

Article

Thermal Comfort in Places of Worship within a Mediterranean Climate

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Abstract: This paper investigates the relationship between the actual thermal comfort levels measured according to EN 16798-1 standard and the expected thermal comfort of attendees in five parish churches throughout 2018. This is carried out through statistical analysis of qualitative research based on questionnaire responses from church goers and quantitative research based on indoor measured data. This investigation includes the gathering of scientific data relating to temperature and relative humidity together with statistical data through thermal sensation surveys (TSSs). Thus, this study provides first-hand information about occupants' diversities of thermal sensations and dynamic behaviour adaptations to the intricate environment within churches. Results determine that a significant correlation exists between the actual thermal comfort levels measured according to EN 16798-1 standard and the expected thermal comfort perceived by the church attendees in most of the parish churches under review. Analysis of the sources of discomfort and suggestions made by the occupants revealed that passive design measures contribute towards improved indoor thermal conditions, reduced energy demand and lower carbon emissions. This information provides assurance for optimised decision-making methods, used to generate accurate solutions for policy-makers, architects and engineers, with an understanding of practical applications of passive measures for places of worship. Moreover, the paper provides insight on indoor comfort levels in places of worship within a Mediterranean context, which is insufficiently addressed by scholars at a global level.

Keywords: thermal comfort; churches; indoor temperature; thermal sensation surveys; relative humidity

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1. Introduction

The physical location of the parish churches in the archipelago of Malta, within the heart of Maltese villages or towns, is of paramount importance in presenting them as central icons within the everyday life of the community [1]. It is a truism to state that Malta has changed over the past 20 years, and so did comfort expectations [2]. The demand to create comfortable indoor thermal environments is no longer considered a luxury, and this has brought unforeseen challenges in places of worship, particularly because these buildings were not designed to be mechanically heated or cooled. Hence, the urge to create the expected 'adequate' indoor thermal environments without altering the general indoor microclimate has contributed to the growth of research on the subject.

The term 'thermal comfort' remains subjective and may be considered as a mindset that depends on the combination of the individual's social and cultural expectations and the physical thermal environment. Those who are accustomed to a higher level of thermal

conditions are more likely to acclimatise to thermal homogeneity, while those who experience different thermal conditions throughout the day can better adapt to variations [3]. It is a proven fact that through self-adaptation, the human physiological indicators generate adaptive measures to address the changes in indoor operative temperatures [4]. Such adaptation often results in attaining thermal comfort and prevents the use of energy for heating and cooling [5].

To this effect, occupants' thermal comfort feedback is imperative to energy efficiency analysis. Studies show that by the implementation of passive design measures, it is likely to broaden the non-heating and cooling periods [6–8], rendering a more comfortable environment. It is pertinent to point out that Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 (amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency) encourage research on historical buildings, including churches, to improve their energy performance ratings [9].

This research supports researchers in promoting the study of passive and low-energy architecture [10]. However, thermal comfort within buildings and the urban heat island effect remain of major concern, and adopting low-energy passive design strategies worldwide is not an option but a must in today's global climate change and emerging infectious diseases [11].

Research in indoor thermal comfort of free-running historical places of worship is often limited to comparison of measured data to the predicted adaptive thermal comfort models.

The aim of this paper is to go a step further and investigate the relationship between the actual thermal comfort levels measured according to EN 16798-1 standard and the expected thermal comfort as experienced by the attendees in these five parish churches throughout 2018. The study is extensively based on solid statistical analysis procedures of 600 questionnaire responses that were collected from church goers, both in summer and in winter seasons, as well as quantitative research based on indoor measured data. The uniqueness of this paper is portrayed in the combination of statistical methods that analyses the outcomes of real user experiences in naturally ventilated places of worship with thermal comfort studies based on adaptive thermal comfort models, as well as the comparison between the impact of building construction practices throughout different eras on the level of thermal comfort. This is combined with the result of identifying potential solutions to thermal comfort, by data analysis and consultation with the target population, in a cluster of buildings that have so far received insufficient attention from scholars and regulatory institutions.

1.1. Church Buildings under Study

Analysis of the physical and environmental factors was conducted for a number of churches, termed 'reference buildings' (RBs). These RBs characterise the different types of churches in Malta and portray 'real examples' with typical, physical and occupational characteristics as proposed by Ballarini et al. [12]. Out of the 359 churches on the Maltese islands, five RBs were specifically chosen. Selection was based on era, construction methodology and materials, form and occupational characteristics. The eras covered are 17th to mid-18th century Baroque period (Balzan, Sliema and Msida parish churches), mid-20th century neo-Romanesque style architecture (Santa Venera parish church) and late 20th century (post Vatican Council II style) contemporary architecture (Fgura parish church) (refer to Figure 1).

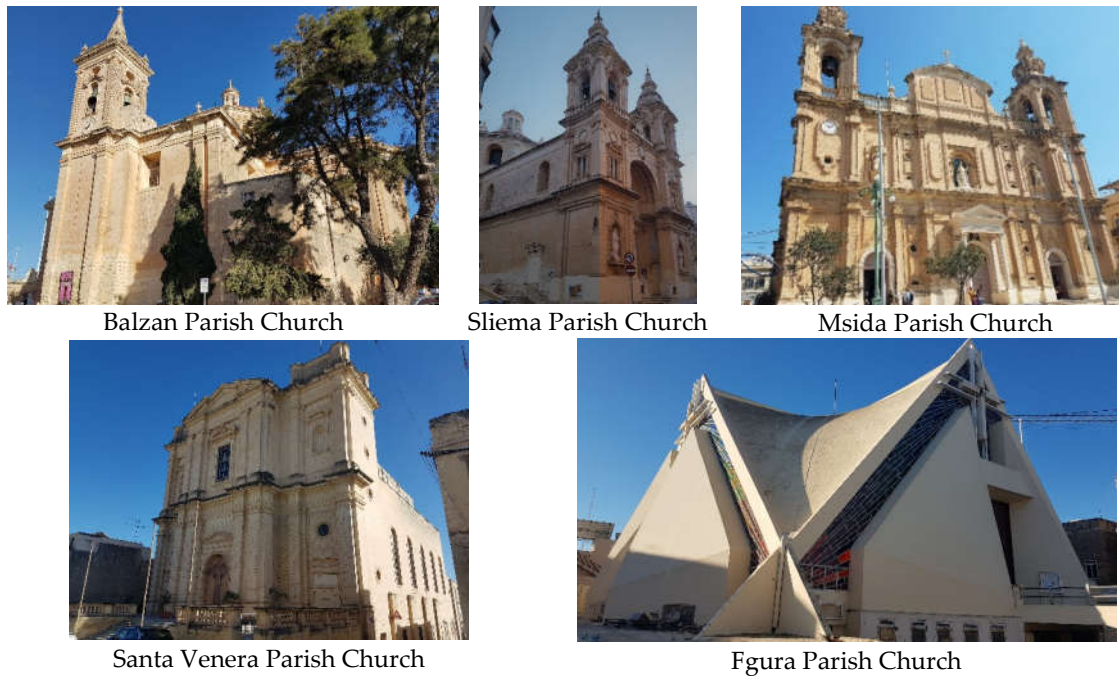


Figure 1. RBs: Balzan Parish Church (1669–1695); Stella Maris Parish Church, Sliema (1853–1877); Msida Parish Church (1867–1889); Santa Venera Parish Church (1954, still with incomplete bell towers); and Fgura Parish Church (1988). Dates shown indicate the period of construction.

1.2. Analysed Factors

The Maltese islands lie within the subtropical zone and therefore experience a typical Mediterranean climate with high levels of humidity [13]. Due to the limited area of the Maltese archipelago (316 km²) and the homogeneity of the land, only one climatic zone is defined [14]. These high levels of relative humidity hinder evaporative cooling, leading to an uncomfortable sensation typical of hot and humid climates, as well as higher perceived coldness in winter [15,16]. The impact of relative humidity and ambient air temperature are considered as determining environmental factors in this study.

In addition to the weather variables, the different construction methodologies of the ‘reference buildings’ (RBs) were analysed. Comparison is made between the modern building slender reinforced concrete structures and the thick walls made of globigerina limestone found in traditional churches. The thickness of the wall affects the thermal inertia, with thicker walls flattening internal temperature fluctuations and improving thermal comfort [17]. The sectional elevations displayed in Figure 2 show the very thick globigerina limestone walls of the Msida Parish Church (ranging from 1000 mm to over 1900 mm) in comparison to the evolved construction methods of the contemporary reinforced concrete adopted in the Fgura Parish Church (150 mm), whereby the stability of the building results from its shape rather than its sheer mass.

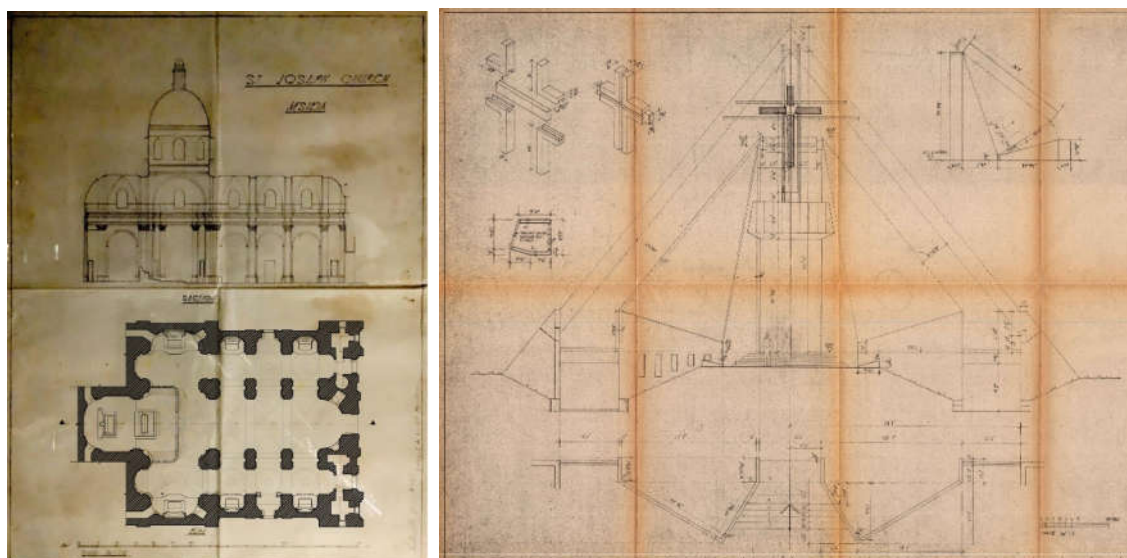


Figure 2. Sectional elevations of Msida Parish Church and Fgura Parish Church. Courtesy of the Archdiocese of Malta.

