A Virtual Reality Window View Evaluation Tool for Shading Devices and Exterior Landscape Design

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Abstract. The window view is an important part of the daylighting design. The current window view analysis based on daylighting metrics does not respond well to user preferences. This study uses an office with a courtyard in Berkeley, CA, USA, as a case study to create a virtual reality-based window view evaluation tool and workflow to analyze the impact of different types of shading devices and different levels of exterior landscapes on user perception. This tool combines quantitative data based on daylighting metrics and users' subjective and physical responses with qualitative analysis based on user feedback and preferences. A two-way ANOVA was conducted in the study to demonstrate that the independent and interactive impacts of shading devices and exterior landscapes on user perception and satisfaction. The results show that users prefer shading types that block less of window views even though they may cause a higher probability of glare. Besides, advanced landscapes tend to enhance user satisfaction with shading devices. This new window evaluation method will help architects make more comprehensive decisions in shading device type selection and exterior landscape design.

Keywords: Window view · Shading device · Exterior landscape · Virtual reality · User perception and preference

1 Introduction

The study of daylighting is an important part of architectural design. Architects and designers often overlook the quality of the occupant's view, an essential analysis factor of daylighting design. The research indicated that reasonable window views can reduce human physical and mental discomfort [1]. Moreover, creating a connection between landscapes and humans by enhancing window views has been proven to positively impact the health of the occupants [2]. Thus, daylighting and window views are increasingly being integrated to consider the impact on occupant health and well-being. As a medium between the interior daylight environment and the exterior landscape, shading devices must balance daylight performance and window views. Appropriate shading devices have been shown to optimize multiple aspects of daylighting, such as daylight distribution, glare, and views [3]. The selections of shading devices and landscaping in the

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previous studies rarely considered end-user preferences and were mostly based on daylight simulation results and subjective design by architects. Thus, to design window views conducive to human health and sustainability, the selection of shading devices and the design of the landscape should accommodate the visual comfort and preferences of users while satisfying daylight standards.

Virtual reality (VR) as an excellent medium can combine simulation-based daylighting analysis with user-based immersive analytics to integrate daylighting metrics and visual preferences of users in the early stages of the shading device and landscape design. VR is becoming an effective alternative for the evaluation of interior visual environments because it has been proven to be superior to video and pictures for subjective perception, and it allows for controlling selected variables, analyzing causal relationships, and saving time and costs spent on real building measurements [4, 5]. Abd-Alhamid et al. [6] confirmed the importance of the information content seen in the window views by analyzing the observation data and feedback from users at different locations in the VR scene and showed that the design of the window view has significant implications for the health and well-being of building occupants. Chamilothori et al. [7] combined VR and wearable biometric devices to study the effect of different shading façades and scenarios for user vision. The results showed that the different patterns and geometries of the shading façade influenced the users' subjective visual evaluation and physiological responses. Lee et al. [8] introduced a method for evaluating view clarity through VR. The study revealed that the geometry and material of the shading system can affect the clarity of the exterior landscape to the degradation of the quality of the view. To sum up, VR has a strong potential to be used as a tool to connect user perception and architectural research. Therefore, more and more architects and designers have the opportunity to gather information about end-user requirements and preferences for window views through VR to make more informed decisions during the preliminary design stage.

The research focused on shading devices and exterior landscapes as the two main points of attention in the window views study. Previous analysis of window views is typically based on a relatively elaborated assessment of the LEED v4 Quality Views (QV) credit [9]. However, this evaluation metric does not require all view criteria to be met the credit, and therefore results in window views that are often low quality and do not respond well to real user feedback [10]. Moreover, other visual perception effects such as glare and thermal discomfort are not taken into account when studying the window views. At this time, there are no established methods to guide designers and researchers in investigating users' perceptions of window views. Based on this, this study proposes the following questions in different stages of workflow:

- How to integrate possible variables affecting window views, including shading devices and exterior landscapes, into the daylight model?
- How to construct an effective and efficient window view evaluation tool that includes other visual factors in VR?
- How to create a workflow through the VR window view evaluation tool to improve the analysis of view quality and user preference? It can assist architects to make comprehensive design decisions.

This study aims to develop a window view evaluation tool and workflow that combines subjective and objective analysis methods. Firstly, the method from daylight models to immersive virtual environments was studied, and the method of constructing a more comprehensive VR window view analysis tool was summarized. This new evaluation tool was then used in the design of shading devices and exterior landscapes for an office in Berkeley, California, and its application to window views perception and feedback for users were explored. This VR window view evaluation tool allows architects to combine daylighting metrics and user preferences at an early stage of design to comprehensively compare and select options for shading devices and landscapes. In addition, the VR window view evaluation tool proposed in this study has been assessed by usability and universal applicability and can be applied to other types of spatial analysis.

