Analysing user daylight preferences in heritage buildings using virtual reality

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Abstract

Technology has always been creating effective ways to support human decisions. Immersive virtual reality (IVR) has emerged to engage users in a simulated world, and this has gained the interest of a wide variety of users in the heritage industry. A historical case study built in the early 19th century is considered for an adaptive reuse exhibition. The palace is located in Cairo, Egypt, and named after Prince Omar Tosson. The current palace state incorporates a smashed top-lit zone, which is being studied and analyzed for daylighting adequacy. Three simulated distinct optimum skylight configurations are suggested for the redesign where the selection should not be based solely on simulation data, but should consider real-user preferences. Most daylight design criteria are previously based on simulation data that do not necessarily indicate the users' preferences. But utilizing user interactive tools such as IVR to test daylight redesign options, a whole new dimension is provided. In this study, the VR users' survey data is statistically analyzed using Statistical Package for Social Sciences (SPSS), where results revealed that the assessment attributes succeeded in reflecting the users' preferences; which, motivated designers to consider potential users' daylight preferences in reused spaces. The paper highlights the most significant emotional attributes that provide cost-effective and reliable information concerned with the performance of daylight in IVR before design implementation. This study compares and analyzes the effect of three skylight designs (Cases A, B & C) on the users' perception before design implementation using (IVR) post-survey. Forty-eight participants have contributed to the study, providing their feedback on six attributes namely: Pleasant, Contrasting, Brightness, Uniform Distribution, Visual Comfort, and Satisfaction. Those attributes are evaluated for the three cases in space using five scale rating values to reveal that the "Pleasant" attribute is most reliable in the study to reflect the users' preferences for design Case B.

Keywords

daylight preferences;
heritage buildings rehabilitation;
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1 Introduction

The significance of daylight adequacy in spaces has been highlighted for multiple reasons. Daylight gives another dimension of beauty to the interior and those spaces that lack daylight are usually considered dull. Most critically to consider, is the positive influence on the human being health and well-fare that has been explained in several studies (Wang et al. 2015; Patnaik et al. 2018; Choi et al. 2019). However, studies also aimed at improving daylight performance interplayed with glazing technologies, building opening ratios, and daylight transporting technologies to avoid glare and

provide visual comfort for users while maintaining acceptable daylight distribution in space (Li and Yuan 2016). However, daylight in museums and specifically in adapted museums has been neglected for the sake of artifacts preservation from harmful daylight exceeding values (Rea 2000). Another challenge would be the uneven daylight distribution of hot climatic conditions and the associated visual discomfort for space occupants due to the direct daylight entering spaces (Marzouk et al. 2020a; Marzouk et al. 2020b). Wang et al. (2021) compared different simulation methods to characterize the reflected sunlight from curtain walls. The results indicated that the sun and sky, ambient calculation, and the modeling

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of the building façade significantly affected the simulation results. Hong et al. (2021) examined the effects of five parameters including transition temperature, solar transmittance in clear state, solar transmittance modulation ability, luminous transmittance in clear state, and luminous modulation ability on the building energy consumption and useful daylighting illuminance ($UDI_{300-3000}$).

Specifically, daylight should be enhanced to reflect the interior beauty of spaces and satisfy the user's visual perspective in improving the museums space experience (Kaya and Afacan 2018). Arising technology provides new ways to assist designers in satisfying potential users' preferences through an immersive vertical reality (IVR) perspective that can identify participants' opinions based on reliable information. Virtual reality (VR) has been adopted recently in many studies since it has been proven by researchers its accuracy in simulating physical environment and capability in providing a reliable method for presenting the physical space to users (Marín-Morales et al. 2019).

Egypt has a wide number of monuments linked to various periods of history. The preservation of these monuments is important for promoting cultural tourism and for contributing to the economy. Tourism is one of the leading sources of income, crucial to Egypt's economy. At its peak in 2010 the sector employed about 12% of workforce of Egypt serving approximately 14.7 million visitors in Egypt, and providing revenues of nearly \$12.5 billion (World Bank 2020). The Government's goal is to enforce the heritage restoration program. Restoration has to be carefully prepared to retain a good user experience. In heritage, It has been encouraged to utilize VR for various purposes including documentation, conservation, restoration, and exploration but none has utilized VR and IVR in heritage for design adapted reuse purposes. Up to the authors' knowledge, there is no existing research that explores daylight enhancement in adapted heritage using IVR. Though few researches have studied generic space evaluation attributes, this research focuses on utilizing significant daylight assessment attributes in reflecting potential adapted space users' perceptions and adding qualitative assessment thread to the simulation of spaces. Daylight visualization utilizing head mounted display (HMD) allows users to experience a virtual space that is used to validate the user's experience to the condition of the daylight inside the historical building through comparing the simulation design results against those concluded from the user's questionnaire survey using HMD. The contribution of the study adds unique daylight oriented evaluating attributes to the participants' responses, to the IVR survey. It provides an approach using IVR to identify user preferences with respect to daylight design options. This study provides a guide for practitioners, to orient their decision-making towards users' preferences in heritage buildings.