Other parameters such as orientation (refer to Figure 3), window-to-wall ratio, solar heat gains through non-operable windows, low insulation levels of the building envelope and lack of air movement all proved to have a direct effect on the indoor comfort of the building and the ultimate ambient temperature and indoor environment [18–20]. On the other hand, the qualitative study of the church attendees took into consideration individual attributes such as age [21] and gender [22,23].

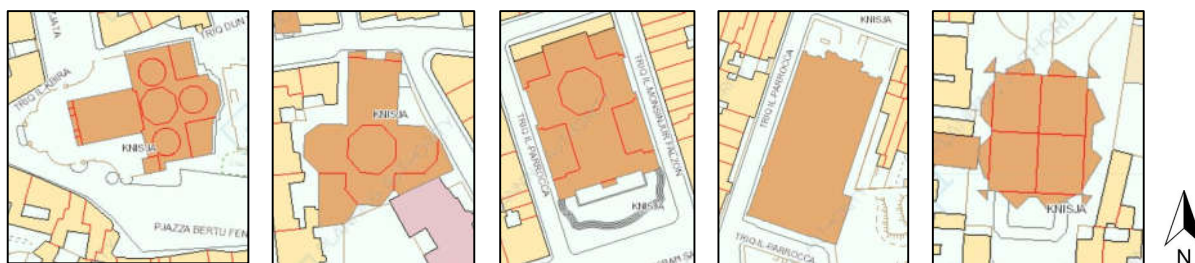


Figure 3. Orientation of the RBs (not to scale) left to right: Balzan Parish Church; Stella Maris Parish Church, Sliema; Msida Parish Church; Santa Venera Parish Church; and Fgura Parish Church. (For all RBs, the north direction is vertically upwards.)

It is pertinent to note that since Malta enjoys high levels of solar irradiation [24], the internal ambience of buildings gets hotter in summer because the rate of heat transfer between external solar-exposed surfaces and internal surfaces increases and also due to the fact that churches many times leave their doors open, allowing warmer air to infiltrate into the indoor zones. Furthermore, since the Maltese Islands lie within the subtropical zone, buildings are exposed for a longer period of time to solar radiation especially during the summer months. According to the Meteorological Office of the Malta International Airport in 2018, the brightest day in July had a total of 14 hours' worth of sunlight with a recorded temperature of 35.7 °C [25].

2. Method

The methodology adopted to conduct the investigation on the actual thermal comfort within the selected RBs and the expected thermal comfort of the occupants within the same RBs, together with onsite measurements and TSSs, is explained below.

2.1. Adaptive Comfort Model

The adaptive model adopted examines the relationship between church goers and the respective places of worship. This is based on the concept that individuals respond to uncomfortable changes by adapting to restore comfort. Such adaptation incorporates a combination of physiological, psychological and behavioural characteristics [26–28]. This model considers the indoor temperature as being strongly dependent on the outdoor temperature, providing a wider range of temperatures more acceptable to the users [29]. To this effect, the EN 16798-1 adaptive comfort model was adopted [30,31]. It must be noted that the difference between the operative temperature (used in standard EN 16798-1) and the apparent temperature, directly measured from the data loggers, is insignificant [32].

It is pertinent to point out that Balzan and Sliema parish churches were equipped with air-conditioning systems to be used intermittently for cooling during weekend and feast day religious services during warm periods. However, they were not being utilised when the TSSs were being conducted. Thus, churches were considered as free-running (naturally ventilated), and the adaptive comfort model was adopted as opposed to the heat balance model (PMV/PPD model). Furthermore, since churches are occupied for a relatively short time, category III comfort level was chosen to reflect an adequate level of expectation [33].

2.2. Onsite Measurements

The RBs were monitored by means of data loggers Onset HOBO MX1101, for the full year of 2018. Each RB had four data loggers, one placed at the back of the main nave, another at the centre of the main nave, the third placed at the altar and one external station in indirect sunlight. Air temperature (°C) and the percentage relative humidity (%) for the interior and exterior environments were continuously measured at 5 min instantaneous intervals [34]. The indoor carbon dioxide levels were recorded for a sample week using an MX1102 HOBO MX CO₂ Logger [35]. The indoor humidity levels of walls expressed as percentages were recorded at 0.5m height of walls from finished floor level (FFL) using the Powerfix HG03064C Moisture Meter. An average of six humidity level readings were recorded along the main aisle for each RB. Moreover, sample data for indoor radiant temperatures were recorded over a one-week period using the MRC wet bulb globe temperature logger Model WBGT-2010SD. Radiant temperature is defined as a measure of the average temperature of all surfaces, which can be different from air temperature under specific conditions.

The 5 min interval indoor air temperature readings recorded in each parish church throughout the year 2018 were transposed to hourly values. These data were then analysed and plotted as a 5-day moving average in the form of line graphs in relation to comfort limits determined by EN 16798-1.

It is pertinent to point out that prior to transposing from hourly values to a 5-day moving average, it was made sure that there was no substantial difference in the recorded indoor air temperature between occupied and unoccupied hours, more so during the presence of large congregations where only limited sporadic minor fluctuations were noted.

2.3. Mathematical Statistics

To establish the relationship between the actual thermal comfort levels measured according to EN 16798-1 standard and that expected by the parishioners, several statistical tests were carried out. Each test specifies two hypotheses, where the null hypothesis specifies that the two categorical variables are independent implying that there is no association between them. The alternative hypothesis specifies the converse (i.e., that the two categorical variables are not independent). Moreover, a 0.05 level of significance was adopted for each test [36].

In order to conduct the investigation on the expected thermal comfort of the occupants within the selected churches, a quantitative, correlational design research was employed [37]. This research is used to examine any correlation between two or more variables through statistical analysis.

2.4. Recruitment Method and Study Population

Whilst the microclimate was being monitored, surveys with sample parishioners were carried out in each RB for both summer (represented by May to September) and winter (represented by November to March) during the peak period of extreme weather. The data were collected through cluster sampling method in which there is an equal probability of respondents being chosen in order to achieve an unbiased representation of the total population [38]. Sixty participants from each RB, totalling 300 participants, were surveyed in summer and another 300 participants were surveyed in winter. Hence, the total study population was that of 600 participants (291 males and 309 females with a mean age of 49.31 years and a standard deviation of 16.778 years), which guarantees a maximum margin of error of 4% assuming a 95% confidence interval.

2.5. Survey Design

The survey addressed one's current thermal state (CTS) inside the church through a 7-point Likert scale [39], where 1 represents the 'hot' extreme and 7 represents the 'very cold' extreme. In accordance with Hawkes' conclusions [40], the 'neutral' point represented as 0 on the Likert scale is interpreted as the point at which the participant is thermally comfortable. On the other hand, S. Shahzad et al. (2018) concluded that measures other than CTS may be needed to fully analyse the thermal comfort of users, such as thermal preference [41]. However, it must be considered that the latter study investigated the application of the neutral thermal sensation within office buildings with an average of eight working hours daily, which is a significant amount of time when compared to about 45 min spent in churches. Thus, the CTS of the parishioners is a good indication to analyse the thermal comfort within the RB. Other questions in the TSS included frequency and time of attendance, whether participants ever attended a different church due to uncomfortable temperatures, whether they ever missed Sunday prayer service due to temperature extremities and identification of sources of discomfort and suggestions to reduce them [42]. Relevant personal data of every participant were also recorded, including age, gender and clothing.

3. Results and Discussion

Analysis of results displayed in this section is divided into two parts. The first part (refer to Section 3.1) investigates the actual thermal comfort of the RB in accordance with EN16798-1 standard, whilst the second part (refer to Section 3.2) investigates the expected thermal comfort perceived by the occupants within the RB.

The scope of the results displayed in Section 3.1, including their respective analysis, is to determine whether the RBs are termed as thermally comfortable. These results are then compared with the expected thermal comfort perceived by the occupants deduced in Section 3.2 to determine any correlation between the actual thermal comfort and the expected thermal comfort within the RB.

3.1. Actual Thermal Comfort (EN 16798-1)

The Baroque comfort analysis graphs (Balzan, Sliema and Msida) displayed in Figure 4 illustrate similar trends of line data, having the indoor air temperature intersecting the lower limit established from the EN16798-1 standard, approximately at the beginning of May and at the end of November. More importantly, during these months (May to November), the indoor air temperature is persistently situated below the upper limit

(EN16798-1). Thus, this result signifies that during these months, these parish churches are termed as thermally comfortable.

Similar time frame intercepts between the recorded indoor air temperature and the established lower limit (EN16798-1) are displayed in the more contemporary parish churches (St Venera and Fgura). However, it is pertinent to point out that during these months (May to November) the indoor air temperature is significantly closer to the upper limit (EN16798-1), where that of the St Venera parish church exceeds this limit for a short period during the month of August.