2 Method

The primary goal of this study is to propose an innovative VR window view evaluation tool and workflow. Thus, the impact of shading devices and exterior landscapes in window views was studied through immersive virtual environments to help architects find a balance between daylight performance and window views. The study uses an office with a courtyard in Berkeley, CA, USA, as an example. Rhinoceros 3D and Grasshopper were used to create a model an office model with shading devices and exterior landscapes, which allowed defining types of shading devices and different levels of exterior landscapes as parametric variables. Daylight simulation and analysis are completed by embedding the required weather files and material data through ClimateStudio to select shading devices that meet daylight requirements. Moreover, the Radiance Render function of ClimateStudio creates scenes of 360 high dynamic range renderings (HDRR) with different shading devices and landscapes. The VR scenes were created by importing high dynamic range renderings into Unity and adding an interactive interface to complete the user evaluation system. Finally, daylighting metrics, user feedback, and physical responses to different VR scenes were compared and analyzed through case studies to help the architects select the appropriate shading devices and exterior landscapes for the office space. Figure 1 shows the research process and methods of this study.

2.1 Experimental Model

The research uses a south-facing office with a courtyard on the first floor of an office building in Berkeley, CA, USA as the case study. The office's length, width, and height are 5 m, 3 m, and 4 m respectively. Moreover, the office has an exterior courtyard without landscaping with a length and width of 15 m and 10 m. In addition, the office has only one window on the south wall, which is 2.9 m in length, 1.6 m in height, 1m in distance from the floor, and with a wall-to-window ratio of approximately 40%. The weather type in Berkeley is a Warm-summer Mediterranean climate (Csb in the Köppen climate classification) with long, mostly sunny summers. Thus, the architect needed to choose appropriate shading devices and exterior landscapes by analyzing window views to create a comfortable daylighting environment. Based on information from the site,

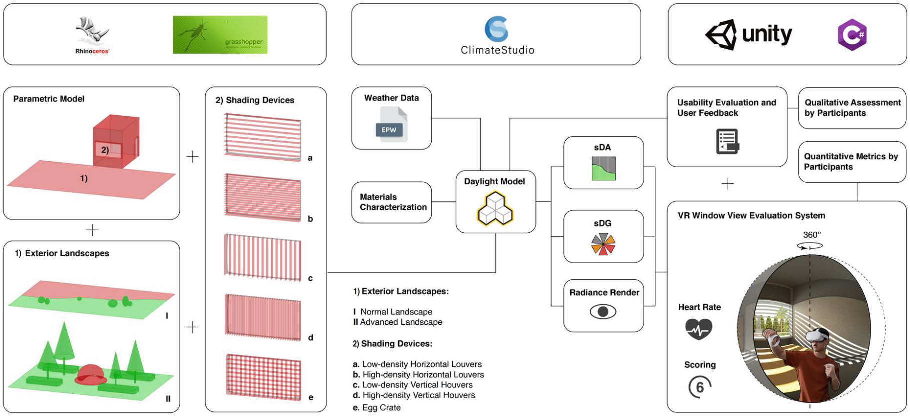

Fig. 1. The workflow specified for the research.

the office was 3D modeled by Rhinoceros 3D and Grasshopper for daylight simulation, system development, and window view analysis (Fig. 2).

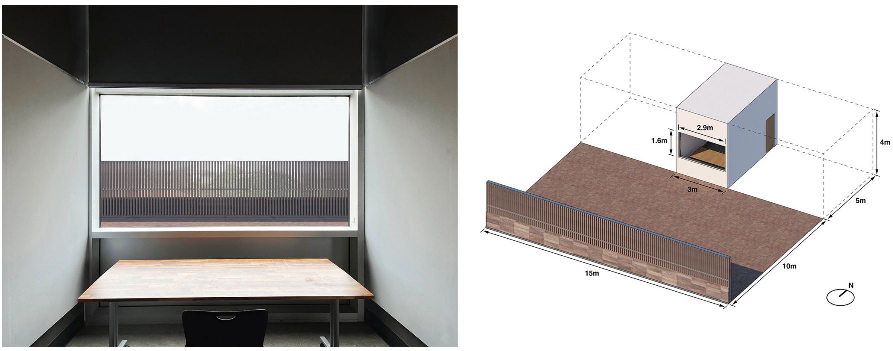

Fig. 2. 3D modeling based on real environment: real office space (left), 3D model for case study (right).

