Future Technology
Open Access Journal
ISSN 2832-0379
November 2025| Volume 04 | Issue 04 | Pages 24-32
Journal homepage: https://fupubco.com/futech
https://doi.org/10.55670/fpll.futech.4.4.3
Future Publishing LLC

Article

Occupants' satisfaction with STPV window design in private and open spaces by VR images

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ARTICLE INFO

Article history:
Received 15 May 2025
Received in revised form
28 June 2025
Accepted 11 July 2025

Keywords:
Semi-transparent photovoltaic,
Cell coverage ratios,
Igroup presence questionnaire,
Occupant satisfaction

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DOI: 10.55670/fpll.futech.4.4.3

ABSTRACT

Semi-transparent photovoltaic (STPV) systems have gained increasing attention for their ability to generate electricity while reducing energy consumption compared to conventional windows, addressing climate and energy challenges. However, STPV systems inherently reduce window transparency, which may compromise occupant visual comfort and satisfaction. This study experimentally investigates occupant satisfaction with crystalline silicon (c-Si) STPV windows at different cell coverage ratios (CCR) in private offices and open spaces using virtual reality (VR) technology validated by the Igroup Presence Questionnaire (IPQ). Forty-five participants evaluated six CCR configurations (0%-50%) across two spatial types. Results show VR environments achieved satisfactory presence levels (IPQ: 70.37% private, 70.06% open), validating the methodology. Occupant satisfaction decreased with increasing CCR in both spaces, from 5.11 to 3.00 (private) and 5.89 to 3.22 (open). Open spaces showed significantly higher satisfaction than private offices for 10%-40% CCR, with convergence at 50% CCR. These findings provide design guidance for optimizing STPV integration while maintaining occupant comfort.

1. Introduction

Solar photovoltaic (PV) technologies have been well-established for several decades and have undergone rapid development in response to pressing climate and energy challenges [1, 2]. These technologies reduce greenhouse gas emissions and enhance energy security while providing sustainable, reliable electricity [3]. Recent economic assessments have demonstrated the significant impact of solar energy integration on local industries and technological advancement [4], while techno-economic analyses have validated the effectiveness of photovoltaic systems across different geographical contexts [5], underscoring the critical importance of optimizing STPV integration for sustainable building design. To enhance PV applications considering energy performance, spatial optimization, economic viability, and aesthetic integration, building-integrated photovoltaic (BIPV) technology has gained increasing attention. Semi-transparent photovoltaic (STPV) systems, which can replace conventional glazing, represent one promising BIPV approach [6, 7]. It can be used on different parts of the windows, which allows for building energy efficiency and solar energy capture, as well as the generation of electrical energy in the system while controlling heat and light transmission [8, 9]. Since visible light transmittance (VLT), which is directly influenced by the cell coverage ratio (CCR) of STPV systems, determines indoor illumination levels, it exerts a significant influence on occupant physiological satisfaction and visual comfort [10-12]. Thus, if the STPV CCR is excessively high, the indoor atmosphere may become overly dark and unpleasant [13]. It is recognised that employees who are more satisfied with their workplace's building internal environment tend to be more productive [14]. Furthermore, the complexity and cost of physically constructing multiple STPV configurations for comparative studies present significant methodological barriers to comprehensive research in this field. Despite their promising potential, current understanding of how different spatial configurations influence occupant satisfaction with varying cell coverage ratios remains limited. Previous studies have predominantly focused on energy performance optimization while neglecting the human-centric aspects of STPV integration. Furthermore, the methodological limitations of conducting physical experiments across multiple CCR configurations have constrained comprehensive comparative studies. Most existing research has been limited to simplified experimental rooms or single spatial typologies, thereby limiting the generalizability of findings to diverse real-world office environments. This limitation is particularly important to address, as occupant satisfaction is crucial for the successful adoption of STPV technologies in commercial buildings. While previous studies have investigated occupant responses to STPV window design, they have predominantly concentrated on satisfaction within small spaces [15] using simplified experimental rooms, thereby limiting the generalizability of findings to diverse office environments. This limitation is particularly problematic, as real-world office spaces vary substantially in scale, layout, and spatial characteristics. Conducting experimental studies on STPV window satisfaction across different spatial typologies with varying CCR configurations is critical for advancing our understanding of human-building interactions. However, physically constructing spaces with different STPV CCR configurations is extremely difficult and time-consuming, particularly when CCR parameters need to be validated before construction.