2 Literature review

Virtual reality (VR) and augment reality (AR) technologies have been recently deployed for various functions and purposes. Their relative significance in each field has been adapting with the arising technology developments every day as being able to simulate a world space virtually. Von Itzstein et al. (2017) explored the VR and AR technologies extent in different fields that cover scientific, educational, as well as entertainment services. Highly engaging users in a non-real environment have been the real challenge perused by the developers to attain users' interest in applications. Abdelmonem (2017) investigated the VR procurement in the Egyptian culture in which he realized the effect of the culture on the perception of new technology and the importance of meeting the archaeologists' interest and engaging them in utilizing such technology that will reform the historical physical aspects as well. Many researchers studied the human behavior in response to interior colors, daylight, external view, site hazards, auditory, and biophilic environments in VR scenery and accordingly, assess the human behavior through various subjective measures that cover physiological responses, emotions, and comfort levels (Yin et al. 2020).

VR has been utilized to assessing the effect of a biophilic environment on users through setting three VR office spaces with different outdoor features, revealing the negative impact of dull spaces on stress levels (Yin et al. 2020). Also, it has been used to study the impact of a construction design review skills of construction students (Kandi et al. 2020), while considering the thermal, emotional, and cognitive effect of external view existence in VR, allowing comprehensive assessment of the positive impact of windows to space users. These studies succeeded in assessing and measuring human behaviour in response to variable stimuli in VR. While other researchers validated the VR environments in effectively reflecting real environments by comparing the human response in both the physical environment and the IVR environment (Heydarian et al. 2015; Chamilothoni et al. 2019).

Heydarian et al. (2015) compared human performance in an office space through a statistical analysis of 112 participants' responses in the physical and immersive environments, to ensure the applicability and the reliability of using the VR in the design phase and giving an accurate indication of potential occupants' feedback. The feedback of occupants was gathered through a unified questionnaire template that included questions that reflect the satisfaction of occupants in the IVE using mean and standard deviation values of experiment participants' survey data. Keshavarzi et al. (2019) analyzed RadVR which is a daylight analysis tool embedded in a VR and Diva for Rhino software that is used as a daylight analysis plugin Rhino+Grasshopper 3D parametric modeling software. The analysis considered performing daylight

simulation models and evaluated their performance in terms of user easiness in navigating and reading results. The study recommended the usage of a virtual environment as a successful simulation tool over the 2D modeling and simulation tool as it additionally prompts for a spatial experience for the user in different daylight simulations. This is done via the RadVR 3D modeling plugin before the RadVR application. Instead of evaluating end-user preferences by occupants, the study introduced a user evaluation method that relies on predefined metrics. The RadVR used the Radiance simulation engine to perform daylight calculations which are widely validated. However, daylight simulation is performed for a defined space using two different tools, and the user's opinion is analyzed against both methods. Jin et al. (2021) have investigated the building interior beauty of spaces and Chinese cultural heritage via the user's visual perspective under IVR. They realized that the human interaction in IVR allows higher experiential level and sense of space. Gómez-Tone et al. (2021) have examined the perception of space in IVR, and recognized high percision with 83.9 % relative to real environemts, where the interior designs have grown in IVR concerning 2D drawings. Chamilothori et al. (2019) investigated the applicability of using the IVR headset in accurately representing daylight simulated spaces to occupants. In which real and virtual environments are both compared in terms of visual daylight perceptions (pleasant, interest, excitement, complexity, and satisfaction) and other physical symptoms (eye soreness, tiredness, clearness of vision); the effect of the display method of a VR environment on occupants is also examined. They indicated the success in measuring the user preferences in a VR environment and there is a high similarity in users' responses to a real environment. Sawyer and Chamilothori (2019) demonstrated six different daylighting scenes using grasshopper modeling tool with unity for IVR experience to explore the users' satisfaction and suggest the optimum design configuration in terms of façade openings and interior daylighting. Marín-Morales et al. (2019) compared virtual and real museum environments through a human navigation tour in an exhibition while proposing questions to illustrate the human experience in both environments. The questions revealed the difference in touring time and examined the difference in sense of space acquisition. In addition, they analyzed the heat map visualization of five different exhibition rooms in the physical and virtual environments. Data obtained from 60 participants were analyzed using their mean value and the standard deviation. This allowed the authors to validate environmental analysis tools through physical existence using *HTC Vive*, providing a novel validating tool for designers.

Hegazy et al. (2022) approached aids in collecting and visualizing brightness perception of daylighting in a large-scale IVR. The proposed approach enables its users to explore

building models at different day times set in VR and report their perceptions in real time. Amirkhani et al. (2018) aimed at satisfying the occupants of an office space in terms of lighting conditions. They investigated the influence of change in the room window to wall ratios (WWRs) and the electric lighting levels, on the occupants' satisfaction in an IVR environment. They used Autodesk 3Dmax software to provide the room materials and rendered scenes. The questionnaire relied mainly on the users' sense of lighting in the space and their satisfaction with the lighting conditions retrieved to assess the rated contrast (RC) on occupants. Hydrarian et al. (2017) examined the user light preferences in IVR experience, analyzing 89 occupants' preferences in the simulated office with and without the addition of shades to a side-opening in the space. The users were able to adjust their electric light preference in addition to the daylight. The analysis grouped IVR users according to the amount of turned lamps to reveal the lux and energy consumption produced by each design group. Quartier et al. (2014) studied the effect of retail lighting conditions on users' behaviour. They experimented with a 3D-simulation setting with three varied lighting conditions. They realized the effect of warm light on the users' emotions and attitudes, where the performed statistical analysis confirmed the positive relationship between preferable light conditions and long hours to be spent by supermarket shoppers.