Different types of shading devices and external landscapes were set as independent variables in this study to investigate the comprehensive effect of user responses in window views. The space size, wall-to-window ratio, and materials of the case model are fixed in the analysis. Figure 3 shows the three levels of exterior landscapes created in the study: a no landscape with brick-paved ground, a normal landscape with partial grass and shrubs, and an advanced landscape with more trees and artwork. Moreover, the study selected five types of shading devices in pre-experiments using Grasshopper and ClimateStudio to meet the requirements for spatial Daylight Autonomy (sDA), i.e., the interior space receives at least 30fc of daylight for at least 50% of the workday [11]. Six types of shading scenes including no shading, low-density horizontal louvers (LH Louvers), high-density horizontal louvers (HH Louvers), low-density vertical louvers (LV Louvers), high-density vertical louvers (HV Louvers), and special egg crate louvers

(EC Louvers) were set up in the study to investigate the effect of shading type and density on the visual comfort of the users (Fig. 3).

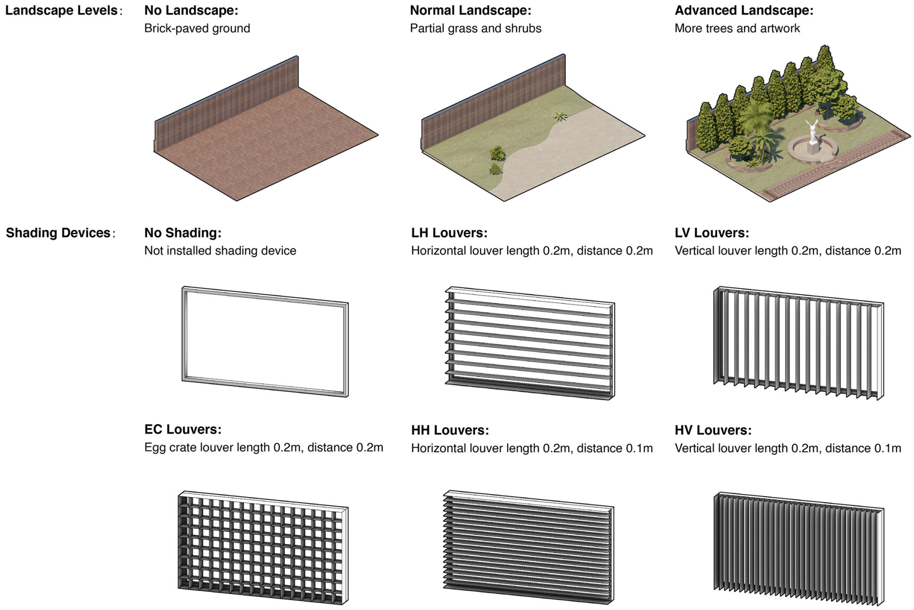

Fig. 3. Three different landscape levels and six different shading devices for window view analysis.

2.2 Daylight Model

The daylight model integrates 3D models, weather data, and materials for window view simulation and rendering of office scenes with different shading devices and exterior landscapes. The EPW weather data files for Berkeley were imported into the daylight model through ClimateStudio using occupancy times from 8 a.m. to 6 p.m. The materials used for simulations and renderings of the office, shading devices, and landscapes are all from the ClimateStudio materials library (Table 1). Daylight metrics were used as supplementary information for window analysis to help architects and users understand the impact of different shading devices and exterior landscapes on interior daylight performance and glare protection. In the study, sDA was used to analyze the annual daylight performance of the space to evaluate different types of shading devices. The analysis grid used to calculate the sDA was located at a table height of 0.73 m, with the sensor points spacing was 0.6 m and their distance from the walls of 0.5 m (Fig. 4). Moreover, the study used Spatial Disturbing Glare (sDG) based on the Daylight Glare Probability (DGP) metric to analyze the annual average glare of the space, i.e., the percentage of space that experiences Disturbing or Intolerable Glare (DGP > 38%) for at least 5% of occupied hours. The analysis grid for the sDG metric used the same sensor spacing as the daylight analysis grids. The default view was located at 1.2 m off the floor (eye height for a seated observer) and the calculation was based on hourly DGP values for eight different view directions at each position in the space (Fig. 4). As a common assessment method of window views, QV credits in this study were always at 100 due to the area of the office (length less than 7.5 m). Thus, the window views analysis method using QV could not be used in this project to investigate the impact of different shading devices and exterior landscapes in more detail. Radiance Render of ClimateStudio was used in this study to simulate the 360 HDRR by daylight model used to create the virtual scene for the window views analysis. The time of the simulation for the scenes was chosen at the highest sDG value of the year (12.30 pm on December 21), and the rendering position P was 2 m from the window at a height of 1.2 m off the floor (Fig. 4).