As a potential solution to this problem, virtual reality (VR) technology through 3D view images has emerged as a popular alternative for experiencing various indoor spaces without creating a physical environment [16]. Therefore, leveraging VR technology within the architecture context has not only streamlined the time, cost, and manpower associated with constructing indoor spaces but has also simplified the process of identifying suitable design alternatives for various office configurations [17, 18]. To address the gap in understanding occupant satisfaction differences across various spatial configurations with identical STPV designs, an area inadequately covered by previous research, this study investigates occupant responses to STPV CCR variations in different spatial typologies. Towards this end, three objectives of experiments in the physical and virtual environments are performed in this study.

(1) to evaluate whether virtual environments adequately represent physical environments in both private offices and open spaces.

(2) to identify differences in occupant satisfaction across varying STPV CCR configurations.

(3) to explore differences in occupant satisfaction between different spatial typologies.

This study can (1) enhance understanding of occupant satisfaction with c-Si STPV systems, (2) inform optimization of design variables (i.e., STPV CCR) for different office configurations, and (3) enable systematic identification of occupant satisfaction patterns based on CCR and spatial typology. Beyond conventional VR applications, this research introduces a novel methodological framework that integrates precision-controlled CCR simulation with validated presence measurement, establishing new protocols for evaluating human-centric performance of emerging photovoltaic technologies. The study advances smart building technologies by developing quantitative design thresholds for automated STPV optimization systems and contributes to user-centered photovoltaic integration through empirically-derived satisfaction models that can inform adaptive building control algorithms.

2. Methodology

An experimental study is designed and performed to investigate occupant responses pertaining to their satisfaction with STPV CCR in physical and virtual built environments. Virtual environments were utilized to assess participants' subjective satisfaction in private offices and open spaces, focusing on variations in the CCR of STPV windows. Participants were recruited from within the same office campus to facilitate on-site participation. The virtual environments were configured with identical dimensions to the actual spaces selected from the architectural drawings. (i). Prior to the experiment, participants' demographic information (i.e., age, gender, color blindness, and age-related eye conditions) was collected, and VR system operation training was conducted. (ii). During the experiment, participants wore a head-mounted display (HMD) connected to the research computer for system control. Participants were given 1 minute to adapt to the virtual environment before proceeding with the evaluation questionnaire [19].

2.1 Step1: Data collection

2.1.1 Target space information

The reference building, located in Chengdu city, southwest of China, is a 6-story office structure with a floor area of 512.20 m^2. Each floor includes four small private office rooms (11 m^2 each), two large private office rooms (30 m^2 and 33 m^2), two conference rooms (18 m^2 and 33 m^2), a public working space (192 m^2), and auxiliary facilities. The net height under the ceiling is 3.0 m. According to the Chinese norm "Standard for Design of Office Building JGJ/T 67-2019," the net height of single and modular offices without centralized air-conditioning should not be less than 2.70 m, and single-room offices should not have a floor area of less than 10 m^2 [19, 20]. Private offices and open spaces were chosen as the research environments, as illustrated in Figure 1.