Lighting evaluation inside space has been claimed to be convoluted with sensational feelings and emotions in both real and virtual environments (Veitch 2001). Several studies indicated that emotional attributes are related to pleasure and arousal attributes expressed earlier by Russell (1980) which have been followed since then to assess the degree of emotions. The measure of emotional attributes in those two well-known dimensions has been utilized in lighting studies to generalize the occupants' satisfaction state with the daylight environment (Russell et al. 1981; Wardono and Wibisono 2013; Clevenger and Rogers 2017, Chamilothori et al. 2018, Chi et al. 2019). Moreover, daylight assessing attributes focusing on daylight quality has been recently introduced and added in research studies to add another dimension of assessment (Xue et al. 2014). Studies assessing user preferences in different daylight and artificially lit spaces have incorporated a scaled rating value to estimate their degree of emotional response and context satisfaction in space (Abboushi et al. 2018; Omidfar et al. 2015). Each study utilizes a unique scale of rating that is mostly used to provide similar information and findings. However, the most valid scaled rating system has been a subject of interest and investigated (Stokkermans et al. 2018), where early research suggested the utilization of both objective and subjective measures are to be utilized as a stronger assessment measure for daylighting (Axarli and Meresi 2008).

Although VR applications have been widely adopted in many studies, yet their limitations in the daylight spaces

have avoided their effective integration in daylight simulation environments. For daylight simulations and graphical visualization, the ray-trace method is used and was initially introduced earlier by Kajiya (1986) and widely adopted by radiance and Velux in providing daylight visual spaces in modeling and simulation software. While ray-tracing in VR environments is possible; yet, still difficulty in providing physical renders in high-frequency rates makes it more challenging. For an efficient visual in a VR environment, it is always required a 6 degrees of space freedom (6DOF). In literature, several studies relied mainly on daylight descriptive attributes to assess virtual environments, while other studies relied only on Russel's emotional attributes. However, for this study, a mix of both related attributes has been selected to give a more comprehensive understanding of the user experience. Not to mention that in previous studies most virtual environments did not necessarily cover IVR which is considered a more user-oriented experience, giving more reliable user preferences.

This research focuses on the potential users' experience of skylight redesigned spaces. The research contributes to the existing body of knowledge by addressing the effectiveness of the IVR in reflecting potential users' experience of a daylight space. Also, it studies the daylight and emotional attributes which are most reliable to identify IVR user preferences of designed skylights in heritage spaces.

3 Methodology

3.1 Research overview and procedure

A case study is analyzed for adaptive reuse purposes and assessment of users' preferences for the redesigned optimized skylight space. Through six defined emotional and physical attributes, a rating scale is selected to evaluate them in a created questionnaire survey for the case-study. In the assessment component, users are introduced to three case-studies in IVR, and afterward, they can fill in the related evaluation survey. While, in the model component, the three selected case studies are adapted for IVR and both grey-scaled models and rendered models are used to test survey results and adjust the assessment attributes. Finally, statistical analysis is performed on survey data to test relationships and provide significant reliable users' assessment criteria in IVR. A flowchart for the research approach is indicated in Figure 1.

3.1.1 Case study description

A heritage palace called after Tosson Pasha, built in the early 19th century located in Shubra, Cairo is analyzed in IVR. Physical data were retrieved for the current palace as shown in Figure 2(a), then a BIM model shown in Figure 2(b) is created for the study.

Fig. 1 Study procedure to evaluate user daylight preferences in IVR

Fig. 2 Tosson Palace and main analyzed hall

The study is based on dynamic simulation for a skylight with an area of 15 m × 15 m, to optimize the rebuilt in function with minimum interventions. The maximum skylight height is 3.00 m. Genetic algorithms optimization was utilized to arrive at three distinct cases that vary in opening ratio, opening orientation, sun breakers. The output design of each case mainly is derived from optimizing the range of recommended skylight parameters to maximize both daylight and cooling load efficiency using the *Octopus* component in *Diva* for *Grasshopper*. The cases were simulated to read their relative Spatial Daylight Autonomy sDA & Annual Solar Exposure ASE values as follows (ElSharkawy 2020):

For Case A: sDA 56.1 %, ASE 35.8%;

For Case B: sDA 52.2 %, ASE 45.4%;

For Case C: sDA 40.6 %, ASE 33.1%.

These results indicated a high similarity in daylight performance between the three distinct cases, the ASE % is considered not sufficient for comfortable levels of daylight. Thus, IVR is recommended to evaluate.

3.1.2 Equipment and tools

IrisVR and *SteamVR* online platforms are used along with the *HTC Vive Pro* headset to allow users to experience three study cases with varied skylight configurations. A unique day is selected for evaluation (21st June) for the three introduced cases. The experiment is performed on an Alien-ware Area

51 computer with capabilities of Intel(R) core™ i9-7980XE CPU @2.6 GHz 2.59 GHz, RAM, operating system 64 Bit, Microsoft Windows 10.