Table 1. Optical properties for objects in the simulation.

Object	Material	The light reflectance value
Concrete walls and ceiling	Concrete	21.4% Diffuse reflectance
Concrete floor	Concrete	28.2% Diffuse reflectance
Plaster walls	Light laminates	54.8% Diffuse reflectance
Metal decorations	Metal	47.2% Diffuse reflectance
Black metal objects	Paint	1.1% Diffuse reflectance
Wood decorations	Wood	25.8% Diffuse reflectance
Exterior surfaces	Paint	35.1% Diffuse reflectance
Exterior ground	Brick	18.4% Diffuse reflectance
Shading elements	Metal	47.2% Diffuse reflectance
Single glazing	Clear glass	87.7% Direct visual transmittance
Leaves and grass	Foliage	26.2% Diffuse reflectance
Trunk	Wood	27.2% Diffuse reflectance
Stones	Stone	35.7% Diffuse reflectance

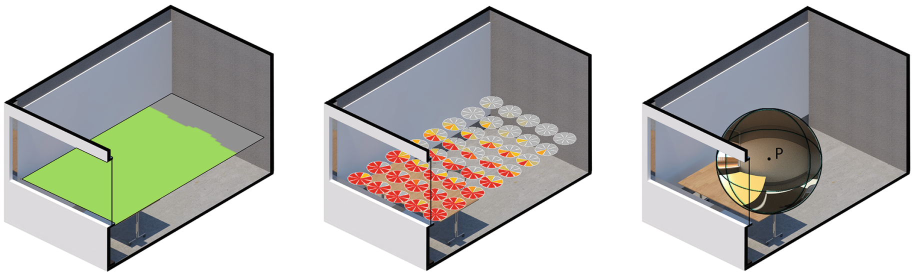

Fig. 4. Example of sensor points with views used for sDA simulations (left), sDG simulations (center), and window view rendering (right).

2.3 Generation of VR Window View Evaluation Tool

The VR window view evaluation tool created immersive virtual scenes for window view assessment by embedding 18 different 360 HDRRs in Unity3D (including a combination of 3 levels of exterior landscapes and 6 types of shading devices in the experimental model). The tool had three main functions to assist users in better completing the window view evaluation. Firstly, a scene-switching function was created to help the user randomly change to the next scene after completing the evaluation of one scene (Fig. 5). Secondly, as glare is an important factor in window view evaluation, the system added a glare observation function (Fig. 5). The system showed the area where the glare existed in the VR scenes by the partial false color (pink area > 2000cd/m^2). Compared to the full false color indication of glare, the partial false color only indicates the glare area to allow the user to intuitively understand the luminance situation in the scene and help the user to complete a more comprehensive window assessment. In addition, users can record their emotions and satisfaction with the different shading devices and exterior landscapes through the evaluation function after completing the observation of each scene (Fig. 5). As listed in Table 2, the evaluation function consisted of 6 questions, all of which are measured on a seven-point Likert scale (mostly 1 = fully disagree and 6 = fully agree). The data collected by the system helped the architects better understand end-user preferences and feedback.

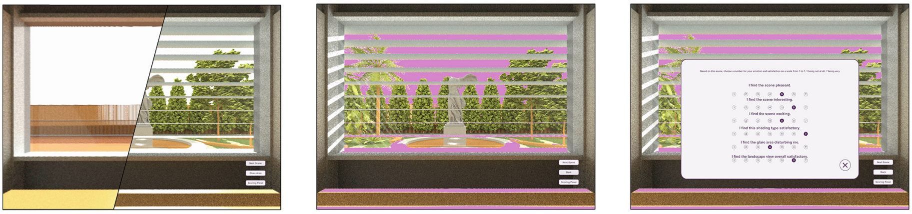

Fig. 5. The three main functions of the VR window view evaluation tool: scene-switching function (left), glare observation function (center), and evaluation function (right).

Table 2. Evaluation questionnaire for window view study.

