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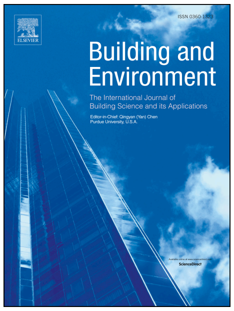

Assessing visitors' thermal comfort in historic museum buildings: Results from a Post-Occupancy Evaluation on a case study

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ASSESSING VISITORS' THERMAL COMFORT IN HISTORIC MUSEUM BUILDINGS: RESULTS FROM A POST-OCCUPANCY EVALUATION ON A CASE STUDY

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Abstract: Adaptive reuse of historic buildings as museums is an effective strategy for retaining heritage architectures while achieving environmental sustainability objectives. Building adaptation, retrofitting and preserving optimal environments for artwork and exhibit preservation are inherently complex, multifaceted tasks. However, indoor microclimates do not only affect collections; occupants and visitors must also be considered. The aim of this research is to explore whether artwork preservation constraints in reused historic building affect patrons. The authors thereby promote a more comprehensive approach, combining the objectives of exhibit conservation, preservation of heritage buildings and adequate indoor conditions, particularly thermal comfort. Data was gathered using the Post-Occupancy Evaluation process applied to a case study where a combination of microclimate monitoring and questionnaire surveys was carried out over a 12-month period. Results demonstrate that: i) the existing microclimate did not always provide visitors with adequate thermal conditions, showing dissatisfaction during the cooling season (July-September), with average TSV values ranging from -1.03 to -1.13; ii) TSV and PMV values were significantly divergent throughout the year, with TSV mainly included within the (-1, 0, +1) band and PMV mainly within the (0, -2) band; and iii) questionnaires show that visitor choice of clothing is made according to outdoor conditions, with some gender-related variations in the clo level (higher for women), not ensuring thermal comfort inside the museum during the warm season. Results of this research highlight the limitations of Fanger's model when applied to such typology of buildings, emphasising the need for more research in this field.

Keywords: Post-Occupancy Evaluation, Thermal Comfort, Indoor Environmental Quality, Historic Buildings, Museum Buildings.

1. Introduction and background

The International Council of Museums (ICOM) defines a museum as a, "non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment" [1]. Buildings not specifically designed for this purpose host a significant portion of current culture-related activities, thereby serving as de facto museums. This use poses additional challenges not only from the artworks' preservation perspective, but also from the viewpoint of architecture conservation, which is especially testing when heritage architecture is involved. Despite the added complexity, adaptive reuse is an effective strategy for the conservation of cultural heritage, as well as for the retention of redundant buildings, which can otherwise become obsolete and deteriorate due to insufficient funds for their upgrading and maintenance. As building adaptation could be an answer to functional obsolescence caused by societal, economic and environmental changes [2], the reconversion of such heritage into culture-related uses (e.g. museums, galleries, libraries, etc.) represents an important asset for starting positive regeneration processes and has been extensively investigated by scholars [3–6].

Although the retrofit of historic buildings has become a recurrent choice when dealing with adaptive reuse for museum uses, the embedded heritage value could represent an additional constraint in the process due to preservation requirements that can limit the range of intervention from an architectural and technological point of view. However, it is to be noted that traditional constructions could also contribute to reduce indoor microclimate variability, particularly when thick walls and porous hygroscopic materials are present, contributing to the indoor environment with a mitigation effect [7]. Additionally, authors working with historic architectures have recognised the positive role played by traditional materials and constructions in passively controlled museums' indoor environments [8,9]. The so-called 'environmental metabolism' of traditional buildings is not only related to the physical characteristics of building materials, but also to an architecture and layout, which promote the building's self-control (through elements such as under-roof cavities or other transitional spaces acting as buffers) and, therefore, a more constant response to external climatic solicitations [10].

The importance of a comprehensive assessment of indoor environmental conditions for the purpose of artworks' preservation has been overtaken by a focus on energy performance, particularly when adapting a historic building such as a museum. For instance, Lucchi developed a simplified method for assessing and comparing "Environmental and Energy Quality" (EEQ) of museum buildings in order to support decision-making processes through preliminary evaluations of the identification of potential risks for future interventions [11]. The method defined "qualitative performance indicators" that have an impact on EEQ, which were tested on 50 case studies across eight European countries, evaluating both new and retrofitted buildings. The research shows that, in general, the focus is more on a building's environmental performance than on the energy performance and reliance on active systems, which emphasises the interest towards the building and conservation of collections. With the aim of avoiding damage over time to collections and vulnerable objects exhibited in museum buildings, Corgnati, Fabi and Filippi pointed out the importance of microclimate conditions and their medium/long-term monitoring, suggesting a “Performance Index” to examine different parameters at the same time [12]. The relevance of indoor microclimate conditions and the importance of environmental monitoring in museum spaces has also been underscored by a number of guidelines [13–17] and by a variety of case studies [8,18–20], demonstrating the complexity of the subject. On the other hand, D’Agostino *et al.* argued that, since the monitoring of indoor environmental conditions and related controlling systems is not common in museum buildings, it is preferable to focus on a preventive strategy accounting for all the Indoor Environmental Quality (IEQ) factors and “aimed to the microclimatic assessment of museum environment, the quantification of factors responsible for the degradation processes and the choice of most appropriate interventions to improve the state of conservation” [21].

The literature cited above highlights the importance of microclimate conditions for museum facilities and the collections exhibited and conserved inside them. Monitoring environmental conditions therefore becomes essential for defining preservation or retrofit strategies, as well as activities for preventive conservation. In the first instance, when performing such monitoring in historic environments on either a short-term basis (few months) or as a part of a long-term, continuous campaign, particular care must be given to the installation of sensors, for the avoidance of damage to historic surfaces and to guarantee reliability of measurements over the entire period [22]. Positioning of measuring equipment can also potentially affect data collection, as the choice regarding the location of sensors can be complex when working with museums placed in historic buildings. For instance, installation could be limited by the exhibition or room layout, the presence of decorated, unstable or damaged surfaces, the presence of factors interfering with the monitoring (such as windows) and the position of power and sockets [23].

The existing literature shows a plethora of research focused on microclimate and environmental monitoring in historic buildings and, particularly, in museum facilities, demonstrating the significant role of field investigations. In many cases, environmental monitoring has been performed with the ultimate goals of risk assessment and/or preventive conservation [24,25], as a base for short or long-term control over significant variations of the different environmental factors involved [12,26,27], for understanding causes of deterioration and defining remediation strategies [28], or for assessing and optimising the building's thermal and energy performance and dimensioning HVAC systems accordingly [29,30]. The focus has only shifted to the visitors after the preservation of the buildings themselves and the collections they house was thoroughly addressed. Human presence and interaction has only been marginally considered and visitors' satisfaction in historic museum facilities is a field of research not yet fully investigated. The challenge of building preservation, safeguarding museum objects and, at the same time, accounting for human comfort has often led to the heavy integration of HVAC systems, with an important impact on architecture. In this regard, this paper attempts to promote a shift from the building and collection perspective to the users' perspective. This approach aligns well with the idea of a "dynamic museum" [31] where the visitor is central to the process and the recipient of the experiential activity. This view does not suggest that the building and its collections are less important than users and visitors, but that a balance between the two should be sought while defining effective strategies for conservation, retrofit and adaptation of historic museum buildings. A similar goal was pursued by Pisello *et al.* who performed a microclimate analysis that dealt with artwork preservation and occupants' comfort as contextual objectives [32]. Jeong and Lee investigated effects of the physical environment of museums on visitors' satisfaction [33]. They distributed questionnaires and observed people's behaviours in 30 museums located in Seoul and its vicinities, collecting general information on visitors, actual circulation path through the exhibition and individual perception of the museum environments, including thermal comfort.