HTC Vive Pro headset is used in the virtual experiment. The headset is connected through *SteamVR* wireless online application before use. It's significant to identify the different specifications of the hardware, to note the quality of the headset and its suitability to the intended application. The HMD is compatible with the software *IrisVR* Platform, which is a cloud-based platform with a linked application named *Prospect* that supports the *HTC Vive Pro* headset. Participants can tour inside the 3D model through the *Rhino* plugin that grasps the model in *Rhino+ Grasshopper* directly to the *VR-Prospect* application for an immersive experience. The software is also capable of dealing with other 3D modelers like *Revit*, *Sketchup*, and *Navisworks*. The immersive experience guides participants into the 1:1 created space. All compatible IVR tools shown in Figure 3 are configured before the experiment kicks-off.

Enhancing the daylight performance inside a heritage space in hot climatic conditions is introduced. Three different optimum skylight configurations are analyzed using the IVR experience. Participants' subjective satisfaction was measured at different timings of the day on 21 June for the three different skylight-optimized configurations. It is worth noting that *IrisVR* software does not allow the selection of the exact climatic location. The plugin in *Rhino + Grasshopper* shown

in Figure 4(a) prepares the model for the virtual experience shown in the *Prospect* platform in Figure 4(b).

Participants are asked to put the HMD and navigate freely through the three spaces. Afterward, they are asked to remove the HMD and answer several questions based on their experience using a rating value from a 1 to 5 scale to rank their subjective opinion, where 1 indicates no preference and 5 indicates a very high preference for the assessed attribute. Also, experiment users are allowed to fill their personality information and preferences. The Palace is studied for adaptive reuse purpose and assessment of the redesigned optimized skylight spaces is performed through defined emotional and daylight attributes in a created survey study for the spaces in IVR. Three distinct main skylights' attached halls are created in both a grey-scaled model and a rendered model for the IVR experience.

3.1.3 Independent variables: Skylight model design

Three cases are assessed for subjective user preferences through IVR analysis, intending to provide information on the most suitable design case to implement in the future for the palace rehabilitation plan. Those design cases with their relative Daylight Autonomy representation (see Figure 5):

- Case A: Minimum size opening in skylight with a light control system;
- Case B: Flat skylight with mullion integration;
- Case C: Tilted skylight with mullion integration.

Fig. 3 IVR adopted tools

Fig. 4 Model view in applications

Pilot grey-scaled design models are used to provide generalized data regarding the participants' feelings towards the three introduced cases (i.e., A, B, and C) in IVR. This step is extremely significant to allow for modifications before rendering and to assess the space quality and users' experience due to different skylight designs. In the three assessed cases through an immersive experience, participants were asked to rate their subjective impressions on a 1 to 5 scale at different hours of the day. The selected measuring attributes are essentially general emotional four preferences which are *Pleasant*, *Interesting*, *Complex*, and *Satisfaction*. These general emotional attributes are selected according to Russel's (1980) model of emotions that has proven that daylight has a strong effect on the emotional state of any space occupant. Three

introduced grey-scaled models with different optimum skylight configurations, as indicated in Table 1 were analyzed at three-time points adjusted in the software to reflect the different daylight angles during the day.

During the IVR experiment, screenshots were taken for the different optimized model views in the HTC Vive headset. The three different skylight configurations are evaluated for four emotional attributes (*Interesting*, *Pleasant*, *Complex*, and *Satisfaction*) with ten participants. The mean rating values are shown in Figure 6 to indicate the results. Through the preliminary analysis of the participants' subjective results, the most recommended skylight integration in Tosson Palace would be Case C that achieves higher mean ratings in the assessed attributes. These attributes are developed in the

Fig. 5 Three optimum models view

Table 1 Analyzed cases in grey-scaled model

Time	Case A	Case B	Case C
9:00			
12:00			
16:00			

rendered IVR study section to significantly indicate the effect of daylight on IVR users.

To understand the effect of time of the day on the participants' experience, Figure 7 depicts the feedback of the participants on the four emotional attributes at three different day timings, which can be interpreted as follows:

Case A: Participants felt more interested, more pleased, and more satisfied especially during the early morning hour evaluated at 9:00. Subjective opinion evaluated at noon and afternoon hours (i.e., at 12:00 and 16:00) respectively, where the sun did not penetrate directly on the skylight opening at all due to its falling on the opaque surface of it. Participants felt bored and not interested in taking the tour inside due to daylight deficiency.

Case B: Participants were found more interested in the patterns created on the ground and walls surfaces that resulted from skylight with mullion reflections. However, during the noon evaluation, the sun was directly above the skylight. Although the patterns created an interesting feeling, the participants felt the experience unpleasant and considered it more complex. During the 9:00 evaluation, it was found more interesting than that of the afternoon at 16:00.

Fig. 6 Evaluation of mean for the four emotional attributes (Interesting: the impressiveness degree of space; Pleasant: space delight effect on the participant; Complex: finding difficulty to understand space; Satisfied: overall experience satisfaction)

Fig. 7 Evaluation of hourly mean for the four emotional attributes

Case C: Participants were found to be overall interested in the three experienced timings during the day. The most efficient results were profound in the early morning hours at 9:00., as sunlight penetrated deeper into space.