Q1	I find the scene pleasant
Q2	I find the scene interesting
Q3	I find the scene exciting
Q4	I find this shading type satisfactory
Q5	I find the glare area disturbing me
Q6	I find the landscape view overall satisfactory

2.4 Experimental Design

Instead of traditional physical window view analysis, the study was observed and evaluated through the immersive virtual environment of the VR window view evaluation tool to analyze users' perceptions and preferences for different shading devices and exterior landscapes. The headset used for VR window view observation in the study was an Oculus Quest 2 with a field of view of 100°, a resolution of 1832 × 1920 pixels per eye, and a refresh rate of 90 Hz. The study created a VR environment through Unity3D that can be used for observation of Oculus devices and interaction with the system through controllers. Moreover, a total of 30 participants (15 males and 15 females) participated in this study. Participants were limited to a range of 20–32 years (mean age: 23.8, SD = 3 years). The study used a within-subject experiment design i.e. each participant was tested on the same 18 scenes to eliminate individual differences between participants. In addition, participants were asked to test individually in a real office space. After confirming familiarity with the equipment and experimental procedures, participants were exposed to neutral scenes and tested for basal heart rate in VR, and then a series of scenes were observed in random sequences. While observing the scene, participants were required to use the glare observation function to identify areas of glare in the window and to receive 30 s of heart rate monitoring (Fig. 6). At the end of each scene observation participants were asked to complete the evaluation questionnaire to collect participants' emotions and satisfaction with the shading devices and exterior landscapes in the window views. The average observation and assessment time for each scene is about 2 min. After completing a window view evaluation of a scene participants could switch to the next scene until they completed 18 scenes. Upon completion of the experiment, participants were requested to complete the feedback on window views and system usability. Furthermore, all participants provided written informed consent before the study and were compensated for their participation.

Fig. 6. Participants performed window view evaluation and monitored heart rate in VR scenes.

3 Results Analysis

3.1 Daylight Analysis

Although the main focus of this study is on window view assessment, daylight analysis as a basis for window view analysis helps architects and users understand the daylighting performance and glare probability of interiors with different shading devices and exterior landscape conditions. As shown in the daylight simulation results in Fig. 7, the five different shading devices in the study kept the annual sDA at 55.0–72.5%. Among them, LH Louvers and LV Louvers had the best daylight performance, with an average annual sDA of 71.3%. Moreover, the five different shading devices reduced annual sDG by 19.4–38.8% compared to the No Shading scene (Fig. 7). HH Louvers demonstrated the best glare protection with an annual sDG of 0.6%. Furthermore, compared to No Landscape and Normal Landscape, Advanced Landscape decreased the DGP of different shading devices by an average of 11.4% in the scene on December 21 at 12.30 (Fig. 7). Daylight analysis proved that Advanced Landscape, which has tall trees and artwork, has an impact on glare protection for users. In addition, the daylighting metrics provided basic information for participants in the window view evaluation and additional support for the architects in the window view analysis.

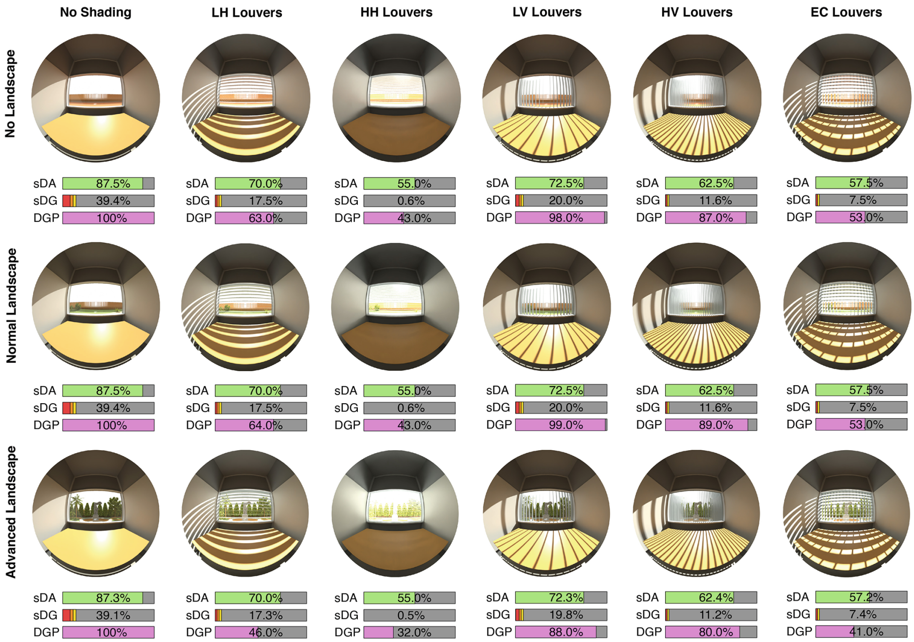

Fig. 7. Daylighting metrics in different window view scenes.