Although the recognised importance of thermal comfort assessment in historic buildings is increasing [34], museum buildings are still not amongst the most investigated uses [35] and literature on this regard is limited. This current gap is mainly related to the many challenges connected to the contextual presence of heritage values and pieces of art, whose importance tends to overcome the need to provide visitors with a comfortable environment. However, some researchers have tried to combine visitors' thermal comfort evaluation with indoor microclimate monitoring in museums, mainly in the attempt to reach a balance with conservation needs and energy reduction by means of climate optimisation. This is the case of the investigation conducted by Silva *et al.* [36], who, by highlighting the limited applicability of ISO 7730 [16] and ASHRAE 55 [37] for museum environments, defined a reduced thermal sensation scale according to typical clothing ensembles documented by observing the visitors. In fact, people visiting the museum were dressed according to the outdoor climate and not for the indoor environment and, additionally, the length of their visit indoors was limited. These considerations were used to assess Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) for visitors and this information was then used both to assess the current thermal comfort in the national museum building in Portugal and to optimise the indoor operative temperature and relative humidity [36]. The conflict between people's comfort and the preservation of works of art was also considered by La Gennusa *et al.* [38]. In this study, a comparison between indoor requirements relating to people's thermal comfort and those for preserving artefacts was performed, introducing a new "simultaneousness index" (I_S), defined as "the ratio between the (possible) common area for people's comfort and preserving works of art, and the whole area representing the conditions of comfort" [38]. With the main aim of reducing the overall energy consumption of a museum building in the Netherlands, Kramer *et al.* [39] introduced visitors' thermal comfort as a parameter affecting the definition of the optimum set-point strategy. They did this by implementing an adaptive model derived from ASHRAE 55, remarking on the lack of guidelines on thermal comfort specifically defined for museums and taking into consideration people’s adaptability and expectations. Additionally, three relevant thermal comfort studies in buildings were conducted by Mishra *et al.* [40,41] and by Kotopouleas and Nikolopoulou [42], where authors also examined transitional thermal responses of visitors and travellers.

The aforementioned studies agree on the lack of research related to thermal comfort evaluation in historic museum buildings and the consequential need to adapt existing standards and guidelines for such conditions, rather than specifically addressing this issue. This research attempts to contribute to this field by implementing a Post-Occupancy Evaluation (POE) process that will enable the collection of qualitative and quantitative data on heritage museum buildings. Although a shared definition of POE does not exist (as it is actually a very flexible methodology), it is intended as “the process of ascertaining the quality and standards of design and construction” [43], or “the process of evaluating any type of buildings in a systematic and rigorous approach after they have been built and occupied” [44]. POE is a very useful method for collecting data on redundant buildings in order to inform their improvement and enhancement. In the case of historic museum facilities, POE is often implemented to assess thermal comfort or, more widely, the overall IEQ, mainly through quantitative monitoring [32,45] and, only in very few studies, with the support of qualitative investigations such as questionnaires [34,46].

2. Goals of the research and methodology

This research paper aims at verifying the relationship between human thermal comfort and indoor microclimate in historic buildings adaptively reused as museums, thus contributing to the current disciplinary conversation regarding the achievement of a balance between preservation issues and visitors’ satisfaction by promoting a shift from a conservation-centric approach to an integrated approach which includes the people’s perspective as well.

A case study building was used for this study, which is the Museu de la Història de València (Valencia History Museum) in Spain. The research rationale was grounded within the investigation on issues related to the thermal environment inside the historic building, as some visitors claimed thermal discomfort during both summer and winter seasons.

The research implemented a POE methodology, combining quantitative (measurement of indoor microclimate parameters) and qualitative (questionnaires to visitors) investigations to assess and verify visitors' satisfaction with the thermal environment. Field measurements and thermal comfort questionnaires were carried out throughout a full year to capture figures during both heating and cooling seasons. The indoor thermal satisfaction questionnaires were thus handed to the visitors while the indoor and environmental monitoring campaign was simultaneously ongoing. Collected data were analysed in order to:

- assess the visitors' Thermal Sensation Vote (TSV);
- compare the visitors' TSV with the visitors' Predicted Mean Vote (PMV) by using Fanger's model;
- assess the visitors' clothing insulation pattern in relation to indoor and outdoor temperatures.

3. Case study description

This research was carried out in a museum building in Valencia (39'28 N – 0'22 W), a city on the Mediterranean coast of Spain. According to the Köppen-Geiger classification system [47], Valencia has a hot Mediterranean/dry-summer sub-tropical climate (Csa-Mediterranean Climate). The evaluated building is approximately 8 km away from the Mediterranean Coast and 30 m above the sea level. Monthly temperatures range from a mean of 22ºC during the hottest month and a mean of 10ºC during the coldest months. The annual mean temperature is 18.4ºC with low levels of precipitation, mostly occurring in fall.

The building was built in 1850 as a main potable water reservoir for the city of Valencia (9,000 m^3 of water could be contained inside the construction) and was used as such for over a century (Figure 1). In 1998, the local government began a process of restoration and adaptation of the building in order to transform it into what today is the Valencia History Museum. The museum is not listed but it is considered as a 'building of cultural interest'.

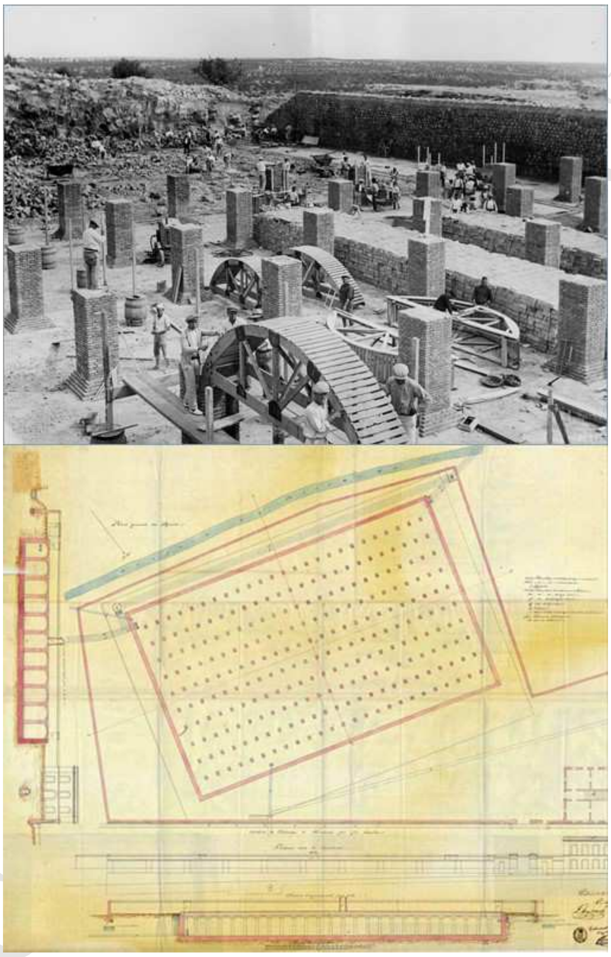

Figure 1. Construction site photo (above) and original building plan (below). Source: Ministry of Development of Spain

The construction has a flat roof supported by a brick structure composed of 11 barrel vaults and a grid of 200 masonry columns. The building is developed on one floor only with no openings in the side walls or in the roof, except for five auxiliary metallic doors and the main entrance. The lack of fenestrations is derived by the original use of the building as a cistern and has been preserved in the adaptive reuse project as a distinctive quality of the historic construction. The building envelope is composed of 95 cm thick uninsulated masonry external walls, an 18 cm thick air cavity and an 18 cm thick external layer of brick veneer. The main façade of the museum has a ceramic tile finishing underneath a waterfall, which falls from the roof to the side of the building (Figure 2). The flat roof is composed of a 20 cm waterproof reinforced concrete slab.

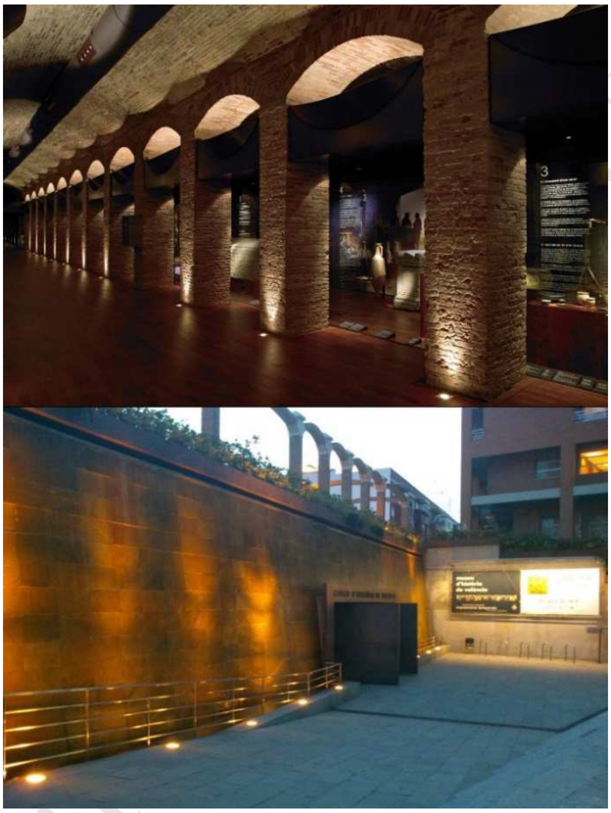

Figure 2. Internal (above) and external (below) building appearance. Source: Valencia History Museum

From the thermal perspective, the most important characteristic of this building is its underground development for over 50% of the volume. Moreover, on top of the flat roof there is a public green area with a small garden, a fountain and two basketball courts. Table 1 summarises the thicknesses and thermal transmittance of the building envelope. Because the building is partially underground and without any fenestrations, natural ventilation does not exist and the building is therefore ventilated continuously (24 hours a day, seven days a week) by means of a mechanical system of ceiling ducting (Figure 3).