Comparing different day timings between optimum cases allows us to reveal the optimum configuration during the working hours of the suggested exhibition palace. It is effective to start by selecting hours of negative subjective impressions to avoid implementing their related skylight configuration in the future as follows:

- At 12:00 noon in Case B, it is considered the most complex experience of all, less complex in Case C, and least complex in Case A.
- At 16:00, Case A is considered the least interesting experience of all.
- At 9:00 in the three cases, the slightest differences revealed the possibility of success for the three assessed configurations.

Yet, the comparison should still rely on a wider survey group and therefore statistical analysis is required to identify the significance of any observed analysis, and evaluation could be more ground-based. Secondary analysis is performed with rendered cases in IVR to tackle participants' both emotional and daylight quality vision for the cases.

3.1.4 Dependent variables: Emotional and daylight descriptive

The study utilizes 1–5 rating scaled values to assess the preferences view for the introduced three distinct designs in IVR. The scale identifies the degree range of relevance to the measured attribute according to Table 2. The five-scale measures differences in preferences efficiently in providing reasonable values for participants to pick on a suitable range and covers minimum, maximum, and median/middle value where appropriate.

3.2 Experimental procedure

Participants' experimenting was briefed about the experiment and the three skylight designs (abbreviated as Cases A, B, and C). The measuring attributes utilized in the experiment were explained and demonstrated clearly to avoid any misunderstanding as depicted in Figure 8. The total number of participants is 48 which consists of 18 males and 30 females. They mostly preferred light conditions with daylighting only (32 participants) and both artificial and daylight conditions (16 participants), none of them preferred artificial conditions over a daylight in spaces. Also, users wearing glasses (13 participants) felt more comfortable taking them off during the experiment and that might have influenced their impressions. Different age groups of participants are considered, who ranged between students with 19 years and professionals to

Table 2 Considered attributes to assess users' preferences

ID	Attribute	Preference scale					Target measure
		5	4	3	2	1	
A ₁	Pleasant	VH	H	M	L	Not	Space delight effect on the participant
A ₂	Contrasting	VH	H	M	L	Not	How you find the shades degree of the space
A ₃	Brightness	VH	H	M	L	Not	The degree of brightness of the space
A ₄	Distribution	VH	H	M	L	Not	The uniformity in daylight distribution
A ₅	Visual Comfort	VH	H	M	L	Not	The comfortable feeling of the space
A ₆	Satisfaction	VH	H	M	L	Not	Satisfaction related to the overall impression

Notes: VH: very high; H: high; M: medium; L: low.

Fig. 8 Experimental procedure for assessing IVR user preferences

cover a wide range of people. The survey experiment data was conducted and collected in three phases (see Figure 9).

First, the experiment is conducted in a workshop that has a heritage theme where most participants were knowledgeable enough and have related research and professional experience. The workshop was conducted in a museum (Museum event). The second phase was conducted with architectural students during their class, most of them aged 19 years (Architecture class). The third phase was conducted during a workshop

that gathered practitioners in the field. The workshop was essentially part of a dissemination event of a research project (Project workshop). The questionnaire content is divided into two main sections; personal information part and scaled measure subjective sense of space attributes part, which is retrieved for analysis.

3.2.1 Experiment practice

A preliminary assessment with a grey-scaled model in IVR was decided to be conducted first to indicate the improvements to be applied in the next stage of IVR assessment. The analysis provided a generalized view of data regarding the users' opinions of space. Subsequently, the palace is assumed to be turned into a museum. Thus, the rendered finished and furniture added is selected to serve the potential users' functional space. Three rendered cases, shown in Table 3, are analyzed for user preferences through IVR.

3.2.2 Survey validity

a) Number of participants

The effect of sample size was calculated using the Wilcoxon Signed-Rank test for a sample attribute in which the least feedback was obtained. It is worth noting that 48 respondents participated in the survey but their feedback for the assessed attributes was not complete. The least checked attributed has been evaluated by 45 participants which are considered in Eq. (1).

Fig. 9 Phases of a survey experiment

$$\text{Effect of size}(r) = \frac{Z}{\sqrt{N}} \quad (1)$$

where r is the effect of size, Z is the sample Z value of Wilcoxon signed test and N is the number of minimum retrieved feedback from participants considered in the analysis. Substituting Z of 1.963 and N of 45, the estimated r value is 0.28 which is considered moderate effect size since it is less than 0.3 as indicated by Faul et al. (2013).

b) Homogeneity of the participants

To check the validity of the data obtained from the survey; the participants were grouped into two different groups based on gender (i.e., females versus males) and occupation (i.e., professionals versus students). Mann Whitney test was used to compare the feedback from the different gender

groups regarding all the survey attributes in the three different cases. Statistical significance was obtained only between males and females regarding the *Contrasting* attribute in Case B only (see Table 4). Also, those survey contributors were grouped by their occupational level into 35 professional and 13 students, the participants' occupational significance effect on the survey data is analyzed through the Mann-Whitney U -test for their feedback for all the attributes within the three cases as shown in Table 4. The test reveals that no significant differences occur between the two groups regarding their feedback on the attributes in all cases. This reflects that the differences in the participants regarding the gender and occupation did not affect the survey results. It is worth noting that statistical analysis was performed using Statistical Package for Social Sciences (SPSS) (Wagner III 2019).