3.2 Window View Analysis

The study analyzed 30 sets of scoring data and physical response data obtained from the VR window view evaluation tool by experiments. The Kolmogorov-Smirnov test showed that the data for all dependent variables were normally distributed, therefore a two-way ANOVA was used to determine the independent and interactive impacts of two factors, the level of exterior landscapes and shading types [12]. Statistical analyses of data were performed in Python, using the toolbox from Pandas, Matlibplot, and Statsmodels. For the multiple independent hypotheses, a Bonferroni-corrected significance level α of 0.0014 is used for the within-subject factor analyses. Thus, the level of the strong effect of significance is 0.001.

3.2.1 Subjective Responses

In this section, user perceptions and feedback regarding shading types and exterior landscape levels in window views were investigated. A two-way ANOVA was performed for each dependent variable to detect the effects and interactions of shading types and exterior landscape levels on users' emotions. The statistical analysis showed a significant effect of shading devices and exterior landscapes on perceived pleasure, interest, and excitement ($SS_{landscape\_pleasant} = 611.411$, $P_{landscape\_pleasant} < 0.001$, $SS_{shading\_pleasant} = 149.817$, $P_{shading\_pleasant} < 0.001$; $SS_{landscape\_interesting} = 549.081$, $P_{landscape\_interesting} < 0.001$, $SS_{shading\_interesting} = 182.326$, $P_{shading\_interesting} < 0.001$; $SS_{landscape\_exciting} = 601.893$, $P_{landscape\_exciting} < 0.001$, $SS_{shading\_exciting} = 180.542$, $P_{shading\_exciting} < 0.001$). The results of the analysis supported the research variables that different shade types and levels of landscape affect participants' responses to the degree of pleasure, interest, and excitement of spatial perception (Table 3). The study demonstrated that participants probably were more pleasant, interested, and excited in advanced landscapes or types of shading devices that blocked less of window views (Fig. 8).

A two-way ANOVA was conducted on participant satisfaction data to investigate the independent and interactive impacts of independent variables on shading device satisfaction (SDS), glare satisfaction (GS), and exterior landscape satisfaction (ELS), ($SS_{landscape\_SDS} = 140.011$, $P_{landscape\_SDS} < 0.001$, $SS_{shading\_SDS} = 921.422$, $P_{shading\_SDS} < 0.001$; $SS_{landscape\_GS} = 47.004$, $P_{landscape\_GS} < 0.001$, $SS_{shading\_GS} = 799.637$, $P_{shading\_GS} = 0.008 > 0.001$; $SS_{landscape\_ELS} = 629.559$, $P_{landscape\_ELS} < 0.001$; $SS_{shading\_ELS} = 173.837$, $P_{shading\_ELS} < 0.001$). The results of the study showed that the interaction of different levels of landscape and different types of shading devices was significant in terms of shading device satisfaction, but not in terms of glare impact and exterior landscape satisfaction (Table 4). Participants tended to score higher on shading device satisfaction and diminished scores on glare discomfort in more advanced landscapes (Fig. 9). Moreover, when the landscape was more obscured by some type of shading device, participants tended to give lower scores on this type of shading device (Fig. 9).

3.2.2 Physiological Responses

The study used a two-way ANOVA to analyze the independent and interactive effects of shading devices and external landscapes in the window views on physiological responses

Table 3. Results of two-way ANOVA testing the effects and interaction of landscape levels and shading types on perceptual feedback of pleasure, interest, and excitement.

	Pleasant				Interested				Excited			
Variation	SS	DF	F	P	SS	DF	F	P	SS	DF	F	P
Landscape	611.411	2.000	283.594	< 0.001	549.081	2.000	275.986	< 0.001	601.893	2.000	333.462	< 0.001
Shading	149.817	5.000	27.796	< 0.001	182.326	5.000	36.657	< 0.001	180.542	5.000	40.010	< 0.001
Landscape/shading	56.922	10.000	5.281	< 0.001	94.519	10.000	9.502	< 0.001	85.019	10.000	9.420	< 0.001

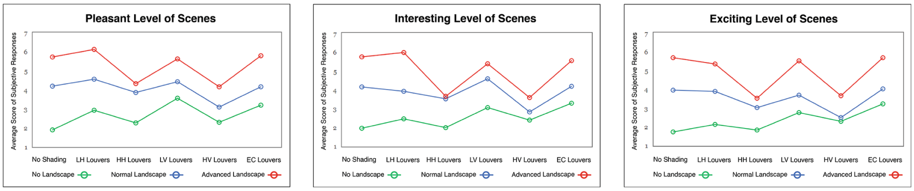

Fig. 8. Interaction plot for average rating of pleasant level (left), Interesting level (center), and exciting level (right) was perceived in different scenes.