Further analysis on the relationship between the recorded indoor and outdoor air temperatures reveals that these do not fluctuate in tandem for the Baroque parish churches, as the indoor air temperature is steadier when compared to that of the outdoor temperature. This is not the case in the contemporary parish churches as, overall, both the recorded indoor and the outdoor air temperatures fluctuate in tandem. This result is attributed to the different methodology of construction in the building envelope between the Baroque and contemporary parish churches, where the U-values are significantly lower amongst those of the Baroque.

It can also be pointed out that the margin difference in degrees Celsius ($^{\circ}\text{C}$) between the recorded indoor and outdoor air temperatures of the contemporary parish churches is more significant in the St Venera parish church than that for the Fgura parish church. This is also attributed to the building envelope of both churches, where although they are termed as both contemporary, the St Venera parish church is a mid-20th century neo-Romanesque style architecture and the Fgura parish church is a late 20th century (post Vatican Council II style) contemporary architecture. This difference in architecture styles is seen through the distinct methodology of construction and building materials. The St Venera parish church is constructed of double-leaf masonry load-bearing walls (lower globigerina limestone) supporting reinforced pre-cast planks. The walls are formed of 0.23 m (9") thick blocks per leaf, with a concrete infill in between, resulting in an overall U-value of 1.8 $\text{W}/\text{m}^2\text{K}$. On the other hand, the Fgura Parish church is constructed using reinforced concrete structure built in the form of identical triangular segments and large stained-glass panels with an overall structural U-value of 2.52 $\text{W}/\text{m}^2\text{K}$.

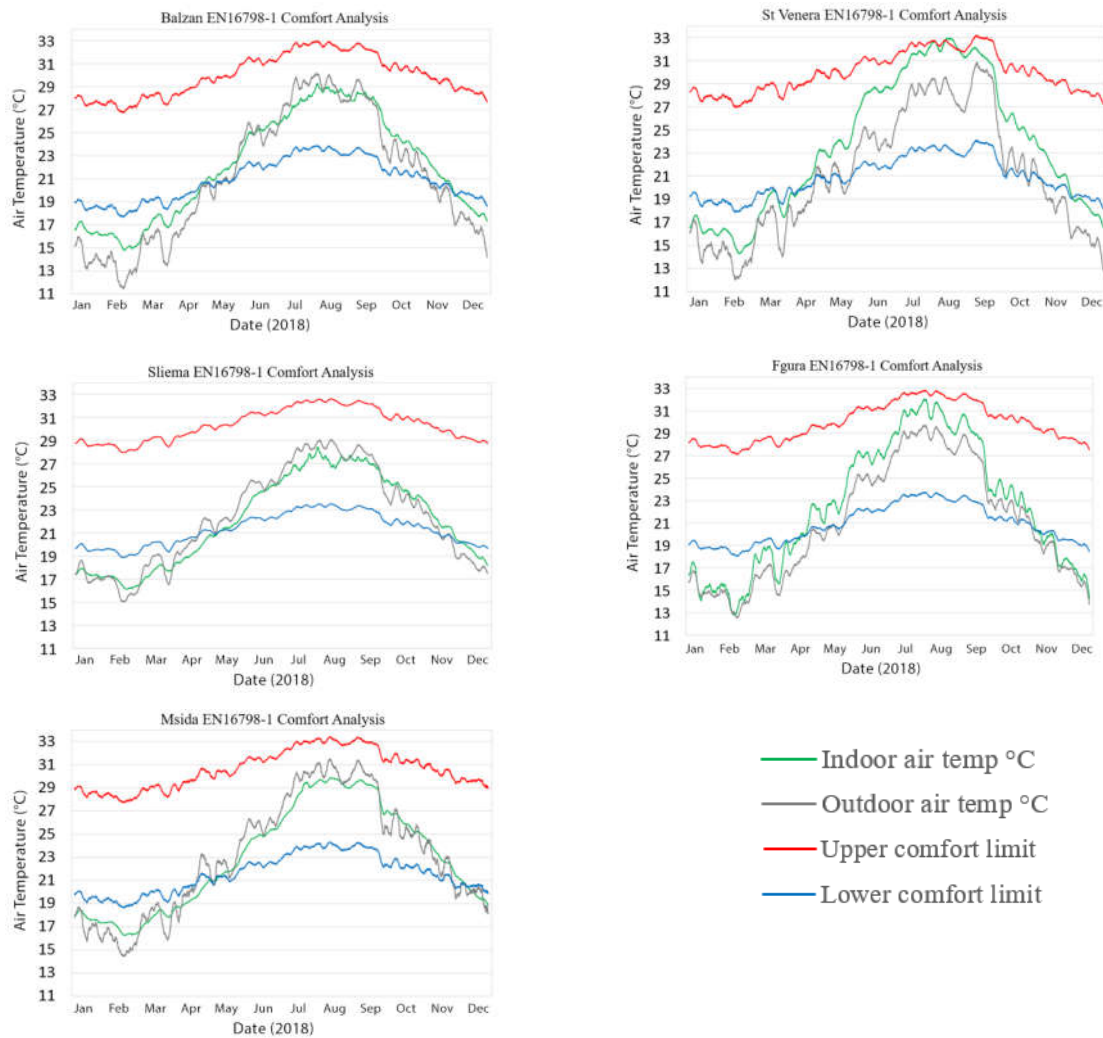


Figure 4. EN16798-1 category 3 comfort analysis.

The thermal comfort within the RB is mainly found by analysing the indoor air temperature with the relative comfort limits as calculated by the EN16798-1 standard method. Although thermal comfort does not depend solely on temperature, it can be deduced from the data collected in this study that air temperature is sufficient to indicate the level of thermal comfort, given that internal wind speed is low and the radiant temperature is very close to that of air temperature, as demonstrated in the results section.

This was further confirmed through a monitoring campaign in the five selected churches, results of which show that the indoor radiant and ambient temperatures were remarkably close in value, as shown in Figure 5.



Figure 5. Indoor radiant and ambient temperatures.

3.2. Expected Thermal Comfort

This section focuses on statistical data analyses using the IBM Statistical Package for the Social Sciences (SPSS) program version 26 [43] to determine the expected thermal comfort perceived by parishioners and its response to the actual indoor thermal environment by considering the factors affecting thermal perception. Most of the variables being studied are categorical, and the only way to investigate the association between these variables

is to carry out the chi-squared test. One of these variables is the parish church (Balzan, Sliema, Msida, St Venera, Fgura), whilst the other variable describes the respondents' views regarding suggestions, sources of discomfort and comfort level [44]. There are two tests that can be used to investigate the association between two categorical variables, and these include the Pearson chi-squared test and the likelihood ratio test. However, when the sample size is large, the p -values of these two tests converge. Thus, in this paper, the Pearson chi-squared test was used as the likelihood ratio test yielded almost an identical p -value to that of the Pearson chi-squared test [45].

On the contrary, some of the variables such as age, humidity and temperature are continuous (have a metric scale), and for these variables, the one-way ANOVA test was chosen to analyse the different parameters between the parish churches after checking the normality assumption. The one-way ANOVA test was used to compare mean temperature and mean humidity between the five parish churches, and this was carried out for each month. Moreover, this test was also used to compare mean ages of parishioners between the five parish churches to confirm that it is not a confounding factor.

The following SPSS results are displayed in a mixture of both graphical and tabular format to avoid redundancy of information. In addition, in all the analyses, the chi-squared test yielded p -values that were less than the 0.05 level of significance, indicating that the two categorical variables are not independent. In other words, there was a significant association between the two variables, thus the alternative hypothesis is satisfied. It must be pointed out that during the summer period on the day when the TSSs were being conducted, all the RBs were termed as being thermally comfortable in accordance with EN16798-1 and thermally uncomfortable during the winter period.

3.3. Perceived Comfort Level

During the summer period (refer to Figure 6), the Baroque parish churches of Balzan (81.7%), Sliema (50%) and Msida (43.3%) resulted in having the most relatively 'neutral' environment. The contemporary parish churches resulted in having a lower percentage of participants selecting a 'neutral' environment with 16.7% of votes for St Venera parish church and 6.7% of votes for Fgura parish church. On the other hand, the contemporary parish churches resulted in having a significantly higher percentage of occupants voting for 'very hot' with Fgura having a total of 73.3% and St Venera parish church having 38.3%, with lower percentages registered in the Baroque parish churches of Msida (25%), Sliema (26.7%) and Balzan (0%). This result signifies that most occupants were satisfied in terms of comfort within the Baroque parish churches, while in the contemporary parish churches, the majority were dissatisfied.

With regards to winter, Figure 6 also shows that the Baroque parish churches of Sliema and Msida, apart from Balzan, have a generally higher degree of 'neutral' votes (56.7% and 43.3%, respectively) when compared to the contemporary parish churches (St Venera 3.3% and Fgura 28.3%). In fact, the contemporary parish churches had a higher degree of 'cold' votes (St Venera 63.3% and Fgura 46.7%) when compared to Msida and Sliema Baroque parish churches (36.7% and 13.3%, respectively). When comparing these results with those established in Section 3.1, it can be deduced that there is a correlation between the actual and expected thermal comfort within the Balzan, St Venera and Fgura parish churches. However, this does not apply to the Sliema and Msida parish churches as most of the votes are neutral. This is possibly attributed to other factors that influence indoor thermal comfort, investigated in further detail below.