Table 3 Analyzed cases in rendered screenshots

Time	Case A	Case B	Case C

9:00
12:00
16:00

Table 4 Mann-Whitney U -test on gender and occupation grouping

	Case A						Case B						Case C					
	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
Gender	0.49	0.92	0.39	0.51	0.85	0.90	0.08	0.03	0.87	0.64	0.13	0.21	0.53	0.69	0.33	0.99	0.90	0.69
Occupation	0.96	0.88	0.80	0.35	0.75	0.93	0.26	0.47	0.80	0.36	0.63	0.74	0.31	0.33	0.09	0.94	0.38	0.52

4 Survey results

Subjective opinions of participants in rendered conditions are analyzed for the three introduced cases (i.e., A, B, and C). All scores of the participants representing their VR lighting evaluation are used to calculate the mean and standard deviation values. Each daylighting attribute is evaluated separately while descriptive statistics give a broader understanding of the results (listed in Table 5). The mean ratings are presented for the different daylight assessing attributes of the three cases as shown in the radar chart in Figure 10. The results reveal a larger area of the radar hexagon illustrates higher rating values and higher daylight quality. The general order of the mean scores provided a generalized view perspective for the daylight quality of the three modelled cases in which Case B has the highest scores, followed by Case C, then Case A.

The survey results were checked for normality using the Kolmogorov-Smirnov test. The data was not normally distributed (non-parametric). Wilcoxon Signed-Rank test was used to identify the statistically significant difference between the compared attributes of different design cases. The difference was considered significant when P -value equals or less than 0.05. Comparing Case A against Case B, significant attributes are *Pleasant*, *Contrasting*, and *Brightness* attribute where their P -values are 0.05, 0.00, and 0.00 respectively. While the attributes of *Distribution*, *Visual Comfort*, and *Satisfaction* are not significant where the

P -values are 0.064, 0.331, and 0.445, respectively. Similarly, comparing Case A against Case C, attributes that are found significant included *Pleasant*, *Contrasting*, and *Brightness*, and attributes found insignificant included *Distribution*, *Visual Comfort*, and *Satisfaction* (see Table 6). This reflects that the presented cases in IVR can influence the participants' daylight assessment of space using the three mentioned significant attributes. Comparing Case B against Case C, the results indicate that there is no significance among mean values which highlight that the two cases are highly similar to participants to the extent they were unable to significantly differentiate them in rated values.

The results (shown in Table 6) reveal the following:

- For the *Pleasant* attribute, Case A is significantly lower than Case B and Case C with Case B being the most pleasant. The same is applicable for *Brightness* and *Contrasting* attributes.
- The daylight *Distribution*, *Visual Comfort*, and *Satisfaction* attributes are not significantly different when compared in the three cases.

4.1 Kruskal-Wallis test

The test compares the results of more than two independent groups using the median values to indicate any differences among the assessed group of variables (Kruskal and Wallis 1952). The test is used to compare median values in the three design Cases A, B, and C for the six attributes where the

Table 5 Mean rating and standard deviations for daylight emotional attributes

Case	Pleasant		Contrasting		Brightness		Distribution		Visual Comfort		Satisfaction	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
A	3.40	1.07	2.95	1.19	2.97	1.17	3.6	1.04	3.57	1.24	3.54	1.15
B	4.00	1.02	4.1	0.92	4.4	0.67	4.35	0.64	3.8	0.99	3.8	0.95
C	3.89	1.07	4.13	0.88	4.23	0.79	3.26	1.34	3.69	1.03	3.8	0.90

Fig. 10 Mean ratings of participants feedback on daylight attributes

Table 6 Checking the mean differences between the three tested cases

	Case A–Case B	Case B–Case C	Case C–Case A
Pleasant	0.05	0.680*	0.048
Contrasting	0.00	0.629*	0.00
Brightness	0.00	0.537*	0.00
Distribution	0.064*	0.535*	0.241*
Visual Comfort	0.331*	0.632*	0.675*
Satisfaction	0.445*	0.779*	0.256*

Note: *P*-value is considered significant <0.05.

sample data is not considered large, and the data distribution is not normal and testing the significance hypothesis (see Table 7). It is shown that the *Satisfaction* attribute of Case B, is the most significant with *P*-value (0.034) among the three collection phases.

Thus, the Kruskal-Wallis test indicates significant differences among the attributes of the three design cases along with the participants' groups of data. Where their mean ranked show the highest values for the Museum event as shown in Figure 11 for the *Satisfaction* attribute assessed in Case B. It is suggested that might attributed to the incident that Project event and Architecture class survey were conducted indoors. While the Museum event survey was conducted in an outdoor setting. The pair-wise adjusted significance shown in Table 8 provides that Project event and Museum event survey data for the *Satisfaction* attribute of Case B are highly significant according to the Bonferroni correction.