(Table 5). The results showed no significant interaction between shading types and landscape levels ($P_{shading\_landscape} = 0.008 > 0.001$). However, the effects of both shading devices and exterior landscapes on heart rate were significant. Figure 10 shows that the advanced landscape scenes had the lowest heart rate differences, meaning that participants were probably in the calmest emotions at that time. Moreover, for scenes with HV Louvers, excessive view blockage and glare may have contributed to the high heart rate differences of participants, meaning that participants may have had uncomfortable emotions at that time (Fig. 10).

3.2.3 User Feedback

Besides the scoring data of window views, the experiment also requested feedback from the participants through questionnaires. Questionnaires are an effective way to collect information on user preferences and behaviors. The study obtained qualitative data on user preferences and usability assessment for the VR windowing evaluation tool through user feedback (Fig. 11). Regarding the window views provided in the study, most users stated that "shading devices that block less of view give me a better visual experience", "I definitely prefer advanced landscapes, it makes me physically and mentally happy", and "I think the combination of low-density louvers and advanced landscapes is my preferred window views". However, a small number of participants indicated "I personally dislike excessive direct daylight, so I prefer shading devices with good shading, even if most of the view is blocked", and "I prefer normal landscapes with only grass and shrubs, such exterior landscapes make me peaceful". The analysis of user feedback showed that users are more concerned about getting relatively unobstructed window views than about glare. Therefore, LH Louvers and LV Louvers with more open window views are the preferred types of shading devices for users. Furthermore, the advanced landscape became the preferred level for most participants. User feedback helped architects to understand user preferences more intuitively and select appropriate shading devices and exterior landscapes.

User feedback also provided a system usability assessment for the study (Fig. 11). On the positive side, users commented that "it provides me with a good visual immersive experience", "the scenes are rendered realistically" and "the system is impressive, comfortable to observe and the interaction menus are responsive". However, users also reported that "I would like to have more interaction with things in the environment", "I wish I could move around in the scenes", and "some parts of the scenes are not clear due to overexposure". Participants' feedback on the system mostly focused on improving

Table 4. Results of two-way ANOVA testing the effects and interaction of landscape levels and shading types on satisfaction of shading devices, glare, and exterior landscapes.

	SDS				GS				ELS			
Variation	SS	DF	F	P	SS	DF	F	P	SS	DF	F	P
Landscape	140.011	2.000	65.567	< 0.001	47.004	2.000	20.916	< 0.001	629.559	2.000	307.937	< 0.001
Shading	921.422	5.000	172.601	< 0.001	779.637	5.000	138.771	< 0.001	173.837	5.000	34.012	< 0.001
Landscape/shading	73.167	10.000	6.853	< 0.001	18.640	10.000	1.659	0.008	61.085	10.000	5.976	0.008

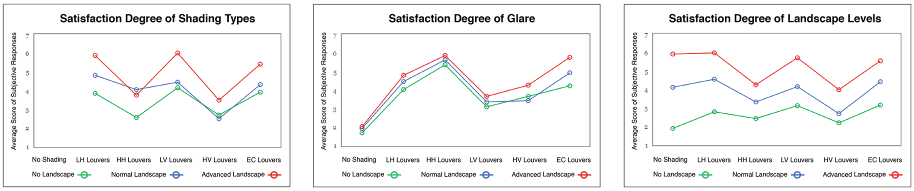

Fig. 9. Interaction plot for average rating of satisfaction with shading devices (left), glare (center), and exterior landscapes (right) in different scenes.

Table 5. Results of two-way ANOVA testing the effects and interaction of landscape levels and shading types on heart rate.