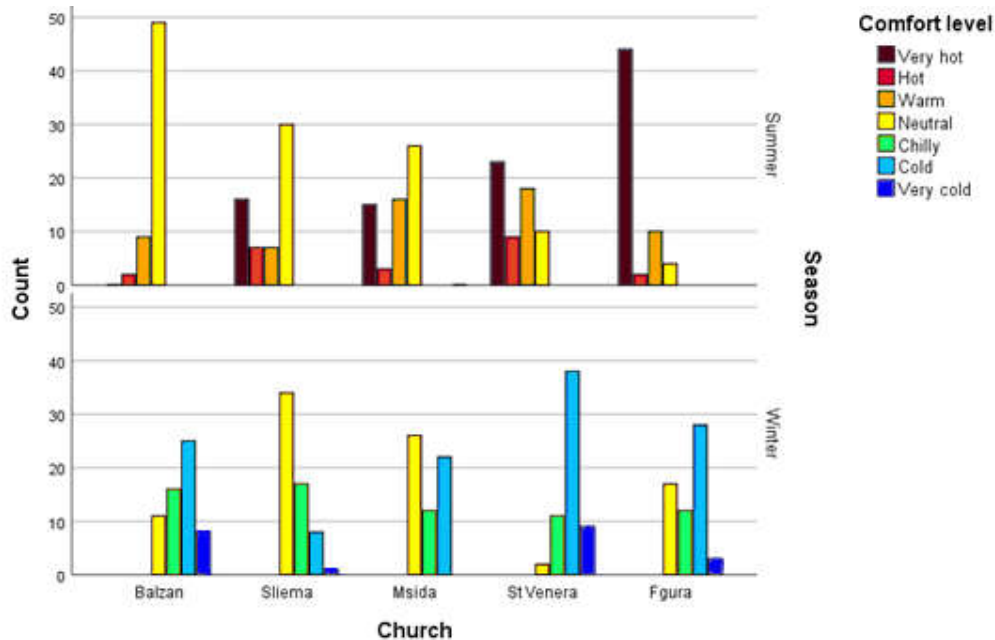


Figure 6. Bar graph representing different comfort levels in the different parish churches in summer and winter.

$$X^2(12) = 121.74, p < 0.001 \text{ (Summer)} \quad (1)$$

$$X^2(16) = 160.55, p < 0.001 \text{ (Winter)} \quad (2)$$

where the number in brackets is the degrees of freedom ($df = (\text{Rows} - 1) \times (\text{Columns} - 1)$) and the value for $X^2(df)$ is the chi-squared value.

The reason behind the high percentage of 'neutral' voting amongst the Baroque parish churches is mainly attributed to their respective thermal transmittance. This relatively low U-value, ranging from 0.49 to 0.54 W/m²K, contributes to low thermal losses or gains through the building material thus maintaining a neutral environment. In addition to the above, these churches have a low percentage of glazed areas, and many of these windows are glazed with stained glass.

With regards to the contemporary parish churches, it can be noted that the U-values for St Venera parish church (1.8 W/m²K) and Fgura parish church (2.52 W/m²K) are significantly higher than those of the Baroque parish churches under review, thus contributing to a higher degree of heat transfer through the building fabric, resulting in an overall more uncomfortable environment. Moreover, the percentage of glazed apertures is higher, allowing a higher percentage of solar radiation to penetrate and overheat the indoor climate in summer. On the other hand, with 28.3% 'neutral' votes, the high percentage area of glazing in the Fgura parish church has helped it achieve a better indoor thermal comfort during the winter than that recorded in the Balzan parish church.

3.3.1. Summer

The results from the survey reveal a trend in the thermal comfort of the RB ranging from the most thermally comfortable to the least thermally comfortable as illustrated in Figure 7. The Balzan parish church ranked as the most thermally comfortable out of all the parish churches under review in summer.

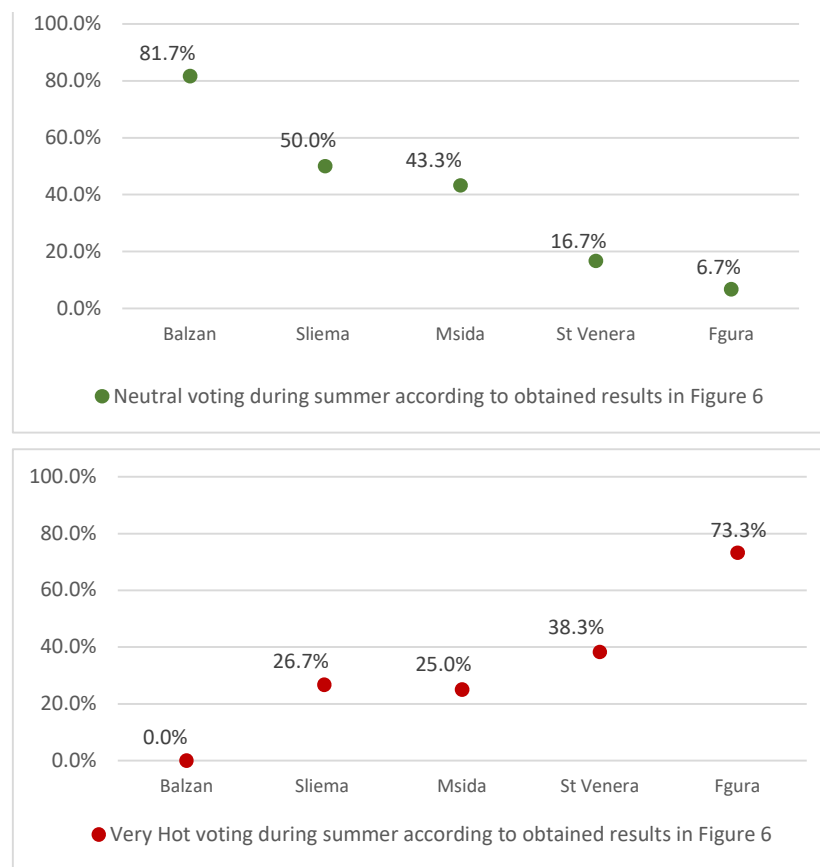


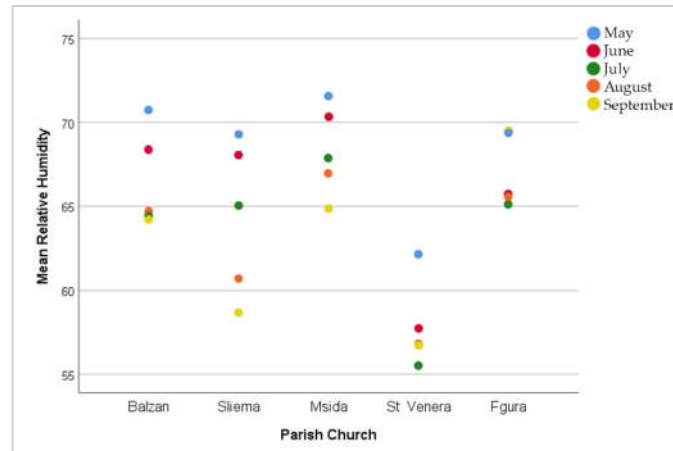
Figure 7. X-Y Scatter graphs showing the comfort level in accordance with the results obtained in Figure 6 during summer.

Analysing in further detail the difference in the indoor environment between the Fgura and St Venera parish churches, it can be noted that the comfort levels voted by the parishioners vary amongst the two. In the case of St Venera, although 38.3% selected *'very hot'*, 30% selected *'warm'* and 16.7% *'neutral'*, thus resulting in having a more comfortable indoor environment when compared to that of Fgura parish church, where most of the occupants selected *'very hot'* (73.3%).

In contrast, from the bottom graph of Figure 8, it can be observed that the monthly mean indoor temperature of the St Venera parish church is recorded as being higher than that of Fgura parish church by approximately 1.5 degrees Celsius for every month. Hence, one would assume that occupants should feel hotter in the St Venera parish church. However, the top graph of Figure 8 illustrates that the St Venera parish church maintains a relatively low monthly percentage of relative humidity throughout the summer when compared to a higher monthly mean humidity in the Fgura parish church. As the air temperature becomes warmer, the relative humidity decreases [46], resulting in a negative relationship as portrayed in Figure 7.

This elevated relative humidity in the Fgura parish church is highly likely to be the reason for most occupants voting *'very hot'* (73.3%), besides the elevated temperatures. This is because high relative humidity influences thermal perception as it hinders evaporation through the skin, resulting in a sweaty feeling. Furthermore, thermal perception may also be affected by the penetration of direct sunlight through the large area of oriented glazed openings [47]. This phenomenon is evidently seen in Figures 9–10, where sunlight is seen to fall directly onto indoor surfaces, resulting in a higher radiative temperature in Fgura as opposed to St Venera parish church. Given that human beings feel

the operative temperature, that is, the resultant temperature derived from air temperature, radiant temperature and air speed, occupants in the Fgura parish church are expected to have a warmer thermal perception due to the direct solar radiation.



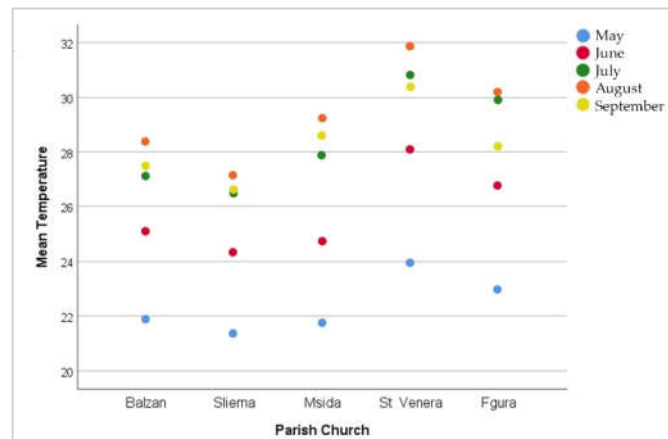
$F(4,3715) = 368.58, p < 0.001$ (May–Relative Humidity)

$F(4,595) = 571.85, p < 0.001$ (June–Relative Humidity)

$F(4,3715) = 330.18, p < 0.001$ (July–Relative Humidity)

$F(4,3715) = 407.34, p < 0.001$ (August–Relative Humidity)

$F(4,3595) = 399.02, p < 0.001$ (September–Relative Humidity)



$F(4,3715) = 402.1, p < 0.001$ (May–Temperature)

$F(4,595) = 1891.75, p < 0.001$ (June–Temperature)

$F(4,3715) = 1509.181, p < 0.001$ (July–Temperature)

$F(4,3715) = 2437.4, p < 0.001$ (August–Temperature)

$F(4,3595) = 605.03, p < 0.001$ (September–Temperature)

Figure 8. X-Y Scatter graphs depicting monthly mean relative humidity and monthly mean temperature of the parish churches in the summer.