Most of the building's central area (main cistern's volume) is used for the exhibition, although the perimeter area is used for small rooms such as storages, toilets and other service rooms. Connected internally to the west side of the main museum building is a newly added office where the administrative personnel work. Museum opening hours are from 9:30am to 7:00pm, Tuesday through Saturday, and 9:30am to 3:00pm on Sundays.

Table 1. Thickness and thermal transmittance of the building envelope and openings

Building Component	Thickness [m]	U-value [W/m^{2}K]
External walls*	1.240	0.623
Flat roof	1.100	0.150
Ground slab	0.850	0.263
Side doors	0.160	3.124
Main door	0.020	5.207

*Weighted average value between the wall above the ground and the wall below the ground.

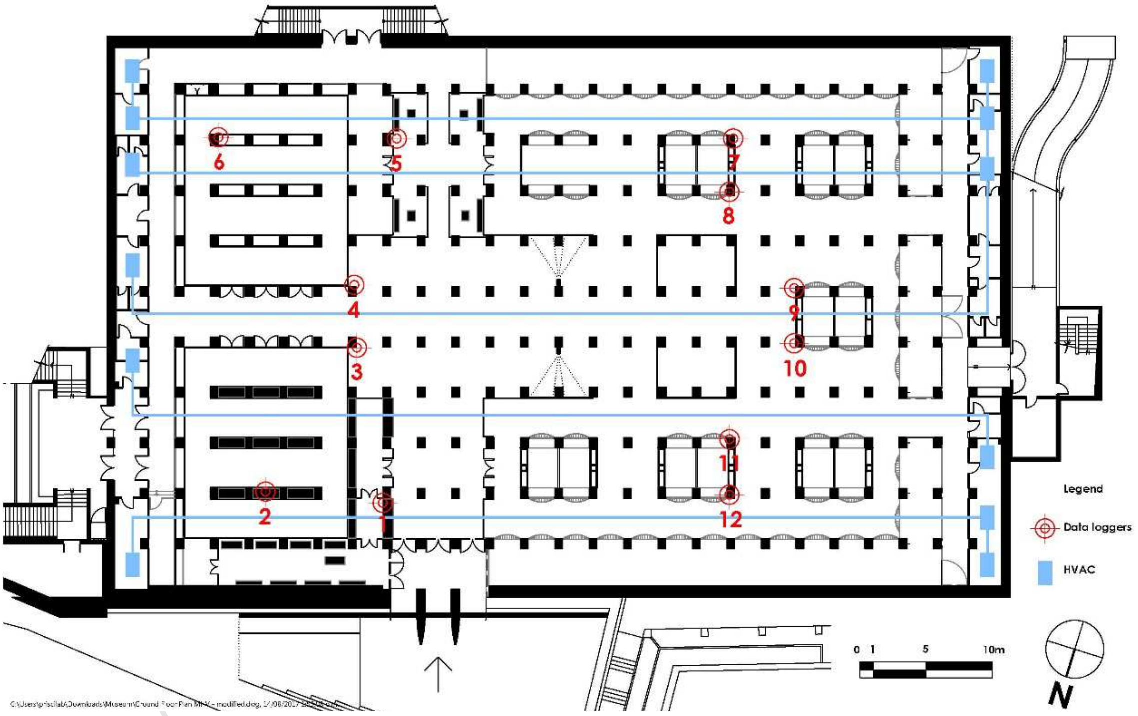

Figure 3. Museum plan with data loggers' locations (red spots) and HVAC units and ducting placement and distribution (blue boxes and lines)

4. Environmental monitoring

To assess thermal aspects of the building's Indoor Environmental Quality (IEQ), a meticulous monitoring campaign was carried out by measuring indoor air temperature and relative humidity, as well as external environmental parameters (Table 2). More detailed probabilistic results are shown later in Figure 7 which gives a comprehensive overview of the indoor environmental conditions.

Table 2. Indoor and outdoor average conditions during the survey period for the days analysed

Month	Indoor Conditions		Outdoor Conditions		
	Air Temperature [°C]	Relative Humidity [%]	Air Temperature [°C]	Relative Humidity [%]	Solar Radiation [W/m^2]
August 2015	22.44	64.23	26.00	63.00	253
September 2015	22.15	64.28	22.00	62.00	197
October 2015	21.97	63.75	19.00	65.00	133
November 2015	21.74	55.65	15.00	61.00	121
December 2015	21.28	51.81	13.00	69.00	82
January 2016	21.34	46.74	13.00	56.00	85
February 2016	21.48	43.51	13.00	48.00	131
March 2016	21.77	41.89	14.00	49.00	198
April 2016	22.12	49.39	16.00	56.00	250
May 2016	21.81	56.85	18.00	58.00	280
June 2016	22.21	63.74	22.00	59.00	316
July 2016	22.21	67.53	25.00	60.00	296

The monitoring period was a full calendar year, from August 2015 to July 2016, and data were collected hourly. Internal monitoring was carried out with the use of a network of data loggers evenly distributed throughout the building (Figure 3). Each device was installed at a height of 1.10 m from the ground and at least 1 m away from any external walls, thereby meeting the requirements of ASHRAE 55 [37] for standing occupants (Figure 4). Regarding the external environment, data were collected from a meteorological station located 3 km away from the building. Specifications of the instruments for data gathering are presented in Table 3.

Figure 4. Data loggers placed inside the building (as per the red spots in Figure 3)

Table 3. Characteristics of monitoring devices

Measured Physical Variable	Brand & Model	Measuring Range	Precision	Response
Indoor Air Temperature	Siemens-Symaro	-30ºC to 50ºC	±0.2 ºC	60 s
Indoor Relative Humidity	Siemens-Symaro	0% to 100% RH	±5%RH	60 s
Indoor Air Speed	Testo – 435-2 Hot Wire Probe	0m/s to 20m/s	0.03m/s	0.5 s
Outdoor Air Temperature	Vantage Pro2	-40ºC to 65ºC	-	2.5 s
Outdoor Relative Humidity	Vantage Pro2	1% to 100% RH	±2%RH	2.5 s
Outdoor Wind Speed & Direction	Vantage Pro2	1 to 320Km/h	±1Km/h	2.5 s
Solar Radiation	Vantage Pro2	0 to 1800W/m^2	±5%	50 s
Rain	Vantage Pro2	-	±0.2mm	-

Temperature and Relative Humidity values (minimum, average and maximum) in Valencia during the study are represented in Figure 5. Additionally, Figure 5 shows the indoor and outdoor temperatures and solar radiation during the same period of time.

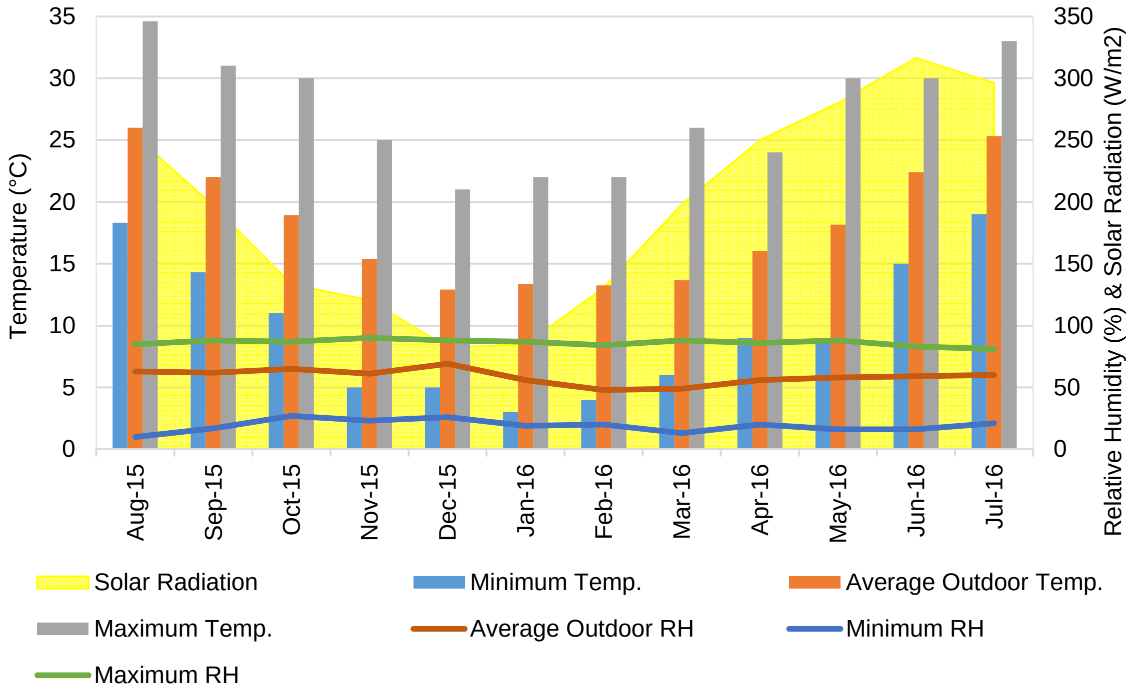

Figure 5. Solar radiation, outdoor temperature (T) and relative humidity (RH) values (minimum, average and maximum) in Valencia during the study

5. Thermal comfort survey

To evaluate the subjective opinions on the occupants' thermal comfort, questionnaire surveys were designed following the parameters of ASHRAE 55 [37] and Fanger's Model [48]. Questionnaires were handed out to the visitors by the museum staff who also provided a brief description of the study in order to clarify the purpose of the questionnaire and to obtain more reliable answers.

