently linked to improved productivity and satisfaction (Shishegar and Boubekri 2022), the results here indicate that residential evaluations are more complex. Residential comfort appears to involve emotional associations, expectations of privacy, and aesthetic preferences that extend beyond measurable illumination levels.

The study reveals a distinct separation between perceptual outcomes (the ability to see light) and affective outcomes (the feeling of comfort) in the virtual environment. Participants were highly accurate at identifying the physical differences between the two simulations, confirming that VR is an effective tool for communicating spatial dimensions and lighting levels. However, the lack of correlation between brightness and spatial comfort suggests that, in a residential context, "comfort" is a multidimensional construct. Home environments involve complex emotional associations, and satisfaction may depend not only on daylight but also on aesthetics, privacy, and personal preferences. This divergence underscores the need to treat residential comfort as a multidimensional construct rather than a purely physical phenomenon.

Furthermore, the demographic analysis presented in this study identified a significant difference in perceived spatial comfort across educational backgrounds. While perceptions of brightness and satisfaction were similar between groups, non-architecture participants reported greater perceived spatial comfort compared to participants with architecture-education background. This suggests that architectural training may develop a more analytical approach to spatial evaluation beyond visual brightness alone. Conversely, lay users may respond more intuitively to the immediate visual appeal of expansive glazing. These findings highlight a perception gap that has important implications for how VR should be calibrated and framed when used for design presentations targeting non-expert audiences.

From a methodological standpoint, this study demonstrates VR's utility as an effective research instrument for isolating design variables and eliciting perceptual differences. The significant brightness distinctions between window sizes confirm that immersive VR can replicate daylight-related stimuli with high ecological validity. This supports prior work advocating VR as a reliable pre-occupancy evaluation tool (Azmi et al. 2022; Heydarian et al. 2015). However, the weak correlations between satisfaction and perceive spatial comfort suggest that VR simulations, while perceptually accurate, cannot fully predict affective outcomes without accounting for broader environmental and psychological moderators.

6. Conclusion

This study examined how window size and orientation, as daylight-related design variables, influence perceptions of brightness, satisfaction, and spatial comfort in VR-simulated bedrooms. Results showed that VR effectively captured perceptual differences in brightness, confirming its validity as a tool for testing daylighting strategies. However, these perceptual differences do not consistently predict emotional or behavioral responses, highlighting the complexity of spatial comfort evaluation in residential settings.

The findings underscore the importance of adopting a multidimensional approach for the application of VR during the design process to evaluate residential comfort. While daylight is a critical determinant, its effects on satisfaction and perceived spatial comfort could be moderated by psychological, experiential, and contextual factors. This suggests that architects and designers should integrate multiple environmental dimensions when evaluating residential quality in the virtual environment. VR provides a valuable platform for exploring these interrelationships by allowing designers to test multiple variables in immersive and interactive conditions.

From a human factor's perspective, this research contributes evidence that VR can support pre-occupancy evaluations, enabling user-centered design decisions. Yet, the weak association between brightness and perceived spatial comfort indicates that relying on daylight alone is insufficient. Future research should integrate additional measures such as affective responses, circadian health outcomes, and long-term behavioral preferences to provide a more holistic understanding of comfort in residential environments.

Despite these contributions, several limitations inherent to VR-based research adopted in this study should be acknowledged. Although immersive VR provides strong perceptual realism, it cannot fully replicate real-world sensory experiences, such as tactile and haptics feedback, thermal sensation, and ventilation, all of which may influence residential comfort perception. Participants' evaluations in this study were based on short-term exposure within the IVE, which may not fully reflect sustained emotional and behavioral responses that develop through prolonged occupancy in the bedroom. In addition, individual differences in VR familiarity and susceptibility to cybersickness may have influenced perceptual judgments. These limitations should be considered when interpreting the findings and highlight the need for physical, real-world and longitudinal studies.

Several avenues for future research remain to be explored to deepen the scientific understanding of virtual environmental perception. First, this study focused primarily on window size and daylight quantity. Future research should incorporate additional variables such as glare analysis, thermal expectations, and views-out (the quality of the scenery outside) as examined by Ko et al. (2023), as these are known to moderate the relationship between brightness and spatial comfort. Second, the current VR simulation utilized static daylight conditions set only at a particular time of the day. Since daylight is inherently temporal, future studies should employ longitudinal VR experiences by simulating different times of day or seasons to evaluate how the sun's path influences long-term residential satisfaction.

In conclusion, this study highlights VR not only as a promising tool for daylight evaluation but also as a medium that can move beyond mere visualization. While its strength lies in providing perceptual accuracy and ecological validity, the real potential of VR is in assessing how future occupants might experience, use, and feel comfortable in architectural spaces once they are built. Its current limitation lies in capturing more complex affective and behavioral outcomes, which underscores the need for interdisciplinary research that bridges architecture, psychology, and human factors. Such efforts will ensure that residential design prioritizes not only visual comfort but also the holistic well-being and lived experiences of future occupants.

Author contributions

Athira Azmi conceived and designed the study. Sarah Abdulkareem Salih and Annisa Ummihusna contributed to the analysis and interpretation of the data. Athira Azmi drafted the manuscript, and all authors revised it critically for important intellectual content. All authors have read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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Ethical considerations

Ethical clearance was obtained from the Universiti Putra Malaysia Ethics Committee for Research Involving Human Subjects (Approval No. JKEUPM-2024–897). All participants provided informed consent to participate in the study, and written consent was obtained prior to data collection.

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