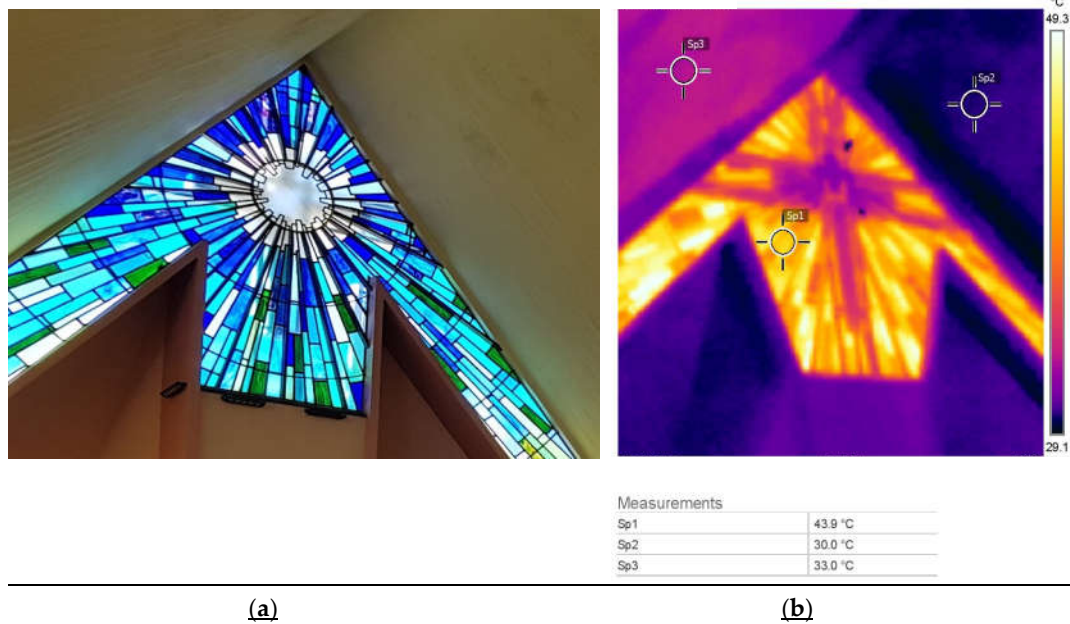


Figure 9. (a) Direct solar radiation falling onto indoor surfaces in the Fgura parish church. (b): Solar radiation transmittance through the building. Envelope of Fgura parish church: reinforced concrete—Sp1 and Sp2; stained glass—Sp3.

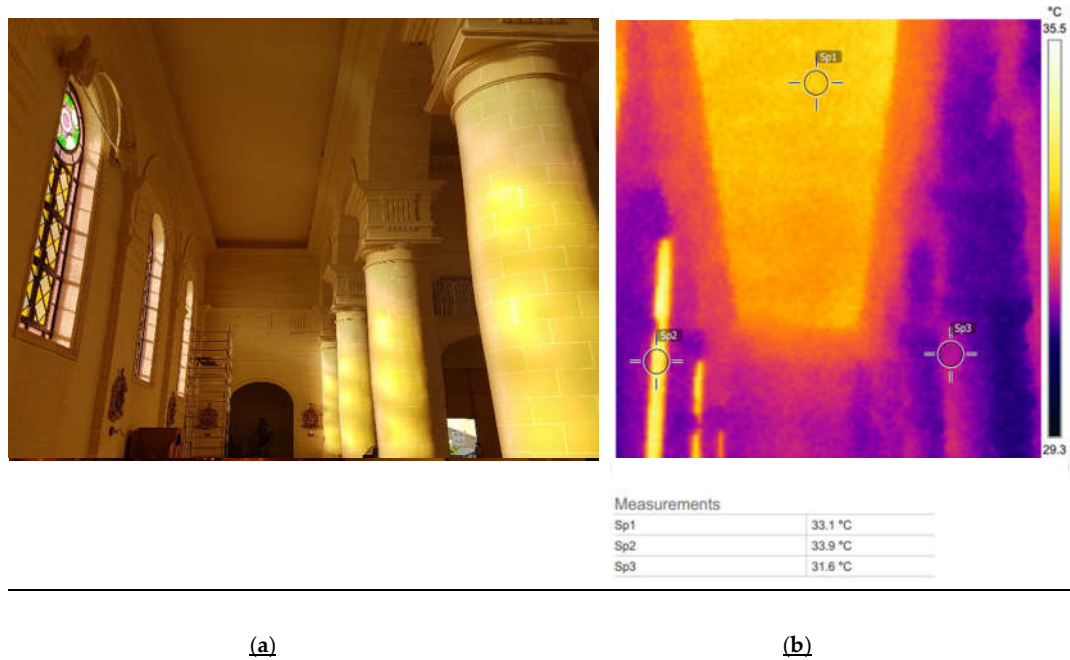


Figure 10. (a): Direct solar radiation falling onto indoor surfaces in the Santa Venera parish church. (b): Solar radiation transmittance through the building. Envelope of Santa Venera parish church: prefabricated pre-cast planks—Sp1; stained glass—Sp2; masonry column with concrete infill—Sp3.

3.3.2. Winter.

According to the survey results, an unexpected trend is shown in Figure 11 where the thermal sensation of the interviewees in Balzan differed from those of the other two Baroque churches. It was expected that results prove a higher degree of ‘neutral’ voting such as that of Sliema and Msida Baroque parish churches. The reason for this anomaly

could have been caused by other confounding factors such as relative humidity and indoor temperature.

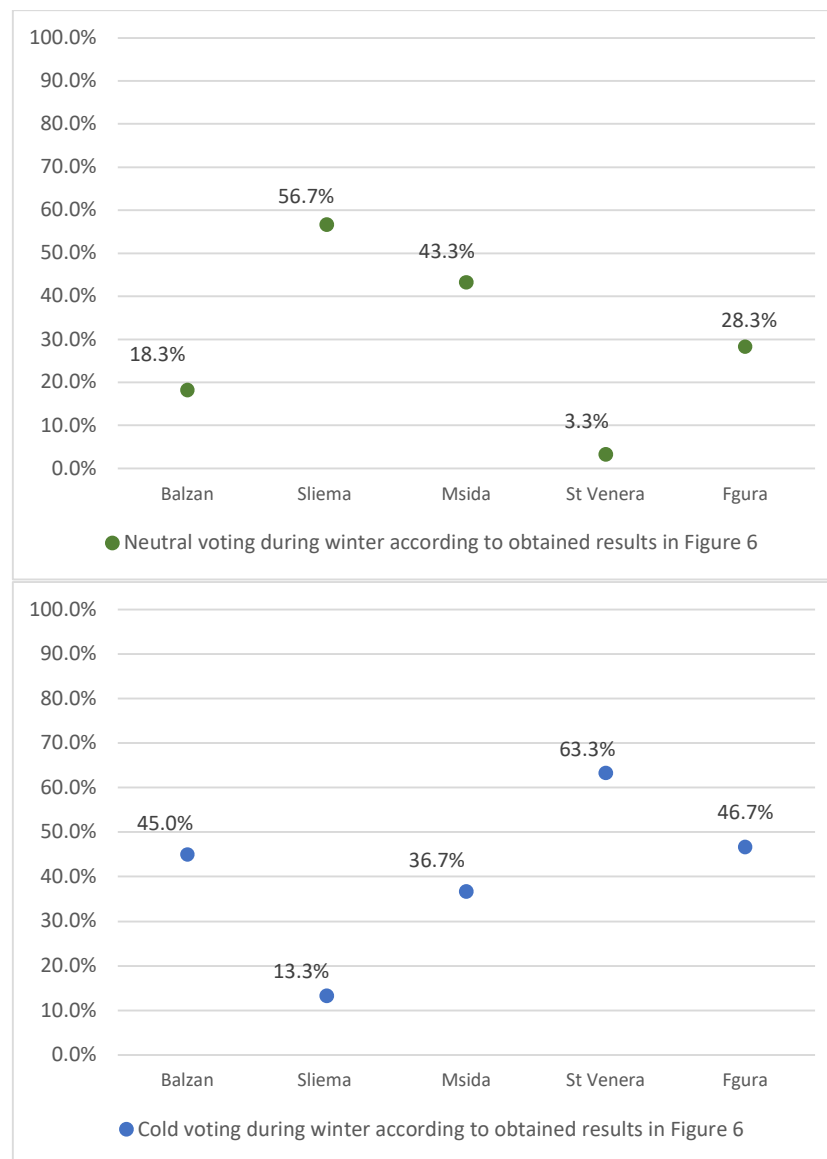
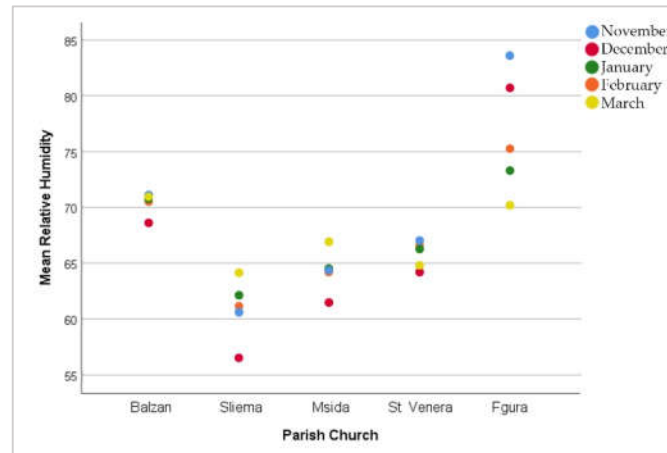


Figure 11. X-Y Scatter graphs showing the comfort level in accordance with the results obtained in Figure 6 during the winter.