5.1. Questionnaire

The questionnaire was designed with the goal of extracting honest and reliable responses with the following considerations in mind: brevity and simplicity. Indeed, it was unlikely that visitors would have filled out the questionnaires if they were too long to complete or too difficult to understand, and responses would not have reflected the real experience. Additionally, the survey was translated into four languages: Spanish, Valencian, English and Italian, as these are the main languages spoken by the visitors of the museum. Questionnaires were offered to adults only (aged 18+ years), in order to avoid problems related to the understanding of thermal comfort conditions, which can be an issue for young people and children [34]. Visitors were given the questionnaire at the entrance and had to return it at the end of their visit, in order to capture their full experience inside the museum.

The filled questionnaires received were 440 out of 18,483 visitors within the study period. However, before the study started, a trial period was set up during which 105 questionnaires were filled by the museum staff over a two-month span (June and July 2015). This testing period was very useful for setting up the protocol and for fine-tuning the questionnaire before distributing it to the visitors, thus minimising any potential misunderstandings of the questions and ensuring trustworthy and sincere answers. Questions aimed at obtaining as much information as possible about the subjective thermal comfort opinion of each visitor during their visit indoors, in addition to collecting the necessary data to calculate the Predicted Mean Vote (PMV) according to Fanger's method. The questionnaire included questions about:

- date and time of arrival to the museum and time of the answer to the questionnaire;
- age (bands arranges as 18-30, 31-40, 41-50, 51-60 or +61), origin (from Spain or from other country) and gender of the visitor (male or female);
- indoor and outdoor Thermal Sensation Vote (TSV), according to ASHRAE 55's seven-point sensation scale (-3, -2, -1, 0, +1, +2, +3);
- clothing insulation, with the most typical fourteen articles of clothing (based on ASHRAE 55) included as choices in the answer options, to help fill the questionnaire;
- visitors' domestic experience with HVAC units (whether he/she owned an HVAC unit at home and whether he/she typically had used it before the visit);
- visitors' Metabolic Rate based on transportation method (walking, running, biking or motorized transportation), and indoor air quality (very good, good, neutral, bad, very bad) and humidity (very dry, dry, neutral, humid, very humid) through a series of simplified questions;
- visitor´s preference for the indoor temperature (much cooler, cooler, slightly cooler, neither warmer nor cooler, slightly warmer or warmer much warmer);
- visitors' opinion about any other aspect regarding their thermal comfort that they might wanted to highlight.

5.2. Clothing Insulation and Metabolic Rate

Clothing insulation (clo) and metabolic rate (met) are the two human factors in Fanger's method; the other measurements collected during the monitoring campaign were considered to be environmental aspects. A set of garments that are typically worn in a mild climate was used to create the different options comprising in the survey taker's outfit (Table 4), according to ASHRAE 55. In an effort to streamline the survey answers, the available garment selections were simplified and stripped down to the basics. Afterwards, clothing insulation was calculated for each filled survey on the clo values given by ASHRAE 55.

Table 4. Garment Insulation Options I_{clu} [clo] included in the questionnaire, according to ASHRAE 55

Garment item	I_{clu} [clo]
Underwear	
Panties	0.03
T-shirt	0.08
Sweaters	
Long-sleeve (thin)	0.25
Long-sleeve (thick)	0.36
Blazer	0.44
Shirts and Blouses	
Sleeveless/scoop-neck blouse	0.12
Short-sleeve dress shirt	0.19
Long-sleeve dress shirt	0.25
Long-sleeve sweatshirt	0.34
Trousers	
Short shorts	0.06
Straight trousers	0.24
Skirt	0.23
Footwear	
Shoes 0.02	0.02
Boots	0.10

Since the average visitor spend 1-2 hours per visitation, the authors followed ASHRAE 55's directions (Table 5) and did not take into account the method of transportation to the museum. Instead, a 2.0 met rate (walking slowly throughout the museum) was applied for the purpose of PMV calculations.

Table 5. Comparison between the standard activities (and metabolic rates) based on ASHRAE 55 and the methods of transportation monitored in the case study during the survey

Activity (surveyed methods of transportation)	Activity (according to ASHRAE 55)	Metabolic Rate (according to ASHRAE 55)	
		[W/m^2]	[met]
Walking	Walking (0.9 m/s, 3.2 Km/h, 2.0 mph)	115	2.0
Running	Calisthenics/Exercise	175 - 235	3.0 - 4.0
Biking	Calisthenics/Exercise	175 - 235	3.0 - 4.0
Motorised Transport	Driving Public transportation	60 - 115	1.0 - 2.0

6. Results of the research

This section presents the findings of the quantitative full-year monitoring campaign and the results of the qualitative data gathered through questionnaires, which were used to evaluate visitors' opinions on indoor environmental conditions. The recorded data were used to calculate and evaluate Fanger's thermal comfort values based on ASHRAE 55 [49] by using MATLAB, and following ISO 7730, Annex D [50]. In this research, indoor environmental conditions such as air temperature, air speed and relative humidity data were measured [51]. Due to the building's very high thermal mass, radiant temperature was estimated based on the approximation that air temperature is close enough to radiant temperature ($T_{air} = T_{radiant}$). Human factors identified in Fanger's method, such as metabolic rate and mechanical power, were also estimated based on the answers to the questionnaires (according to ASHRAE 55 [49]). Finally, clothing insulation was calculated for each answer based on visitors' replies, according to ISO 7730 [50].

Figure 6 summarises indoor and outdoor temperature and relative humidity values monitored during the study, showing a mainly stable average indoor temperature, possible thanks to the building's high thermal mass, hypogeum space and absence of windows. Figure 7 illustrates a histogram of operative temperatures recorded in the museum, over the complete survey campaign. It shows that indoor temperatures vary within a very narrow range of ~3 ºC. Figure 7 also illustrates the cumulative probability distribution curve of the indoor operative temperatures. This curve shows a more detailed distribution of temperatures and was obtained using the cumulative values (temperatures in ºC) that are equal to or lower than the operative temperature value at each particular plots on the curve.

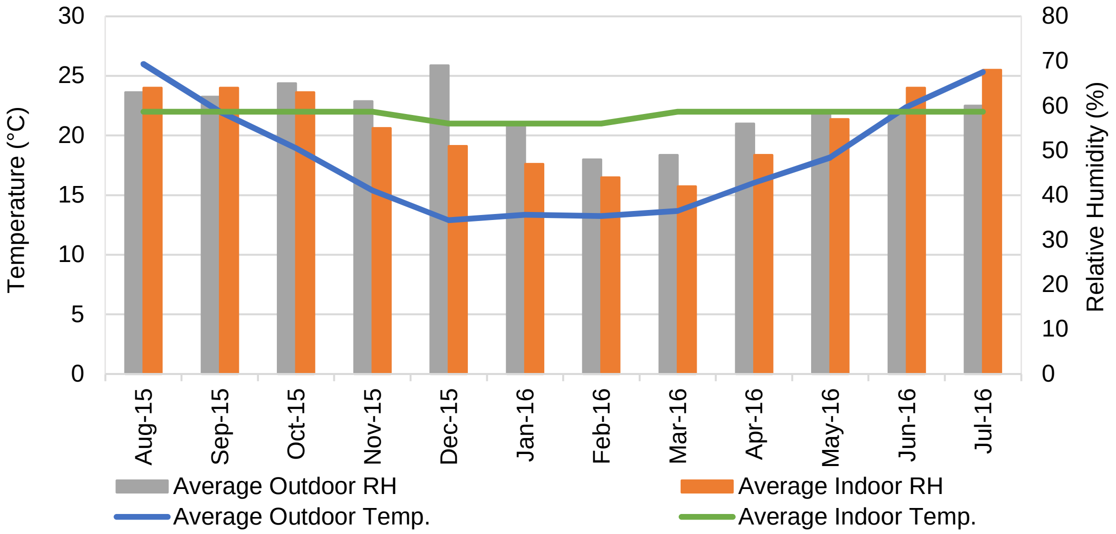

Figure 6. Indoor and outdoor relative humidity and air temperature average values during the study in Valencia