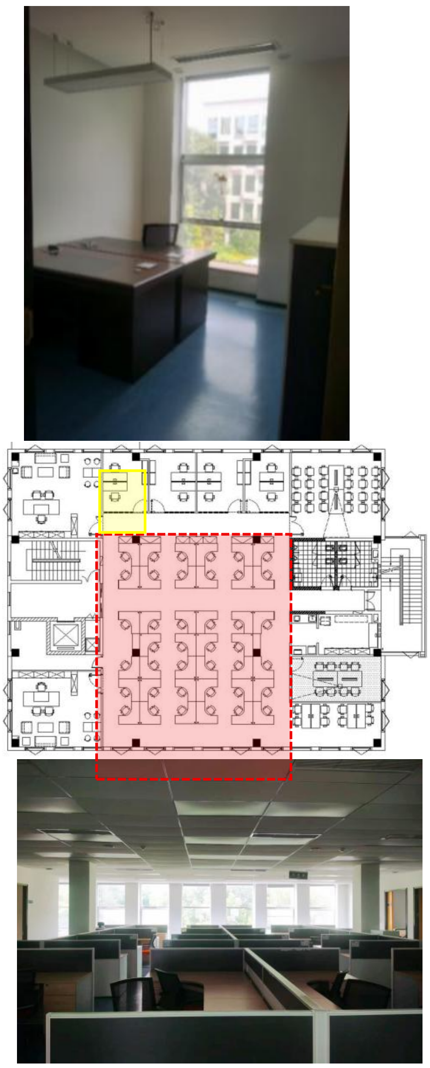


Figure 1. Information about the building and space (Source: drawn and photographed by the author)

2.1.2 STPV window information

The STPV structure was configured as 3mm glass + 0.76mm PVB + crystalline silicon (c-Si) PV cell + 0.76mm PVB + 3mm glass, which is similar to the original glass structure. According to the Chinese norm "Design Standard for Energy Efficiency of Public Buildings," the visible light transmittance (VLT) of windows must exceed 0.40 [21]. Additionally, considering the integration of PV cells within the glazing system, the coverage ratio of semi-transparent photovoltaic (STPV) systems should not exceed 0.50. In this study, the STPV coverage ratio was varied from 10% to 50%, with a fully glazed window (0% CCR) selected as the comparative benchmark [19], as shown in Table 1.

Table 1. Crystalline Silicon solar Window with different cell cover ratio (CCR), (South: Author)

	CCR:0
	CCR :10%
	CCR:20%
	CCR :30%
	CCR:40%
	CCR :50%

2.2 Step 2: Construction of virtual environment

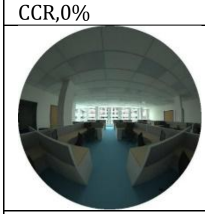
2.2.1 Virtual environment setting

In this study, Rhino 7.8 and ClimateStudio were used for modeling and rendering the virtual environments. Pigasus served as the image player engine for converting two-dimensional fisheye images into three-dimensional spaces, while Meta Quest 2 was employed as the head-mounted display (HMD) device. However, specific technical specifications such as frame rate, image resolution, and latency were not systematically documented, representing a methodological limitation for replication and technical validation. For STPV configurations with different CCR values, the virtual environments were implemented identically, with only the window configurations varying. The study used standardized lighting conditions and did not account for time-of-day variations or real environmental lighting changes, representing a limitation that should be addressed in future dynamic lighting studies. The VR environments of private offices with different STPV CCR configurations are presented in Table 2. The VR environments of open spaces with different STPV CCR configurations are presented in Table 3.

Table 2. VR environment of private office with different STPV CCR configurations (South: drawn by the author)

		
CCR,0%	CCR,10%	CCR,20%
		
CCR,30%	CCR,40%	CCR,50%

Table 3. VR environment of open space with different STPV CCR (South: drawn by the author)

		
CCR,0%	CCR,10%	CCR,20%
		
CCR,30%	CCR,40%	CCR,50%

2.3 Measurement of occupants' satisfaction between the physical environment and the virtual environment

This study received institutional ethics approval, and all participants provided informed consent before VR participation. To mitigate potential evaluation biases arising from familiarity with the experimental setting or researchers, none of the participants was affiliated with the host institution or personally acquainted with the research team. All participants were recruited from the same campus, with a total of 45 participants (aged 23-44 years) taking part in the experiment. Post-hoc analysis indicates adequate statistical power for detected effects, though a priori power calculation was not conducted. The homogeneous sample (educated adults, single location) limits generalization across age groups, cultural backgrounds, and socioeconomic levels, requiring future validation in diverse populations. To validate the reliability and effectiveness of the virtual environment research methodology, the Igroup Presence Questionnaire (IPQ) was employed, as referenced in previous studies [18, 19, 22-24]. This questionnaire measures differences in the visual sense of presence between real and virtual environments as follows:

Igroup Presence Questionnaire for VR Environment Validation To what extent did the spatial experience in the virtual scene correspond to that of a real scene? 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ How aware were you of real-world visual surroundings while navigating the virtual environment? 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ How consistent was your visual experience in the virtual environment compared to real-world experience? 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ Level legends: 1, Strongly different / 7. Absolutely the same

The obtained results were compared with IPQ scores using qualitative grading descriptions [25], as shown in Table 4.