In fact, Figure 12 clearly indicates that the Balzan Parish church had a high percentage of mean relative humidity and a relatively lower mean indoor temperature when compared to the other Baroque parish churches in the winter. Building moisture readings at a height of 0.5 m from the finished floor level revealed high humidity levels due to rising damp (refer to Table 1). This rising damp (4%) is mainly attributed to the fact that, apart from having an underground water reservoir under the parvis, it is the only church out of all the five RBs that has an extensive abandoned subterranean crypt. This high relative humidity is further aggravated by the fact that the percentage of glazed area openings in the Balzan parish church is 0%, thus minimizing the air exchanges and resulting in a constant level of high relative humidity. Likewise, Table 1 shows that the Msida parish church revealed a high percentage (3.7%) of building moisture evident through rising damp. This high percentage of building moisture is attributed to the fact that Msida is a harbour town

in East Malta, where the lower part lies at the outlet of a valley and the land in front of the parish church is reclaimed. At the time of building the church, no humidity barrier was incorporated in the construction of its walls.



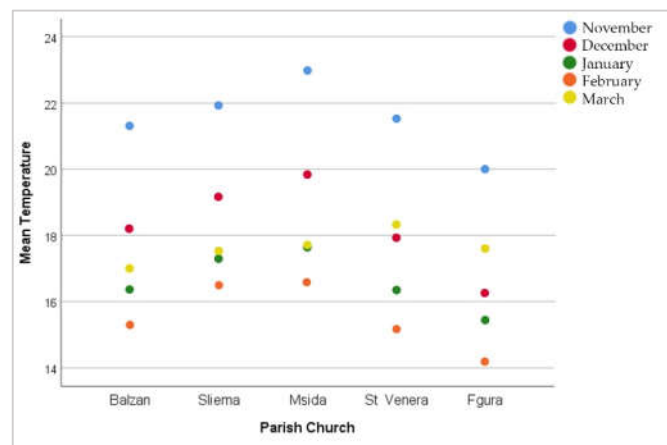
$F(4,3595) = 1635.07, p < 0.001$ (November–Relative Humidity)

$F(4,3525) = 1820.09, p < 0.001$ (December–Relative Humidity)

$F(4,3715) = 564.93, p < 0.001$ (January–Relative Humidity)

$F(4,3355) = 754.09, p < 0.001$ (February–Relative Humidity)

$F(4,3715) = 235.49, p < 0.001$ (March–Relative Humidity)



$F(4,3595) = 520.26, p < 0.001$ (November–Temperature)

$F(4,3525) = 1020.57, p < 0.001$ (December–Temperature)

$F(4,3715) = 686.27, p < 0.001$ (January–Temperature)

$F(4,3355) = 709.03, p < 0.001$ (February–Temperature)

$F(4,3715) = 109.93, p < 0.001$ (March–Temperature)

Figure 12. X–Y Scatter graphs depicting monthly mean relative humidity and monthly mean temperature of the parish churches in the winter.

Table 1. Reference values for humidity expressed in percent by weight at 0.5-metre height of masonry wall from finished floor level (FFL).

Church	Measuring Range (0.0–4.1%)	
Balzan	4.0%	<0.5%—Dry
Sliema	1.0%	0.5–1%—Borderline
Msida	3.7%	> 1%—Too humid
St Venera	0.7%	
Fgura	0.0%	

In the contemporary parish churches, the St Venera parish church had a higher percentage of ‘cold’ votes than the Fgura parish church during the winter period. This is attributed to the difference in the building envelope. With respect to the latter, it is imperative to point out that St Venera parish church has a flat roof constructed of prefabricated concrete planks, whereas the Fgura parish church is covered by a reinforced concrete roof whose axes form a symmetrical cross. This gives the church a multifaceted exterior with an interplay of plain solid inclined triangles and stained-glass panels. The combined effect is that the Fgura parish church absorbs relatively higher amounts of solar radiation in winter, both on its roof as well as through the inclined glazed surfaces, which favourably improves the indoor ambient conditions in winter. However, this added benefit of solar gains is ephemeral as at night it is re-radiated through the building’s envelope [48].

On the other hand, the window-to-wall ratio of the St Venera parish church is significantly lower than that of the Fgura parish church, with a calculated percentage of 11% on the south-east and north-east facades with respect to St Venera parish church and 18% on all facades with respect to Fgura parish church. Thus, in conformity to the phenomena of the U-value explained by A. Lymath (2015) [49], there is a higher degree of heat transfer through the glazing system of the Fgura parish church, resulting in an overall more thermally comfortable environment.

3.4. Physiological Factors—Gender

The total study population consisted of a relatively equal number of male (48.5%) and female (51.5%) participants.

Overall, the results obtained from Figure 13 for summer suggest that at higher temperatures, females tolerated them more than males with 45% and 35%, respectively, voting for ‘neutral’. Y. Zhai et al. (2014) concluded that males tended to be more dissatisfied in warm temperatures when compared to females [50]. Moreover, B. Kingma (2015) concluded that females were more comfortable at temperatures that were 2.5 degrees Celsius higher, hence preferring warmer temperatures [51].

On the other hand, the scenario was different in winter with 25% and 28% of females and males, respectively, voting for ‘neutral’, indicating that, overall, both genders were comfortable in lower temperatures.

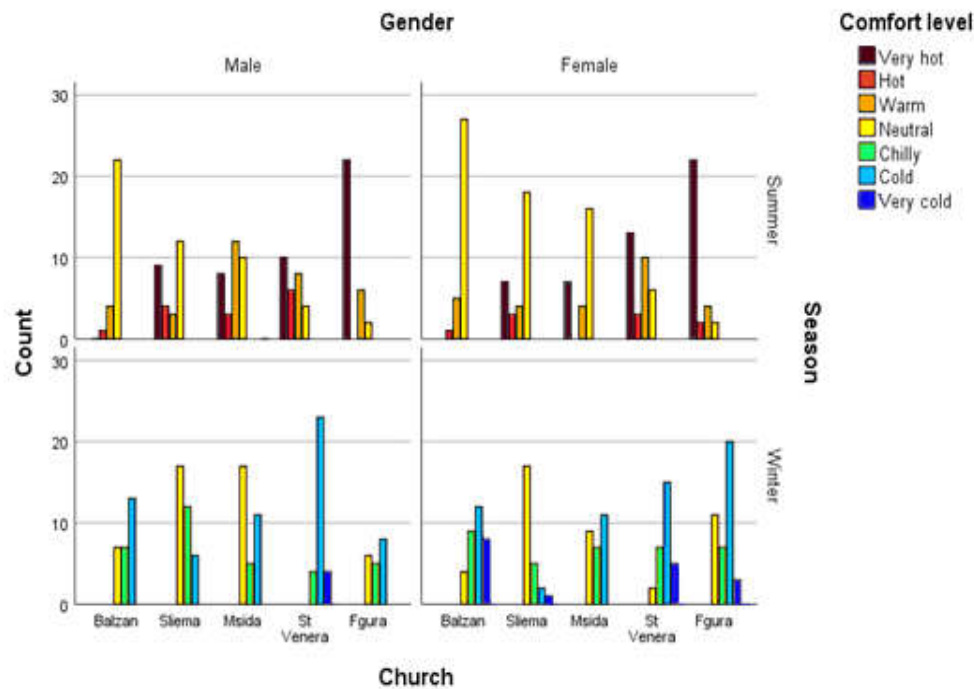


Figure 13. Bar graph representing the difference in comfort levels between males and females in the different parish churches in summer and winter.

$$X^2(12) = 66.75, p < 0.001 \text{ (Summer-male)} \quad (3)$$

$$X^2(12) = 63.54, p < 0.001 \text{ (Summer-female)} \quad (4)$$

$$X^2(12) = 49.69, p < 0.001 \text{ (Winter-male)} \quad (5)$$

$$X^2(12) = 42.90, p < 0.001 \text{ (Winter-female)} \quad (6)$$

where the number in brackets is the degrees of freedom ($df = (\text{Rows} - 1) \times (\text{Columns} - 1)$) and the value for $X^2(df)$ is the chi-squared value.

3.5. Physiological Factors—Age

The age of the 600 male and female participants was also considered as a physiological factor in this study to attain a more accurate result. Age has been found to contribute to thermoregulatory mechanisms due to factors such as differences in metabolic functioning, where the older generations tend to exhibit lower body temperatures than the younger generations [52].

The study population consisted of 24% being 35 years old or less, 27% between 36 to 50 years of age, 20.3% between 51 to 60 years and the highest being 28.7% of 61 years and over, with the majority wearing light and adequate clothing in view of the high temperatures during the summer and the majority wearing multi-layered clothing during the winter.

In Figure 14, one can note that the older generations felt more thermally comfortable in hotter temperatures and less thermally comfortable in colder temperatures, when compared to the younger generations. During the summer, in the Balzan parish church there were more 'hot' and 'warm' votes coming from the younger generations (35 years or less to 50 years), whereas there were very few 'warm' votes coming from the older generations (51–61 years and over). In the Sliema parish church, most of the 35 years or less age group selected 'very hot' with very few voting for 'neutral'. However, as the ages increased, so did the 'neutral' votes which spiked for the oldest age group. Even though quite a few occupants also selected 'very hot', 'hot' and 'warm', the overall vote was still 'neutral'. Once

again, in the St Venera parish church, most of the younger age groups (35 years or less to 50 years) voted mostly for 'very hot', 'hot' and 'warm', and although these votes were still present in the oldest age group, the 'neutral' comfort level became much more evident when compared to other age groups. With regards to the Msida and Fgura parish churches, it seems that all age groups had similar perceptions of the indoor thermal comfort level.