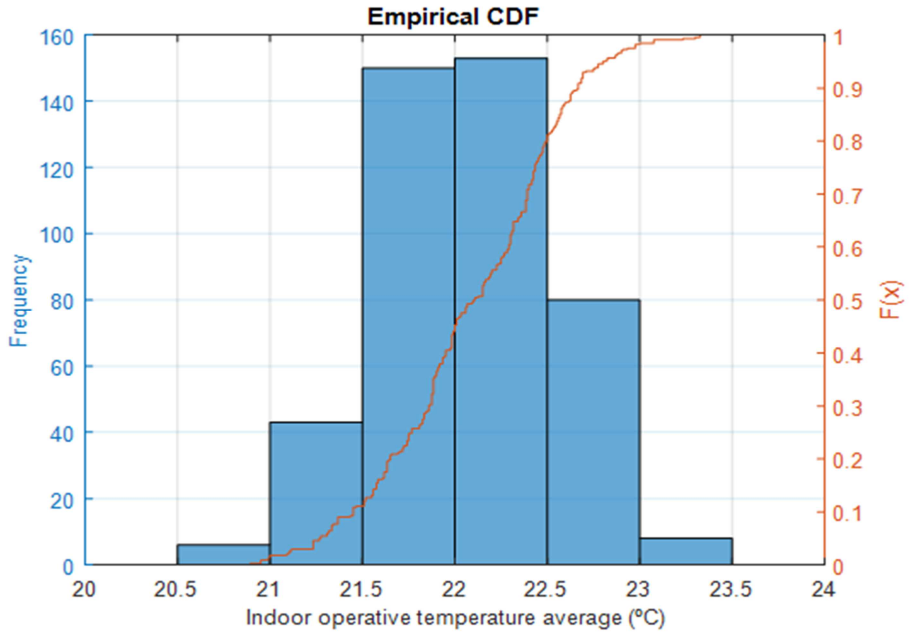

Figure 7. Histogram and cumulative probability distribution curve of the indoor operative temperatures recorded in the museum.

6.1. Thermal Sensation Vote (TSV) values assessment

Results show that there was a negative correlation between outdoor and indoor temperature, and thermal sensation. As Figure 8 shows, the warmer the outdoor temperatures, the colder the visitors felt inside the museum and *vice versa*. This means that visitors felt discomfort inside the museum due to the temperature gap during the summer and winter seasons. Although the same correlation existed between indoor temperature values and thermal sensation, it should be noted that the real indoor temperature values were practically always constant. This is due to the building being mechanically ventilated 24/7, as thermal consistency is necessary for artwork and artefact preservation. Hence, we can assume that the differences in the visitors' answers were affected only by outdoor temperatures and, therefore, by the difference between indoor and outdoor temperatures (thermal leap).

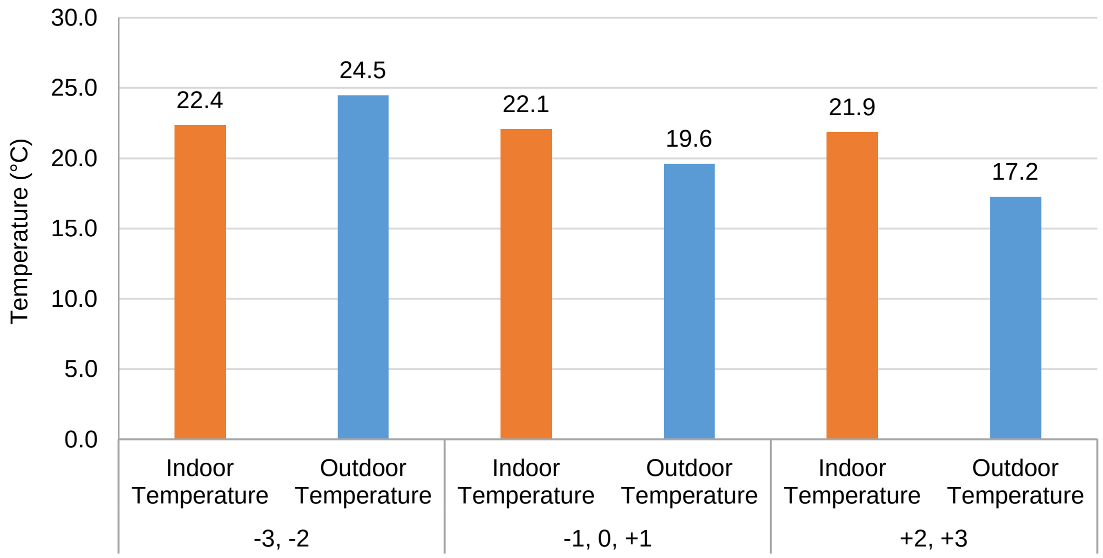

Figure 8. TSV ranges against average indoor and outdoor temperatures

To further support this consideration, there is a clear correlation between outdoor and indoor temperatures and the visitors' answers ranges (>1, 1 - -1, <-1). Figure 8 also proves the theory that the warmer the outdoor temperatures, the colder the visitors feel. The difference between the visitors who felt neutral and hot is very limited and it is therefore considered negligible. On the other hand, individuals who felt cold were more affected by outdoor temperatures than the other two groups, following the tendency previously presented.

Environmental temperatures and Thermal Sensation Votes (TSV) were evaluated by using Pearson product moment correlation [40]. If p is smaller than the significance level (default is 0.05), then the corresponding correlation in r is considered significant. As such, TSV had a significant correlation with the indoor temperature ($r= -0.34$, $p < 0.001$). This correlation, although statistically significant, is quite weak. The plots for TSV VS operative temperature for a whole period (1 year) are shown in Figure 9. It may be observed that the correlation, although significant, is still quite weak.

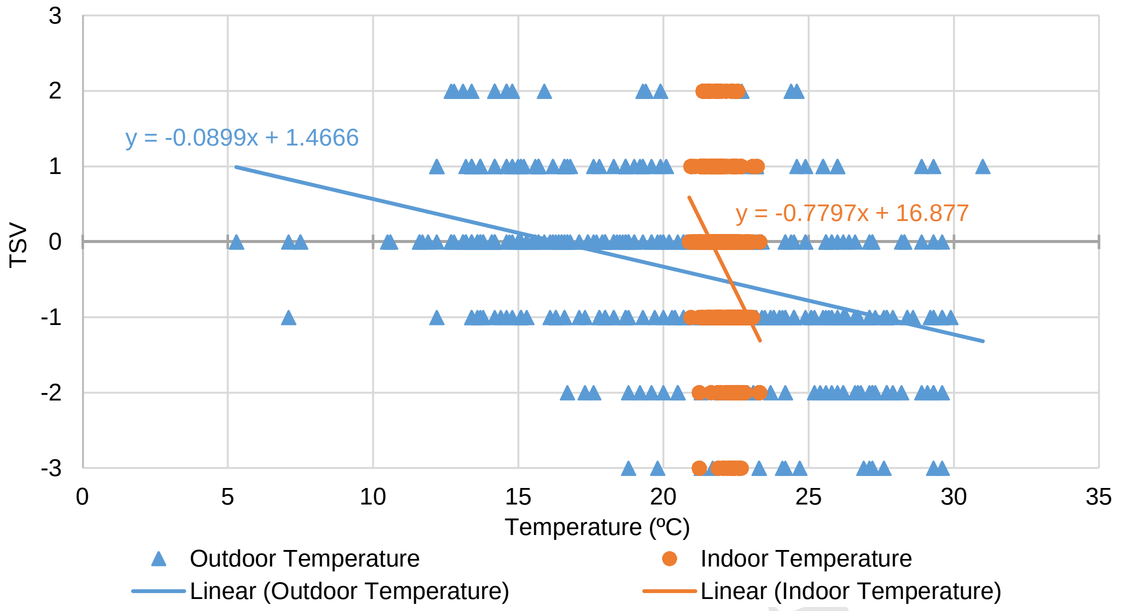

Figure 9. Correlation between Thermal Sensation Vote (TSV) VS outdoor and average indoor temperatures.