Table 4. Qualitative grading description of IPQ for VR environment valuation [23]

Percentile	Grade	Adjective	Acceptability
≥ 90	A	Excellent	Acceptable
≥ 80	B	Very Good	Acceptable
≥ 70	C	Satisfactory	Acceptable
≥ 60	D	Marginal	Marginally acceptable
≥ 50	E	Unsatisfactor y	Marginally acceptable
< 50	F	Unacceptable	Not Acceptable

2.4 Measurement of occupants' satisfaction for different STPV CCR

Following the IPQ survey, a subsequent questionnaire was administered to assess occupant satisfaction levels regarding indoor lighting conditions and spatial perception under different CCR configurations. Subjective feedback was also collected to inform future research directions. The questionnaire was structured as follows:

Questionnaire for Spatial Perception Assessment Based on STPV CCR Compared to the indoor daylight conditions and spatial quality of the CCR 0% (baseline) scenario, what is your satisfaction level with this STPV design? 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ What factors influenced your evaluation rating? Level legends: 1. Absolutely dissatisfied / 7. Very satisfied

3. Results

3.1 IPQ survey of private office and open space

3.1.1 Analysis for the IPO value separately

To evaluate the sense of presence among the 45 participants in the virtual environment, the IPQ survey results examining four presence factors were analyzed. Statistical analysis for IPQ results in private offices is presented in Table 5. Statistical analysis for IPQ results in open spaces is presented in Table 6. The total presence values for private offices (P total) and open spaces (O total) were 4.926 and 4.904, respectively, on the 7-point Likert scale. Converting these values to percentages yielded 70.37% and 70.06%, respectively. Comparing these values with the IPQ thresholds in Table 4, both configurations achieved Grade C (Satisfactory, Acceptable), indicating that the VR environment evaluation results can be applied to equivalent physical environments.

Table 5. Data analysis for the IPQ of a private office

ITEMS	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		df	Shapiro-Wilk Sig (N D)
				Lower	Upper		
Ptotal	4.92600	0.80070	0.11936	4.68544	5.16656	45	0.000162
Pspatial	4.44444	1.17851	0.17568	4.09038	4.79851	45	0.005959
Pinvolve	5.08889	1.01852	0.15183	4.78289	5.39488	45	0.000121
Pexperience	5.24444	0.95716	0.14269	4.78289	5.39488	45	0.000003

Table 6. Data analysis for IPQ of open space

ITEMS	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		df	Shapiro-Wilk Sig (N D)
				Lower	Upper		
O_{total}	4.90444	0.74766	0.11146	4.67982	5.12907	45	0.0000400
$O_{spatial}$	4.42222	1.05505	0.15728	4.10525	4.73919	45	0.0031410
$O_{involve}$	5.11111	0.85870	0.12801	4.85313	5.36909	45	0.0000030
$O_{experience}$	5.17778	0.96032	0.14316	4.88926	5.46629	45	0.0000002

These IPQ scores exceed the 70% threshold established for architectural research applications and align with validation studies demonstrating that presence levels above 70% correlate strongly with real-world perceptual responses in daylight and visual comfort assessments. The consistent presence values across both spatial typologies (difference < 0.5%) ensure that satisfaction differences reflect actual spatial and CCR effects rather than varying immersion quality, validating the methodology for drawing conclusions equivalent to real-world settings in light perception and subjective satisfaction studies.