During the winter, in the Balzan parish church, 'very cold' was voted amongst the older age generations (51 to 61 years or more). However, this vote became less popular amongst the younger age groups (35 years or less to 50 years). This was also the case for the Fgura parish church, where younger generations were seen to be more thermally comfortable than the older generations since the degree of 'cold' votes was increasing from youngest to oldest. In the Msida parish church, the younger generations seemed to feel more thermally comfortable since there was a considerable number voting for 'neutral'. However, this vote decreased significantly in the oldest generation. In the Sliema parish church, it seems that occupants of all ages had similar thermal comfort perceptions as the most popular vote was 'neutral' in all age groups. On the other hand, the most popular vote for the St Venera parish church was 'cold', which was especially high in the younger generations (35 years or less to 50 years) and decreased in the older generations (51 years to 61 years or older).

Notwithstanding that the occupants participating in the TSS were not stratified by age but chosen through convenience sampling, a trend could be seen in parish churches during both the summer and winter. This corresponds to a study carried out by Blatteis, C.M et al. (2012) [52], whereby it was concluded that older generations tend to exhibit lower body temperatures, and hence, they would feel more thermally comfortable in warmer environments during the summer and feel more thermally uncomfortable in colder environments during the winter.

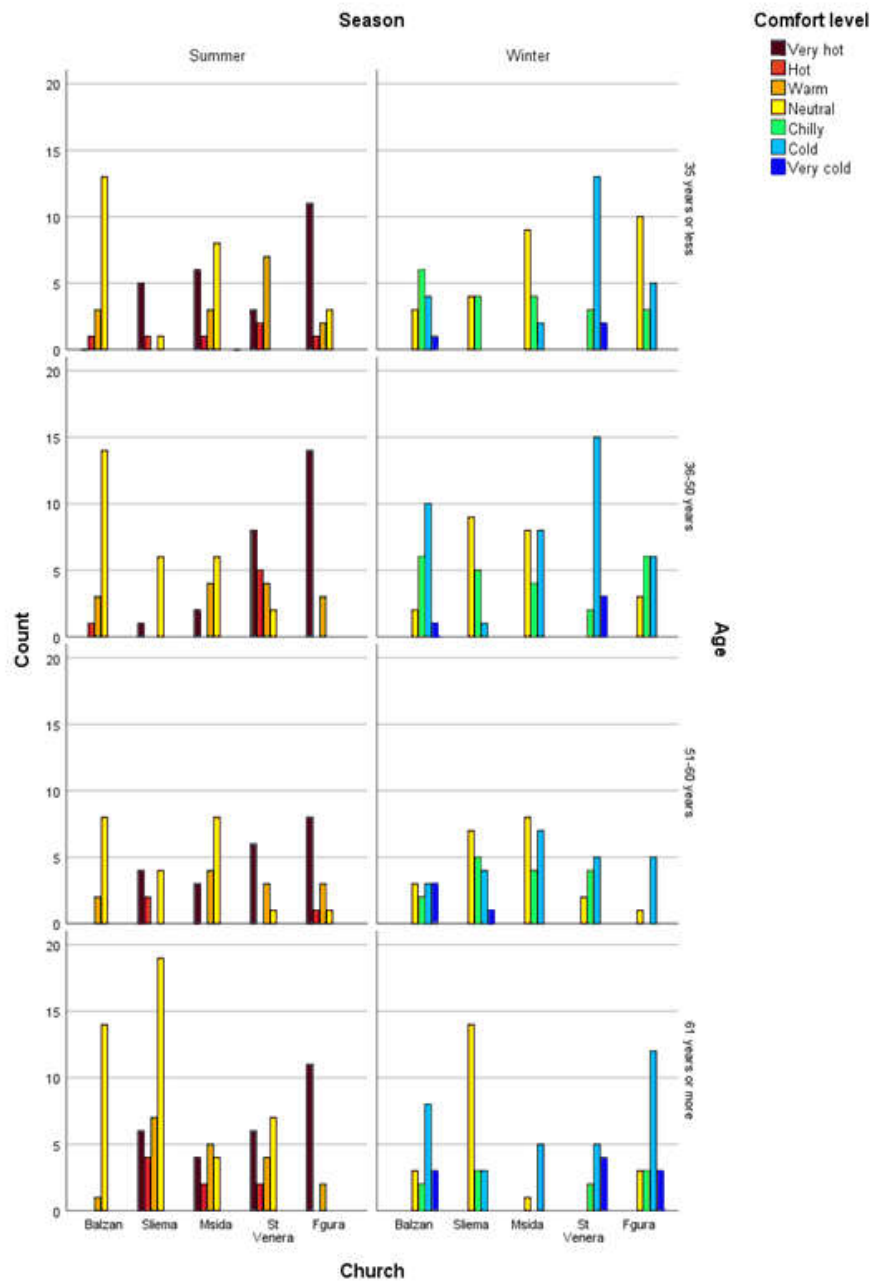


Figure 14. Column graph representing the difference in comfort levels between the four different age groups in the different parish churches in both summer and winter.

- $X^2(12) = 40.41, p < 0.001$ (Summer–35 years or less) $X^2(16) = 50.73, p < 0.001$ (Summer–51 to 60 years) (7)
- $X^2(12) = 55.46, p < 0.001$ (Winter–35 years or less) $X^2(16) = 45.07, p < 0.001$ (Winter–51 to 60 years) (8)
- $X^2(12) = 28.43, p = 0.005$ (Summer–36 to 50 years) $X^2(16) = 48.15, p < 0.001$ (Summer–61 years or more) (9)
- $X^2(12) = 42.90, p < 0.001$ (Winter–36 to 50 years) $X^2(16) = 54.51, p < 0.001$ (Winter 61 years or more) (10)
- where the number in brackets is the degrees of freedom ($df = (Rows - 1) \times (Columns - 1)$) and the value for $X^2(df)$ is the chi-squared value.

3.6. Sources of Discomfort

The survey was also intended to identify the sources of discomfort. Table 2 shows the outcome of the responses.

During the summer, most of the participants in the Balzan parish church selected '*no discomfort*' (45%). Slightly smaller percentages of participants selected this option for the Sliema (35%) and Msida (33.3%) parish churches. However, in the contemporary parish churches, votes for '*no discomfort*' had decreased significantly with 11.7% for St Venera parish church and 5% for Fgura parish church. This result supports the findings defined in Section 3.1 that the Baroque parish churches perform better in terms of comfort during the summer. Analysing the parish churches in further detail, it can be noted that whilst during the summer the Balzan parish church ranked the highest in terms of '*no discomfort*', it also had a relatively high percentage of votes for '*direct sunlight*' (35%).

The percentages of Sliema church parishioners selecting '*insufficient air movement*' (36.7%) and '*insufficient cooling/heating*' (20.0%) were amongst the largest. Although the Sliema parish church has the highest percentage of glazed area openings (20%) when compared to Balzan (0%) and Msida (3%) parish churches, thus expecting better air movement, this is not the case. *Casement windows* are located in the dome, and the natural flow of air through the church due to vertical differences in temperature is not sufficient to create air circulation. The lack of air infiltration is further aggravated by closed doors, short-circuiting the stack effect ventilation of fresh air thus preventing any significant draft movement [53].

Like the Sliema parish church, the Msida parish church achieved a high percentage of votes for '*insufficient air movement*' (58.3%). This result was expected since the percentage of area openings is very low (3%).

With regards to the contemporary churches, the Fgura parish church had a relatively high percentage of votes for '*insufficient air movement*' (35%) but an even higher percentage for '*direct sunlight*' (55%). Similarly, the St Venera parish church also had '*direct sunlight*' as the most popular vote amongst the occupants (55%). This spike in '*direct sunlight*' voting in the contemporary parish churches when compared to the Baroque churches is mainly attributed to the fact that both contemporary churches have a high percentage of glazing (refer to Figures 9 and 10). Nevertheless, parishioners' vote for '*insufficient air movement*' was still relatively high. As the overall thermal comfort level of the church was '*very hot*', ventilation proved not sufficient to compensate for the overheating and direct sunlight that affected the thermal perception of the occupants.

As for the winter, '*no discomfort*' ranked as the most popular vote in the Sliema parish church (68.3%) followed by Msida (53.3%), Fgura (25%) and St Venera parish church (21.7%). This result does not support the findings defined in Section 3.1. With regards to the Balzan parish church, one would expect it to have a similar thermal comfort level as the other Baroque parish churches. Nevertheless, this was not the case as findings show that there were 0% of participants voting for '*no discomfort*'. However, findings resulted in an overall increase of discomfort, especially when compared to the other two Baroque churches, including '*too much air movement*' (26.7%), '*cold ambience*' (25%), '*insufficient heating*' (20%) and '*insufficient air movement*' (15%).

In this study, consideration was also given to CO₂ levels within all respective parish churches. M. Kuru et al. concluded that an increased concentration of carbon dioxide (CO₂), especially in an already significantly humid area, would result in low indoor air quality and decrease the thermal comfort of such occupants [54]. The average indoor CO₂ levels recorded in each parish church were within the acceptable EU recommended range of 600 to 1000 ppm [55,56]. This threshold was only exceeded for an interim period in Fgura parish church when considering readings at 5 min intervals on Sunday (refer to Figure 15). Improved ventilation rates ought to keep carbon dioxide concentration lower than 1000 ppm. Thus, the determination of indoor air quality (IAQ) levels through CO₂ readings, amongst other parameters, indicates that there is no direct link between exposure to measured CO₂ concentration and comfort of building occupants [57].