Table 7 Kruskal-Wallis test for collection phases

	Case A						Case B						Case C					
	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
<i>P</i> -value	0.884	0.878	0.716	0.609	0.739	0.873	0.236	0.478	0.342	0.808	0.176	0.034	0.409	0.578	0.072	0.854	0.642	0.615

Fig. 11 Kruskal-Wallis test for survey phases—satisfaction attribute of Case B

Using the Kruskal-Wallis test, the preferred light variable was tested using the Kruskal-Wallis test for the significance and adjusted significance using Bonferroni correction. It is shown in Table 9 that none of the participants preferred artificial light, and all participants chose daylight or mixed-mode light but mostly preferred daylight over mixed-mode lights with high significance 0.013 values that are subject to adjusted significance with 0.038.

4.2 Kendall's Tau correlation analysis

Kendall's Tau correlation is utilized to describe the relationship between assessed attributes and the relationship type presented between them (Newson 2002; Mat Roni et al. 2020). Table 10 indicates the high and low correlation coefficient values between the attributes, where in some cases; there is a negative correlation that indicates the opposite relationship between the attributes. The results show that correlations between *Pleasant*, *Brightness*, *Visual Comfort*, and *Satisfaction* were most significant ($P < 0.05$, shown in Table 10). While not for daylight *Distribution* where there was no significant correlation with other daylight subjective attributes. This means that changing daylight attributes would affect the subjects' impression of the rest of daylight attributes as well excluding the *Distribution* attribute.

The strongest correlations are presented in Table 10 which equals 1. Similarly, strong correlation values are those closest to 1 as indicated. For Case A, strong correlations exist in attributes with values higher than 0.5 and less than 1 (such as

Table 8 Pairwise comparisons for survey phases—satisfaction attribute of Case B

	<i>P</i> -value	Adjusted <i>P</i> -value
Project event vs. Architecture class	0.149	0.446
Project event vs. Museum event	0.009	0.028
Architecture class vs. Museum event	0.280	0.839

Table 9 Pairwise comparisons of preferred light

	<i>P</i> -value	Adjusted <i>P</i> -value
Daylight	0.013	0.038
Mixed mode	0.004	0.011
Daylight vs. mixed	0.602	1.000

Table 10 Correlation coefficient and significance among attributes for the three cases

Attribute		Pleasant	Contrasting	Brightness	Distribution	V. Comfort	Satisfaction
Case A	Pleasant	Coef.	1	0.330**	0.213	0.350**	0.584**
		P-value		0.007	0.08	0.005	0.000
	Contrasting	Coef.	1	0.564**	0.106	0.312**	0.428**
		P-value		0.000	0.381	0.010	0.000
	Brightness	Coef.		1	0.070	0.169	0.252*
		P-value			0.563	0.162	0.040
	Distribution	Coef.			1	0.386**	0.377**
		P-value				0.002	0.002
	V. Comfort	Coef.				1	0.785**
		P-value					0.00
	Satisfaction	Coef.					1
		P-value					
Case B	Pleasant	Coef.	1	0.153	0.035	0.254*	0.516**
		P-value		0.239	0.797	0.044	0.000
	Contrast	Coef.		1	0.338*	-0.005	0.130
		P-value			0.012	0.966	0.311
	Brightness	Coef.			1	0.055	-0.124
		P-value				0.680	0.351
	Distribution	Coef.				1	0.349**
		P-value					0.005
	V. Comfort	Coef.					1
		P-value					0.000
	Satisfaction	Coef.					
		P-value					
Case C	Pleasant	Coef.	1	0.189	-0.028	0.188	0.378**
		P-value		0.143	0.828	0.130	0.003
	Contrast	Coef.		1	0.298*	0.025	0.080
		P-value			0.025	0.843	0.535
	Brightness	Coef.			1	-0.018	0.179
		P-value				0.0891	0.168
	Distribution	Coef.				1	0.306*
		P-value					0.013
	V. Comfort	Coef.					1
		P-value					0.000
	Satisfaction	Coef.					
		P-value					

Notes:

** Correlation is significant at the 0.01 level (1-tailed).

* Correlation is significant at the 0.05 level (1-tailed).

Pleasant and *Visual Comfort* [0.584]; *Pleasant* and *Satisfaction* [0.650]) and weaker correlation are shown in values less than 0.5 (such as *Pleasant* and *Brightness* [0.213]). This could explain why Case B ranks very high in most of the daylight attributes since most attributes (*Pleasant*, *Brightness*, *Comfort*,

and *Contrasting*) are strongly correlated to each other. Thus, high ranks in one attribute are usually associated with high ranks in the others. However, negative correlation indicates that the attributes affect each other inversely, such as in Case B where the increase in the *Distribution* attribute

rating means a decrease in the *Contrasting* attribute ratings. However, since the provided negative correlation is close to zero (-0.005) it should be statistically ignored (i.e., very weak correlation indicated).

4.3 Friedman test

The test was used to compare the three attributes (i.e., *Pleasant*, *Contrasting* and *Brightness*) that were statistically analyzed as significant in the study between the three different cases (A, B, and C). Figure 12 illustrates the variance rank in which each attribute differs in the contribution rate accordingly and highlights its weight in assessing the daylight performance of the presented case. The weight sequence of each indicated attribute in all cases is expressed as *Pleasant* less than *Contrasting* less than *Brightness*. The results show that the *Pleasant* attribute is the least important for having the lowest weight percentage than the other assessing attributes. Case A shows high explained variance percentages in the different daylight assessing attributes that covered (i.e., *Pleasant*, *Contrasting*, and *Brightness*). In Case A, attributes show the lowest mean ranks within participants. The Friedman test reveals that participants prefer Case B over the other Cases in IVR. The highest mean ranks tell that

the *Brightness* of Case B (2.39) is the highest of all. Also, the *Pleasant* of Case B (2.17) is highlighted as the highest of other Cases. But *Contrasting* mean ranks of Case B (2.28) and Case C (2.29) are highly similar and considered higher than Case A (1.42).