Variation	SS	DF	F	P
Landscape	250.300	2.000	10.921	< 0.001
Shading	483.950	5.000	8.446	< 0.001
Landscape/shading	276.90	10.000	2.416	0.008

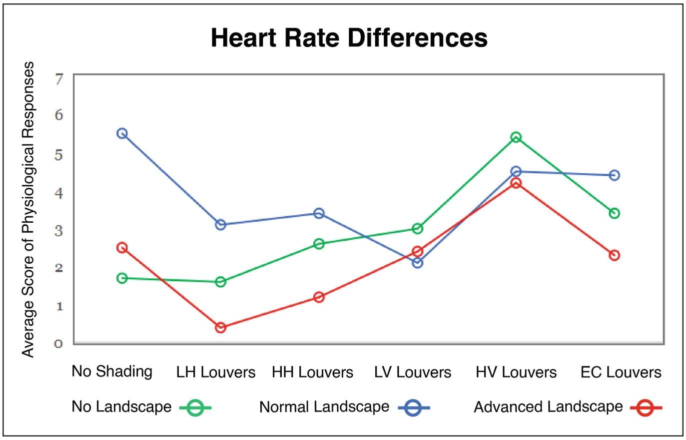

Fig. 10. Interaction plot for average heart rate differences in different landscape levels and shading types.

hardware technology and enhancing interactive functions. The user feedback will inform and assist in the future development of the VR window view evaluation tool.

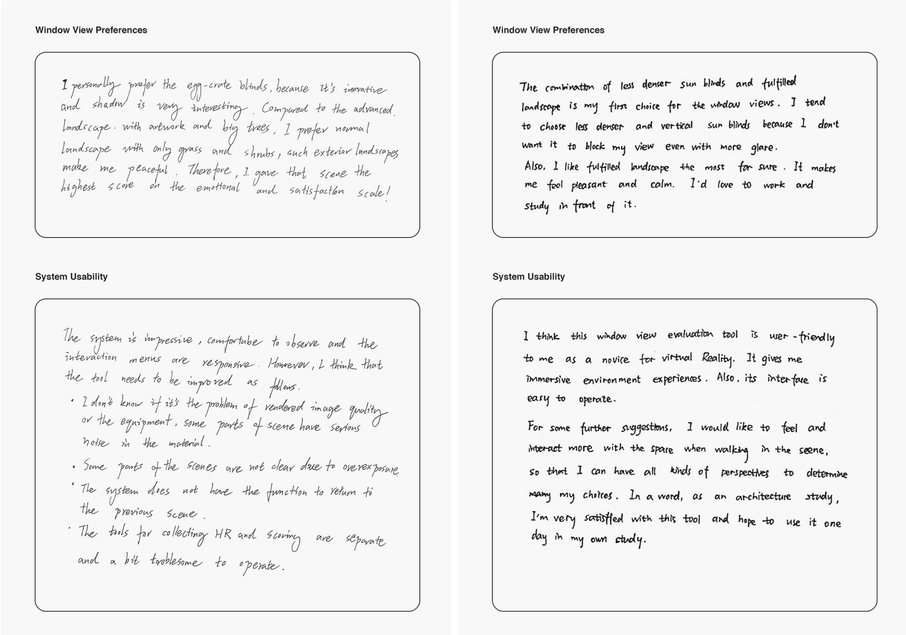

Fig. 11. Excerpts from questionnaires of user feedback.

4 Conclusion

The evaluation of window views requires consideration of several aspects, including shading devices, exterior landscapes, wall-to-window ratios, window materials, observation locations, etc. This research focuses on shading devices and exterior landscapes in the window view evaluation. The VR window view evaluation tool and workflow developed in this study can help architects to comprehensively assess window views and apply them to the design of shading devices and exterior landscapes. The originality and value of this window view research are as follows:

- The study used VR to create an immersive window evaluation environment and false color HDRR to mark glare areas to optimize the user's evaluation process.
- The study conducted a two-way ANOVA with user evaluation data on landscape levels and shading types in window views to investigate their independent and interactive impact on users' emotions and perceptions.
- In this study, the window view analysis combines quantitative data based on daylighting metrics and user subjective and physical responses with qualitative analysis based on user feedback and preferences.

The results of the window view analysis showed the effects of different shading devices and landscape levels on user emotion, satisfaction, and physical responses. Most users preferred shading devices that block less of the view, such as LH Louvers and LV Louvers, even if they have a higher DGP. Moreover, most users preferred the advanced landscape, which tends to increase user satisfaction with shading devices. Furthermore, the user feedback presented in the study can help users to select shading devices and landscape levels that have specific preferences. These analyses of user preferences helped architects to make more comprehensive window view evaluations and design decisions.

The scenes used in the VR window view evaluation tool for this study are simulated based on the case model, which can be replaced with different window view scenes through the design workflow proposed in the paper. Moreover, the system has only one fixed observation position that does not allow for a multiple-perspective window view observation. Therefore, the collection of user perceptions and feedback may be defective. A movable immersive observation environment and more comprehensive physical detection equipment may be added in further studies to complete a more comprehensive window view evaluation tool.

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