3.1.2 Comparative analysis for the IPQ between private office and open space

To ensure that differences in occupant satisfaction between private offices and open spaces were not influenced by varying VR immersion levels (as indicated by the Presence values P total and O total), a statistical comparison between the two IPQ values was necessary. The Total Difference value (D total) was calculated as follows:

$$D\ total = O\ total - P\ total \quad (1)$$

Since the significance value ($p = 0.019$) of D total in the Shapiro-Wilk normality test was less than 0.05, indicating non-normal distribution, the parametric t-test requirements were not met. Therefore, the Wilcoxon signed-rank test was employed for comparing P total and O total values, with results presented in Table 7. The asymptotic significance (2-tailed) value of 0.862 exceeded 0.05, indicating that the difference between P total and O total was not statistically significant. Therefore, P total and O total values demonstrated equivalent presence levels, confirming that VR environment immersion was consistent across both private offices and open spaces.

3.2 Analysis of occupant satisfaction with STPV CCR configurations

3.2.1 Individual analysis of occupant satisfaction

Following confirmation that total presence values showed no significant difference between private offices and open spaces, comparative analysis between the two spatial typologies was conducted, with results presented in Figure 2. For both spatial configurations, occupant satisfaction levels decreased as CCR increased. In private offices, mean satisfaction scores decreased from 5.11 (P 10%) to 3.00 (P 50%), while in open spaces, values declined from 5.89 (O 10%) to 3.22 (O 50%). Occupants demonstrated higher satisfaction levels in open spaces compared to private offices. Participants explained that they focused more attention on environmental details in smaller spaces, particularly the windows that connect indoor and outdoor visual experiences.

3.2.2 Comparative analysis of occupant satisfaction between private offices and open spaces

To validate the observed differences, a comprehensive statistical analysis was performed to examine the comparative values between the two spatial configurations. The analysis commenced with calculating the difference values between private offices and open spaces according to the following equations:

$$D\ (10\%) = O\ (10\%) - P\ (10\%) \quad (2)$$

$$D\ (50\%) = O\ (50\%) - P\ (50\%) \quad (3)$$

Normality tests conducted for D (10%) through D (50%), as presented in Table 8, revealed significance (p) values below 0.05 across all configurations, thereby precluding the application of parametric t-tests due to non-normal data distribution. Given the non-parametric nature of the data, Wilcoxon signed-rank tests were subsequently employed for comparative analysis, with comprehensive descriptive statistics detailed in Table 9.

Statistical significance test results, as documented in Table 10, demonstrate that while the O (50%) - P (50%) comparison yielded $p > 0.05$, all remaining comparisons produced $p < 0.05$, indicating statistically significant superior satisfaction levels in open spaces relative to private offices across CCR configurations ranging from 10% to 40%, with satisfaction convergence occurring at the 50% CCR threshold.

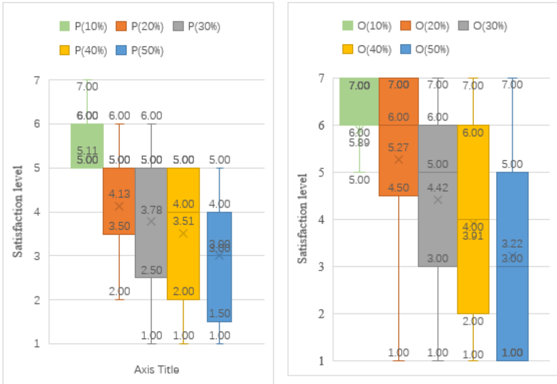


Figure 2. The occupants' satisfaction level with the private office and open space

4. Discussion

The methodological validation, achieving satisfactory presence levels (70.37% for private offices, 70.06% for open spaces), transcends conventional virtual reality applications by establishing epistemological foundations for architectural phenomenology research, fundamentally reconceptualizing how environmental perception can be systematically investigated within controlled experimental paradigms. Contemporary systematic reviews confirm that immersive virtual environments demonstrate exceptional effectiveness in occupant comfort and adaptive behavior research, providing controlled laboratory circumstances that enable systematic environmental manipulations impossible in real occupied buildings [26]. This achievement represents a paradigmatic shift from positivist measurement approaches toward phenomenological inquiry methodologies that acknowledge the embodied nature of spatial experience, challenging traditional boundaries between physical and virtual environmental cognition research while establishing new epistemological frameworks for understanding occupant-environment interactions that transcend the limitations of both reductionist laboratory studies and uncontrolled field observations.The observed satisfaction degradation pattern as CCR increases provides quantitative evidence for establishing design thresholds in STPV implementation. Specifically, the convergence threshold at 50% CCR suggests that beyond this point, spatial typology becomes irrelevant to occupant satisfaction, indicating a universal limit for human environmental tolerance. This finding has profound implications for building codes and design standards, as it establishes an empirically-derived upper boundary for STPV cell coverage that maintains acceptable occupant comfort levels regardless of spatial configuration.