5 Discussion

Both quantitative and qualitative daylight analyses are performed to ensure the applicability and efficiency of the skylight daylight enhancement plan. The adapted heritage space proposed to be used as an exhibition space is studied in terms of daylight. Different strategies are followed and applied to participate in reasonable choices and fine-tuning in favor of efficiency. The IVR experience was essential to compare the quantitative analysis to a real qualitative assessment like the real-life experience that has revealed triggered issues during the simulation analysis and emphasized the decision-making process. Highlighted findings are identified:

The significance value (P) of *Pleasant*, *Contrasting*, and *Brightness* attributes between the assessed cases is lower than 0.05 which shows the high significance of the attribute in the assessment study. While the attributes of low significance

Fig. 12 Friedman test for the most significant assessed attributes

(>0.05) included *Distribution*, *Visual Comfort*, and *Satisfaction*. The correlation between the daylight assessing variables in the IVR experiment indicated that some attributes are significantly related to others. An increase in rating value of *Pleasant* is associated with a significant increase (positive correlation) with *Satisfaction*, *Visual Comfort*, *Brightness*, and *Contrasting* rating values. Also, an insignificant negative correlation exists between *Distribution* and *Brightness* attributes. Unsuccessful daylight assessment in the IVR experiment would be related to solely utilizing attributes of daylight *Distribution*, *Visual Comfort*, and *Satisfaction* with the daylight environment. As the survey group of data did not reflect any significant weighted variance between these variables. Thus, those three attributes rated values may be neglected during the application of the daylight redesign of the space skylight. The most reliable attribute in the assessment of the IVR cases is the *Brightness* since the analysis indicated that it has the highest cumulative variance percentage in all the assessed Cases. The statistical analysis results reveal that both Case B and Case C show insignificance in values of compared attributes, which reflects the similarity between the two cases that created confusion between participants.

Generally, Case B is considered the most pleasant of all cases. But in particular, the survey results were categorized into two groups where a single group recommended Case A to be used as an adapted museum as it provides a clearer view for the wall hangings, while the other group recommended Case B and Case C as they were more interested with the *Brightness* and the dynamic feeling of the space associated with the daylight patterns created by the mullions. That is why it is recommended to apply the design of Case B only if valuable wall hangings are not to be presented on the staircase walls. If adapting the palace space into museums and walls will be associated with paintings, it would be recommended to rely on design A for application. In the study, reliability of the survey rated values of some attributes more than the aid of the others in the decision-making and allowed relying on the three most significant which are *Pleasant*, *Contrasting*, and *Brightness* attributes. Through the adopted methodology, in computing the grey scaled and rendered model component, formulating the assessment component, and analyzing the users' behavior using the statistical analysis component; the most significant assessing attributes allowed a reliable comparison between the three studied cases in terms of daylight. It is worth mentioning that Case B has been preferred by users in IVR, even when the simulation results revealed the highest daylight discomfort levels indicated by ASE 45.4%, yet still users preferred this design option for various reasons that included the high daylight coverage, and the appealing experience of daylight resulted from the widest skylight to floor area.

6 Conclusion

This research considered the study of three distinct skylight design alternatives which were developed for the main space hall of the heritage case in order to evaluate potential space users' opinions in IVR. The research studies the effectiveness of the IVR in reflecting potential users' experience of a daylight space. Also, it investigated the daylight and emotional attributes which are most reliable to identify IVR user preferences for designed skylights in heritage spaces. The skylight design alternatives are meant to satisfy potential users' needs and participate in enhancing their emotional experience. The reliability of the daylight simulation results is coupled with potential user-oriented experience in IVR which can verify simulation results and further simulate potential experience before construction. The IVR survey allows the assessment of the users' daylight and emotional attributes through a rating criterion. The survey results are further statistically verified for significance, correlation, and weight to evaluate their effectiveness for the analysis of the three introduced design alternatives. Six assessment attributes were considered in the analysis, namely, *Pleasant*, *Contrasting*, *Brightness*, *Uniform Distribution*, *Visual Comfort*, and *Satisfaction*. The most statistically effective in assessing daylight in IVR are considered *Pleasant*, *Contrasting*, and *Brightness* attributes. Thus, the identification of significant attributes would provide cost-effective reliable information concerned with the performance of daylight in IVR. The study revealed the most reliable assessment attributes in the IVR and aided in selecting the optimum skylight design case. The results indicate the effectiveness of the user oriented IVR approach in selecting the most preferable daylight design skylight. But the limitations of the VR headset in adjusting accurate brightness levels have been ignored. This study can be extended in the future to model the degree of reliability between the physical space and the VR space where it may be encountered for calibration, practicing with different VR headsets and VR simulation engines. Also, the wider variety of IVR users including age, and background can be further studied in future research.

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