The influence of gender in indoor thermal comfort opinions can be seen seasonally in Figure 10. Generally, gender did not prove to be very influential on thermal comfort perceptions, but there was a seasonal caveat. During summer months, the answers within the middle range (-1, 0, +1) were different, with an 82% satisfaction for males and only a 68% satisfaction for females across the band. Additionally, during the same period, answers showed gender-based differences with 17% of males and 27% of females who reported feeling either cool or cold. Some gender variations were noticeable in winter and spring, although values remained in the central comfort band: a 15% gap was present in correspondence to the 'neutral' value in winter and in the 'slightly cool' in spring, with men feeling slightly warmer than women in winter and women feeling slightly cooler than men in spring. During the remaining periods, values by gender varied only slightly and thermal comfort ranges values were very similar. In addition to providing a gender perspective, Figure 10 supports the earlier finding of a negative correlation between warmer outdoor temperatures and visitors' cooler thermal sensations.

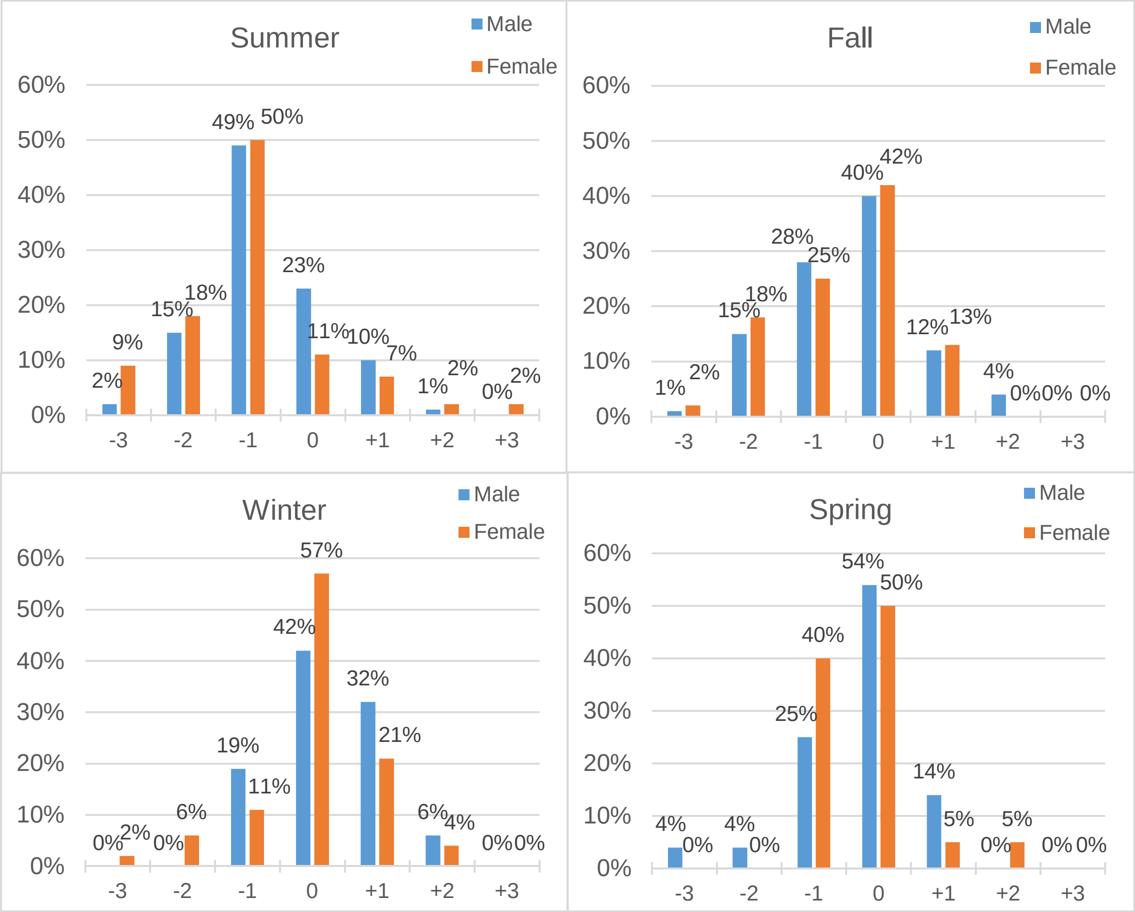

Figure 11 depicts the Thermal Sensation Votes of visitors. Data were summarised monthly, using the average and the standard deviation values. Even though the mean values showed that occupants felt comfortable almost the entire year (a part from July, August and September when average values move below the -1 band), the standard deviation demonstrated a wider amplitude of values during the cooling season (particularly June, August and September), with visitors feeling uncomfortable (cool or cold), while, during the heating season (December, January and February), visitors did report feeling comfortable.

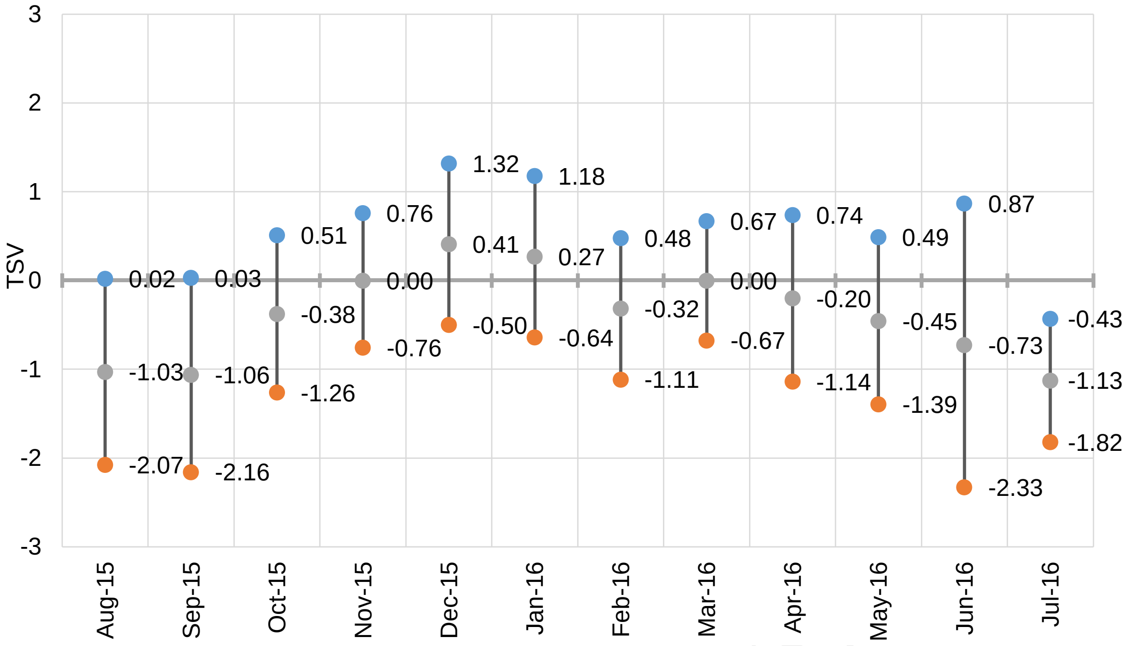

Figure 11. Average and standard deviation of overall TSV values by month

6.2. Comparison between Thermal Sensation Vote (TSV) values and Predicted Mean Vote (PMV) values

Figure 12 compares the calculated Predicted Mean Vote (PMV) average values and measured Thermal Sensation Vote (TSV) average values, by month. While TSV values were mainly concentrated in the neutral area (-1, 0, +1), PMV values were mainly lower than TSV values and shifted towards the cooler bands, except for the cooling session months (May-September) during which occupants reported to be colder. According to Fanger's model, visitors should feel uncomfortable due to the HVAC system performance; however, since the results in this investigation exhibited fairly stable TSV values in the comfort zone, Fanger's model does not prove to be reliable in this case.