Table 7. Descriptive Statistics of P total and O total in Two related samples Wilcoxon test

	N	Mean	Std. Deviation	Min	Max	Percentiles		
						25th	50th (Median)	75th
P_{total}	45	4.9260	0.80070	2.00	6.33	4.6700	5.0000	5.3300
O_{total}	45	4.9044	0.74766	2.00	6.33	4.6700	5.0000	5.3300

Table 8. The test of normality for the differences in occupants' satisfaction between private offices and open space

	D (10%)	D (20%)	D (30%)	D (40%)	D (50%)
Sig	0.0000004	0.0000002	0.0001549	0.0000049	0.0000009

Table 9. The test of normality for the differences in occupants' satisfaction between private offices and open space

	N	Mean	Std. Deviation	Min	Max	Percentiles		
						25th	50th (Median)	75th
P (10%)	45	5.1111	1.66818	1.00	7.00	5.00	6.00	6.00
P (20%)	45	4.1333	1.65968	1.00	6.00	3.50	5.00	5.00
P (30%)	45	3.7778	1.73059	1.00	6.00	2.50	5.00	5.00
P (40%)	45	3.5111	1.63237	1.00	5.00	2.00	4.00	5.00
P (50%)	45	3.0000	1.39805	1.00	5.00	1.50	3.00	4.00
O (10%)	45	5.8889	1.96818	1.00	7.00	6.00	7.00	7.00
O (20%)	45	5.2667	1.92354	1.00	7.00	4.50	6.00	7.00
O (30%)	45	4.4222	2.02809	1.00	7.00	3.00	5.00	6.00
O (40%)	45	3.9111	1.89284	1.00	7.00	2.00	4.00	6.00
O (50%)	45	3.2222	1.69074	1.00	7.00	1.00	3.00	5.00

These empirically derived satisfaction thresholds and spatial typology effects provide critical foundations for next-generation smart building technologies. The quantified CCR-satisfaction relationships can inform automated building control algorithms that balance energy generation with occupant comfort in real-time, while the identified 50% convergence threshold offers a universal constraint for adaptive STPV systems. Furthermore, the differential satisfaction patterns across spatial typologies enable context-sensitive optimization algorithms that can personalize environmental control based on space configuration, advancing user-centered photovoltaic integration in intelligent building management systems.

The differential satisfaction patterns observed across spatial typologies illuminate fundamental principles of environmental psychology that extend beyond superficial design preferences toward deeper questions of human territoriality, cognitive load distribution, and attention restoration mechanisms within technologically mediated environments. Recent experimental investigations demonstrate that optimal visible light transmittance for STPV systems varies significantly depending on spatial context and occupant psychological responses measured through virtual reality methodologies, with satisfaction levels showing pronounced sensitivity to both transparency characteristics and environmental settings. This finding challenges deterministic approaches to sustainable building design by demonstrating that technological interventions interact with spatial cognition through complex psychosocial mechanisms that cannot be reduced to simple visual comfort metrics, thereby necessitating holistic design philosophies that recognize the co-constitutive relationship between built environments and human consciousness rather than treating occupants as passive recipients of environmental stimuli.