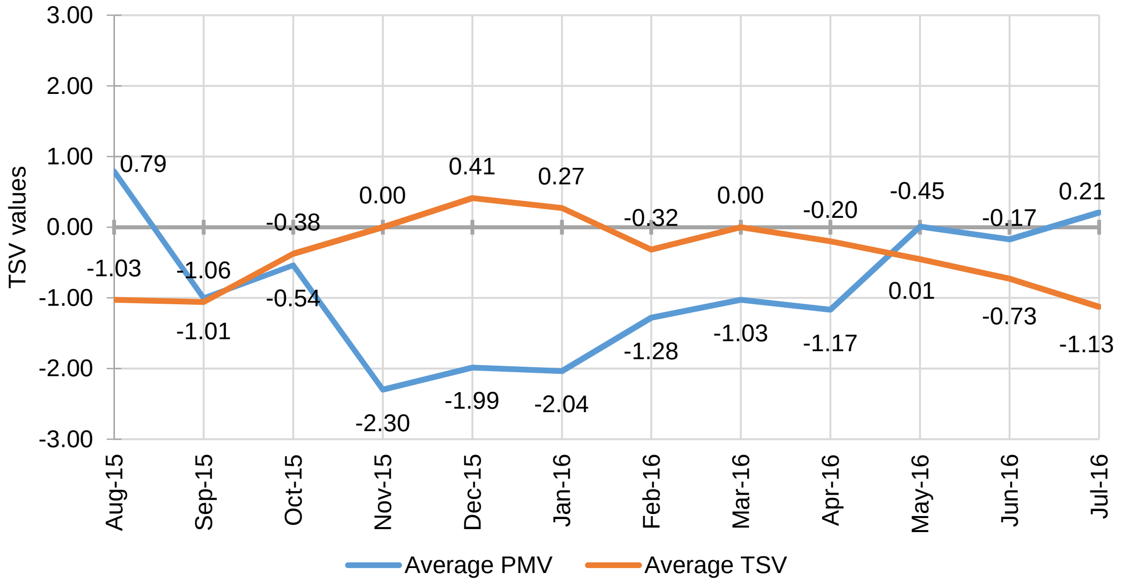

Figure 12. Comparison between PMV and TSV average values by month

As argued by other researchers [36], visitor metabolic rate is a critical factor when using Fanger's model for museum buildings. In order to take as many factors as possible into consideration, the transportation method employed by each visitor to arrive at the museum was considered according to the options as directed in the ASHRAE 55 [49] and listed in

Since the average visitor spend 1-2 hours per visitation, the authors followed ASHRAE 55's directions (Table 5) and did not take into account the method of transportation to the museum. Instead, a 2.0 met rate (walking slowly throughout the museum) was applied for the purpose of PMV calculations.

Table 5. Since the average visiting time was between 1 and 2 hours, a fixed value for metabolic rate has been assigned for all visitors to calculate PMV values (slowly walking 2.0 met). Therefore, PMV and TSV average values were calculated and measured, respectively. As depicted in Figure 13, while TSV values remained within the neutral range (-1, 0, +1) throughout the year, PMV values had diverse results. TSV values lingered between 0 and -1, independent of the transportation method, in accordance to Mishra *et al.*'s [40] results, while PMV values were quite different. In particular, visitors who used motorised transportation had average PMV

values of +2.1, whereas the PMV values for methods of transportation with higher metabolic rates were as follows: biking +1.0, walking +1.3 and running +1.2.

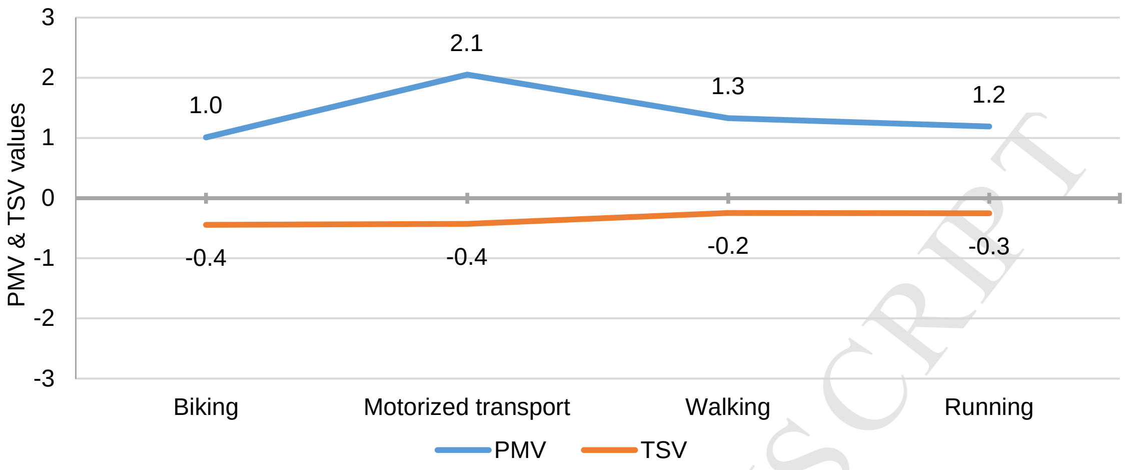

Figure 13. PMV and TSV average values comparison between transportation methods for visitors staying less than one hour.

6.3. Clothing insulation assessment

In public buildings, such as museums, occupants do not have any control over indoor temperature or natural ventilation, therefore adding or removing garments is the only adaptive choice that is available to them. The type and amount of clothing worn is thus a very important factor to consider while assessing subjective thermal comfort. Figure 14 shows the average clothing levels and standard deviations for each month of the monitoring campaign. It is very clear that during colder months, visitors' clothing level was much higher than during the warmer ones. Looking at the standard deviation, values were very stable, reaching a gap between the highest and lowest values around 0.30 clo or even 0.40 clo. There was a slight reduction in this standard deviation amplitude during the coldest months (January and February) which may have been due to the very uncertain weather conditions.

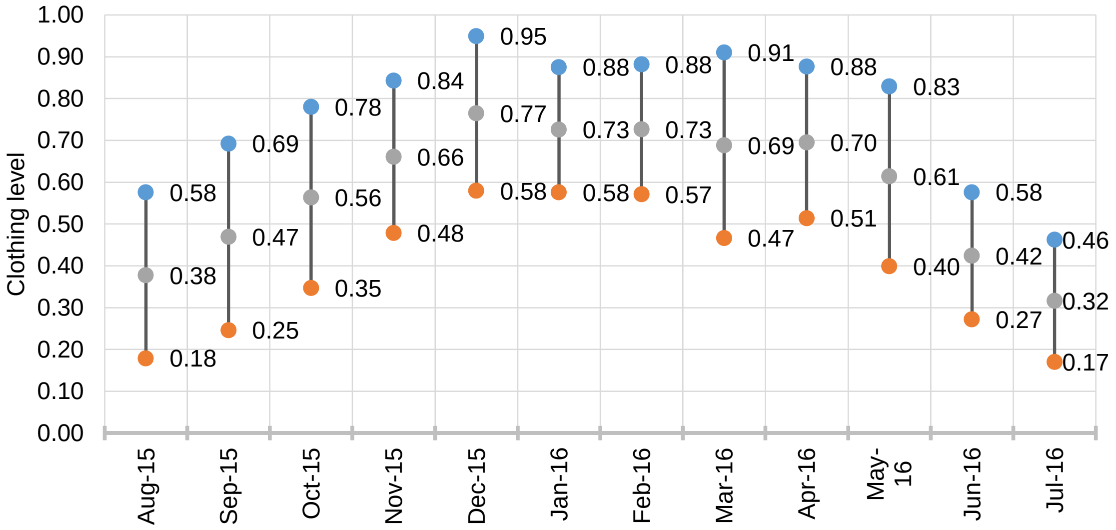

Figure 14. Average and standard deviation of clothing levels by month

Figure 15 displays the correlation between clothing levels and outdoor temperature by gender. Outdoor temperatures are obviously very unstable. Clothing levels, as expected, decreased when outdoor temperatures increased. Finally, male and female choices were slightly different when considering the same outdoor temperatures, with females choosing a slightly warmer clothing combination.