The convergence threshold phenomenon at 50% CCR reveals universal limits of human environmental tolerance that transcend cultural and spatial boundaries, establishing theoretical foundations for sustainable building design that acknowledge fundamental anthropological constraints on technological integration. Contemporary workplace research confirms that office spatial typology fundamentally influences occupant cognitive and aesthetic appraisal, with design parameters including ceiling height, partition configuration, and spatial contour creating measurable impacts on environmental satisfaction that extend beyond traditional privacy-communication trade-offs [27]. Contemporary research utilizing cadmium-telluride thin-film photovoltaic technologies confirms that psychological satisfaction exhibits consistent inverse relationships with reduced visible light transmittance [28]. This study focused exclusively on occupant satisfaction metrics without measuring actual photovoltaic performance parameters such as power output or thermal characteristics, limiting its utility for comprehensive energy-comfort optimization. Furthermore, office layout typology research demonstrates that spatial configuration significantly influences user satisfaction and comfort through circulation patterns and spatial accessibility that interact with technological interventions in complex ways [29]. These convergent findings establish philosophical foundations for sustainable architecture that balances environmental performance with fundamental human needs for visual connection, spatial autonomy, and psychological comfort within the built environment. The study's limitation to Chengdu restricts global applicability, as cultural lighting preferences and climate conditions may influence STPV satisfaction differently across regions. Validation across diverse cultural and climatic contexts is needed before generalizing these CCR thresholds globally.

5. Conclusion

This experimental investigation verified occupant satisfaction differences between private offices and open spaces under varying CCR configurations of crystalline silicon STPV systems using advanced virtual reality technology. The research framework encompassed four comprehensive objectives:

(1) Evaluation of occupant responses regarding presence perception between physical and virtual environments across both private offices and open spaces.

(2) Comparative assessment of occupant presence responses within virtual environments between distinct spatial typologies.

(3) Quantitative analysis of occupant satisfaction levels under various STPV CCR configurations within virtual office environments.

(4) Comprehensive comparison of occupant satisfaction responses across five CCR variations (10%, 20%, 30%, 40%, and 50%) between private offices and open spaces within virtual environments.

A comprehensive analysis of experimental findings reveals several significant outcomes:

IPQ assessments of virtual environment presence achieved "Satisfactory" levels across both private offices and open spaces, thereby validating VR methodology applicability for occupant satisfaction surveys in scenarios where physical environment access remains challenging or impractical.

Statistical validation through Shapiro-Wilk normality testing and Wilcoxon signed-rank analysis confirmed equivalent presence effects between private offices and open spaces on occupant perception, establishing consistent baseline conditions for comparative satisfaction assessment. Occupant satisfaction demonstrated a consistent inverse correlation with increasing CCR values across both spatial configurations, indicating systematic degradation of visual comfort as photovoltaic cell coverage intensifies. Comparative satisfaction analysis revealed significantly higher occupant preference for open spaces across CCR configurations ranging from 10% to 40%, with satisfaction convergence occurring at 50% CCR between both spatial typologies, as statistically confirmed through Shapiro-Wilk normality and Wilcoxon signed-rank testing protocols. The research demonstrates methodological innovation and theoretical contribution through: (i) development of accessible VR environment creation protocols utilizing Rhinoceros and ClimateStudio platforms for non-specialist implementation; (ii) comprehensive virtual environment experimentation combined with rigorous IPQ validation methodology for STPV CCR assessment; and (iii) pioneering investigation of comparative STPV performance evaluation across diverse architectural contexts. While the investigation presents significant methodological advancement, several limitations warrant future research attention: (i) the scope remained confined to c-Si STPV systems with characteristic visual properties, necessitating expanded investigation of thin-film STPV technologies with subtle visual characteristics; and (ii) the assessment framework concentrated exclusively on satisfaction metrics without incorporating task performance evaluation, which constitutes a critical factor in office space functionality assessment. This investigation establishes foundational methodology for occupant satisfaction evaluation across diverse STPV CCR configurations within varied office environments, providing a framework for future comprehensive research incorporating expanded STPV typologies and environmental variables.

Abbreviations

BIPV	Building-integrated photovoltaic
CCR	Cell coverage ratio
c-Si	Crystalline silicon
HMD	Head-mounted display
HVAC	Heating, Ventilation, and Air Conditioning
IEQ	Indoor Environmental Quality
IPQ	Igroup Presence Questionnaire
PV	Photovoltaic
SHGC	Solar heat gain coefficient
STPV	Semi-transparent photovoltaic
VLT	Visible light transmittance
VR	Virtual reality

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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