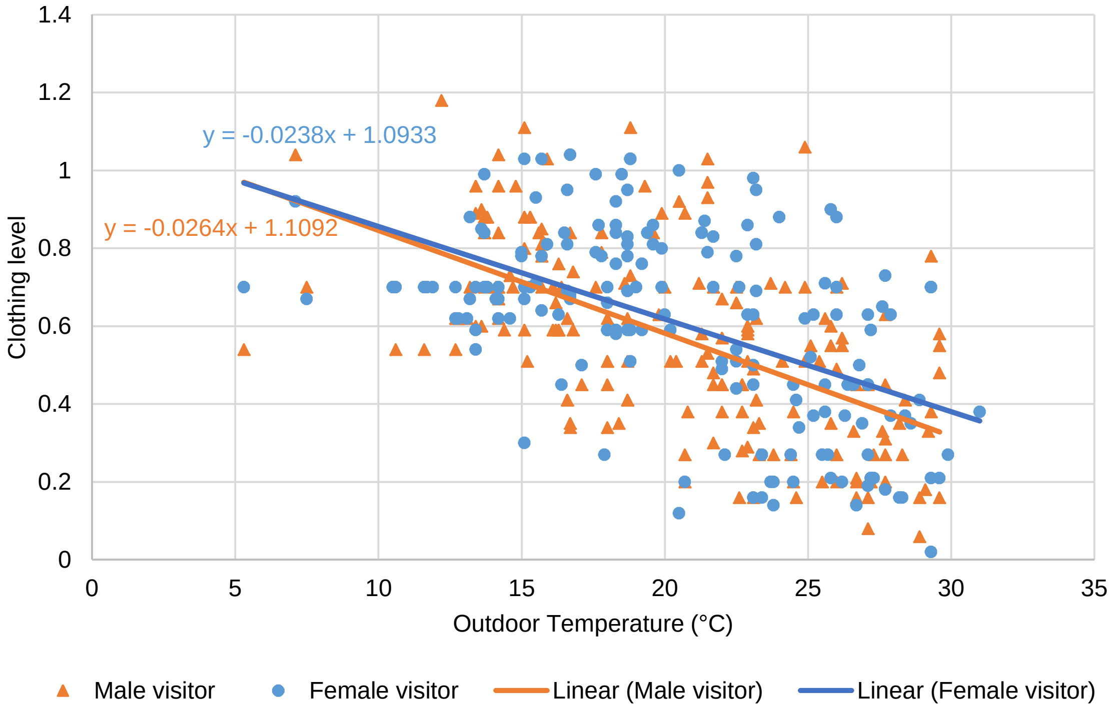

Figure 15. Correlation between clothing level and outdoor temperatures by gender for each survey answer.

7. Discussion

The case study investigated in this research offers an opportunity to understand occupants' satisfaction with a thermal environment in which their stay is limited to a short amount of time (1-2 hours), but yet affects their overall experience. Being mainly a hypogeum space with no windows, which is an important component of the building's heritage value that has been preserved and integrated in the adaptation project, the building offers a peculiar environment for art collection and for visitors at the same time. On one side, more stable conditions in terms of air temperature and relative humidity offer the most suitable microclimate conditions for the preservation of artefacts and the building itself; on the other, the few times that visitors reported discomfort, this discomfort was generated by the gap between indoor and outdoor temperatures. In order to guarantee indoor microclimate stability for conservation purposes while providing the airflow rates suitable for its use, the building is equipped with a mechanical system working on a 24/7 basis which generates more challenging situations for human thermal comfort, mainly due to the temperature gap between the inside and outside. Therefore, the negative thermal leap affects visitors' satisfaction with the thermal environment, while the positive gap does not, as participants did not express any discomfort during the winter season.

Some minor fluctuations in the indoor air temperatures were, however, registered during the field monitoring, mainly during the winter season (November-March), with a drop of 1.2ºC (Figure 6). This demonstrates the effectiveness of the building's thermal masses (roof and walls), along with the hypogeum development of the building, producing a positive effect in mitigating the heat transfer and in keeping the indoor temperatures more stable, despite the combined effect of: i) the heat transfer through the uninsulated extended flat roof surface; ii) the almost absence of winds cooling down the roof's surface; and iii) the unobstructed surrounding environment, with no shadows from adjacent buildings. If the thermal mass is an effective hygrothermal barrier during the warm and hot seasons, it appears to affect the indoor environment negatively in the cold season.

An interesting point worth-discussing is the divergence between TSV and PMV, as shown in Figure 14. The PMV values calculated according to Fanger's model suggest that visitors should have expressed satisfaction with the thermal environment between May and November only, with a limit condition in August shifted towards the warmer side of the central band (-1,0,+1), and feeling cool or cold for the rest of the monitored period. In reality, visitors expressed a different opinion, as the average calculated TSV sits within the central band for almost the entire year, with the exception of the summer season, as discussed before. This worth-mentioning difference points out the fact that the metabolic rate does not have a significant impact on the visitors' thermal comfort sensation in this building. The divergence between TSV and PMV is clear when analysing the method of transportation utilised by the visitors to arrive at the museum (even though PMV values were calculated with the same met rate of 2.0 met) (Figure 13). Once again, PMV show values out of the neutral band, while TSV values are within the neutral band. The most relevant result is related to the use of motorised transportation, where metabolism levels are very low and, according to PMV results, people should feel cool or cold in fall, winter and spring, and comfortable in summer, a result in contrast with TSV values. Overall, results demonstrate the limits of Fanger's model when used in museum environments and in mechanically controlled climates, as in the case study investigated in this research.

A possible direction for mitigating summer discomfort could be working with indoor temperatures in summer, currently ranging between 22.21ºC and 22.44ºC, by moving the set-point towards the upper threshold of the temperature range recommended for artwork conservation (21ºC-24ºC), in order to reduce the temperature gap between outdoors and indoors. This will have a positive effect not only on visitors' thermal comfort, but also on the museum's management due to the energy savings resulting from a lower pressure on the cooling system during the hot season. However, moving forwards from Fanger's model, considering seasonal temperature variations in the set-up of optimal temperature conditions in indoor environments would produce positive effects on occupants' comfort, artwork preservation and museum environments. In fact, the application of an adaptive approach would account for the human response to fluctuations related to different seasons [52], establishing a direct connection between outdoor and indoor thermal conditions that would not necessarily affect the requirements for the preservation of art and the built heritage in a negative way, as long as it is associated with the extension of the temperature bandwidth, producing positive effects on overall energy savings as well [39,53].

A final reflection should be made on the visitors' participation in the survey. If compared to the total amount of people visiting the museum during the research period (18,483), those who accepted to undertake the questionnaire (440) were only 2.4%. This means that the issue of visitors' thermal comfort in museum buildings is still understood as a secondary aspect and people do not engage with this enough. Considering the scarcity of resources on this topic, more research needs to be done, in order to contribute to the development of an integrated approach towards a combined conservation and human comfort based adaptive reuse and building retrofit.

8. Conclusions

This paper investigated the relationship between human thermal comfort and indoor microclimate in a historic building in Valencia, which has been adaptively reused as the Valencia History Museum. The research implemented a Post-Occupancy Evaluation methodology, performing a field monitoring on indoor microclimate conditions and a questionnaire survey to visitors over a period of one year, in order to assess the level of comfort perceived by the visitors during their stay inside the heritage building.

The main results of the research are:

- TSV assessment: visitors showed more dissatisfaction with the indoor thermal environment during the cooling season (July-September), possibly because of the gap between indoor and outdoor temperatures, with males and females generally in agreement on this;
- comparison between TSV and PMV: Fanger’s model for calculating PMV does not prove to be representative of the real thermal environment as perceived by visitors in this case study, as TSV and PMV values were significantly divergent across the year, also in regard to metabolic rates;
- clothing assessment: visitors choose a clothing combination according to outdoor conditions; however, this choice does not appear to be successful during their visit in the museum, mainly during the summer season, contributing to discomfort.

The paper suggests that the conservation criteria of artworks should not be the only parameters to be taken into account, rather, a more comprehensive approach should be considered that also includes human thermal comfort. The resulting integrated approach should assess the suitability of the indoor microclimate to foster artwork preservation, heritage adaptation and indoor environmental quality for occupants. Also, when retrofitting heritage buildings and adapting them to new uses, this combination could have a significant impact on existing historic structures. Similar to the role of structural monitoring for the upgrade of existing structures, environmental monitoring should be performed in historic buildings to understand their indoor microclimate and its variations compared to the external environment, in order to inform the retrofit project. Monitoring techniques should be non-invasive and, possibly, contactless, in order to avoid any damages to the existing materials and surfaces.

Historically, the adaptation of heritage buildings into museums has been driven by the goal of achieving optimal environmental conditions for artwork conservation. This single objective has often resulted in the integration of very intrusive plant systems in the building in order to provide the required hygro-thermal conditions, to the detriment of existing materials and to the neglect of the cultural value of the building itself. This approach has exacerbated the loss of materials in buildings originally constructed for different uses and later adapted to museums, as adaptive reuse itself can have high impacts on building fabrics due to compliance with mandatory requirements (such as structural, mechanical, fire protection, etc.). On the contrary, more recent approaches [54] promote a convergence between the conservation of the building and the conservation of artefacts by taking fully advantage of both passive and active systems, thus limiting the loss of materials and, consequently, of heritage value. Ultimately, this approach will improve the level of sustainability of the overall intervention, from an environmental (reduced energy consumption and improved indoor environmental quality), social (reduced impact of heritage value as manifestation of a social responsibility) and economic (reduced operation costs) point of view, in an attempt of achieving a comprehensive, yet respectful adaptation process [55,56].

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- A Post-Occupancy Evaluation of a museum in a historic reused building is performed.
- Quantitative monitoring and qualitative assessment are used for one year.
- Customized questionnaires for visitors are developed to assess visitors' thermal comfort.
- Artwork conservation, heritage adaptation and indoor environmental quality are considered.