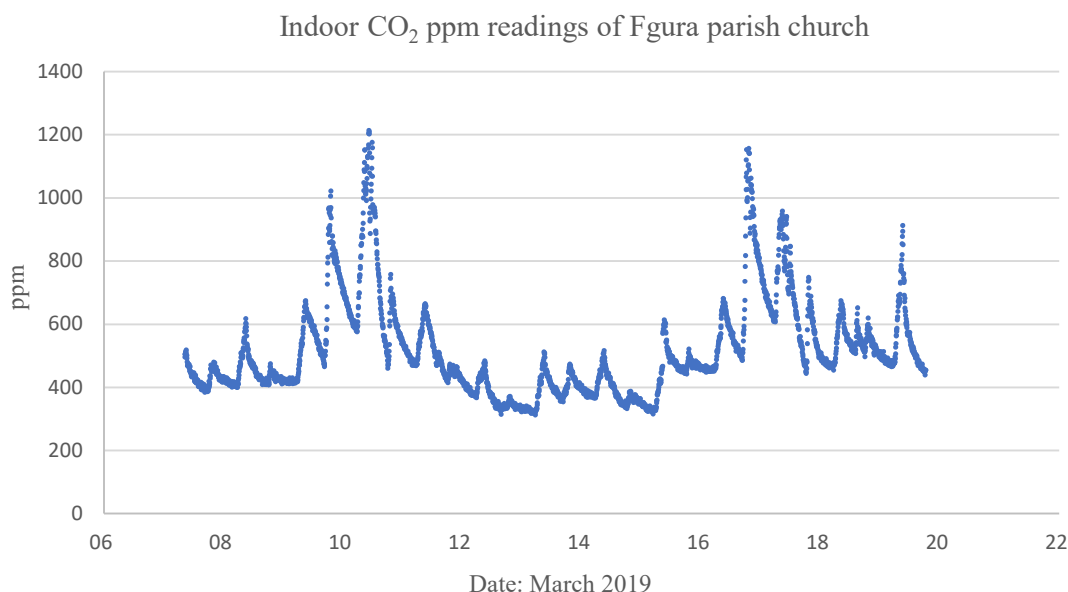


Figure 15. X–Y Scatter graphs showing the CO₂ readings of Fgura parish church.

The Balzan parish church also had a relatively high percentage voting for ‘cold ambience’ (25%). This is the result of lowest indoor recorded temperatures combined with the highest percentage of indoor relative humidity. A high percentage of occupants also selected ‘insufficient heating’ (20%), possibly due to being exposed to higher quality of thermally controlled environments [58].

Further analysis of the results displayed in Table 2 showed that votes for ‘no discomfort’ spiked up to a total of 68.3% in the Sliema parish church with an insignificant degree of votes for other sources of discomfort, all of which ranked below 2%. Sliema parish church also proved to have the lowest recorded indoor relative humidity, whilst maintaining a thermally comfortable indoor temperature [59] and good indoor air quality due to air movement and ventilation. One must take into consideration the fact that Sliema parish church had the largest percentage (33.3%) of parishioners over 61 years when compared to the other Baroque churches under study. Similar results were attained in the Msida parish church with a slight decrease in ‘no discomfort’ voting (53.3%) and a slight increase in ‘too much air movement’ (25%).

The results obtained for the contemporary churches are as anticipated. The indoor air temperature results have already shown that the overall indoor thermal comfort is relatively low when compared to the Baroque churches.

Table 2. Showing the different sources of discomfort in the different parish churches in both summer and winter.

Season	Sources of Discomfort	Parish Church				
		Balzan	Sliema	Msida	St Venera	Fgura
Summer	Too much air movement	1	2	0	0	0
	Insufficient air movement	6	22	35	14	21
	Direct sunlight	21	3	2	33	33
	Insufficient cooling/heating	4	12	3	5	2
	Irregular temperature	1	0	0	1	1
	No discomfort	27	21	20	7	3
Winter	Too much air movement	16	5	15	27	16

Insufficient air movement	9	0	2	0	2
Direct sunlight	1	0	0	0	1
Ambience of church is hot/cold	15	6	4	12	12
Insufficient cooling/heating	12	4	3	5	13
Irregular temperature	7	4	4	3	1
No discomfort	0	41	32	13	15

$$X^2(20) = 120.34, p < 0.001 \text{ (Summer)} \quad (11)$$

$$X^2(24) = 127.47, p < 0.001 \text{ (Winter)} \quad (12)$$

where the number in brackets is the degrees of freedom ($df = (\text{Rows} - 1) \times (\text{Columns} - 1)$) and the value for $X^2(df)$ is the chi-squared value.

Source of discomfort voting for 'too much air movement' (45%), followed by 'cold ambience' (20%), was recorded highest for the St Venera parish church. This results from the lack of a porch (known in Maltese as an *antiporta*), causing substantial indoor fluctuations during service hours. It is pertinent to point out that out of the five selected churches, St Venera parish church is the only church that does not have an *antiporta*.

Similar results were attained in the Fgura parish church however with fewer votes for 'too much air movement' (26.7%) and more votes for 'insufficient heating' (21.7%). This difference in percentages is mainly attributed to significantly higher percentage of relative humidity together with lower indoor recorded temperatures, which in turn results in an overall cooler indoor ambience.

3.7. Suggestions from Parishioners

According to Table 3, suggestions taken during the summer once again confirmed that the Balzan parish church was the most thermally comfortable out of all the parish churches under study since most of its parishioners selected 'no suggestion' (81.7%), as shown in Column 1 of Table 3 (Qty. 49). Only nine votes were registered suggesting an 'air-conditioner'. It is pertinent to point out that Balzan parish church, such as that of Sliema, has already installed an air-conditioning system. This was intermittently operational on the day the TSS was conducted in Balzan, resulting in cooler temperatures and more comfortable indoor conditions. The fact that some parishioners still suggested the use of 'air-conditioning' may be attributed to the need for more frequent use, lower set temperatures or better positioning of the indoor units.

On the other hand, votes for the 'air-conditioner' were more pronounced in the Sliema parish church with a total of 36.7%, as shown in Column 2 of Table 3 (Qty. 22). It is pertinent to point out that although Sliema parish church is equipped with an air-conditioning system, this was not operational on the day of the TSS. Nonetheless, a number of occupants still felt that the overall ambience of the church was thermally comfortable since a total of 46.7% votes (Qty. 28) were given to 'no suggestion'. This is in accordance with the findings portrayed in Figure 6, whereby Sliema ranked as being the second most thermally comfortable out of the Baroque parish churches under review. On the other hand, the main sources of discomfort were 'insufficient air movement' and 'insufficient cooling'. This explains why occupants felt the need to vote for making use of air conditioners, which though installed are only used occasionally.

The Msida parish church ranked just below St Venera parish church in terms of 'no suggestion' with a total of 31.7% and 35%, respectively, as shown in Columns 3 and 4 of Table 3 (Qtys. 19 and 21). This result deviates significantly from the established ranking of indoor thermal comfort (refer to Figure 6), where the Msida parish church showed to be much more thermally comfortable than the St Venera parish church. However, when it came to the sources of discomfort, the Msida parish church had a significantly greater number of votes for 'insufficient air movement' than the St Venera parish church, which explains why many occupants selected 'fans' (28.3%) and 'air conditioner' (25%) in their

suggestions. Moreover, it must be noted that only 3% of glazing area openings were being used in the Msida parish church, which further explains why quite a considerable number of occupants also opted for 'open windows/doors' (15%).

Out of the contemporary parish churches, the St Venera parish church had more votes for 'no suggestion' than the Fgura parish, with votes ranging from 35% to 20%, respectively. Once again, St Venera parish church ranked as being more thermally comfortable.

With regards to the suggestions given by parishioners, the St Venera parish church had a significantly high percentage of occupants voting for 'curtains/blinds' (36.7%) and much fewer votes for 'air-conditioner' (18.3%) and 'fans' (10%), as shown in Columns 4 and 5 of Table 3. On the contrary, the suggestions for 'air-conditioner' (50%) and 'fans' (28.3%) spiked in the Fgura parish church, whereas votes for 'curtains/blinds' (1.7%) were insignificant. The reason behind this result is associated with the fact that curtains/blinds are not practical for triangular-shaped inclined apertures, such as those of the Fgura parish church. In fact, though the latter has a higher window-to-wall ratio when compared to the St Venera parish church and thus is exposed to a higher degree of sunlight, votes for curtains/blinds were close to none. Hence, installing air conditioners or fans was seen to be a more practical solution for this church. Contrastingly, the St Venera parish church's glazing design is traditional to the Maltese urban landscape, and therefore installing vertical curtains/blinds was seen by most occupants as a feasible solution.

In winter, the ranking of 'no suggestion' (refer to Table 3) voting of all the parish churches portrays a similar trend to the obtained results in thermal comfort ranking (refer to Figure 6) and sources of discomfort (refer to Table 2).

In the Balzan parish church, there were no votes for 'no suggestions' and a greater percentage of votes for 'heaters' (38.3%), 'dehumidifiers' (33.3%) and 'close windows/door' (25%), as shown in Column 1 of Table 3. These results are in tandem and correlate with other findings in this regard. Since the Balzan parish church has a very high percentage of indoor relative humidity and a low indoor temperature, with the highest values for humidity in the masonry walls due to rising damp out of all RBs (refer to Table 1), the overall thermal ambience of the church is cold and humid. Thus, votes for heaters and dehumidifiers to be installed in the church are coherent. Moreover, parishioners stated that there was a relatively high degree of 'too much air movement' (26.7%) within the church, which explains why 25% of occupants selected 'closed windows/door'.

The Sliema parish church had the highest percentage for 'no suggestion' (75%) and a few votes for 'heaters' (18.3%), as shown in Column 2 of Table 3. This reflects the fact that this church is overall thermally comfortable with very few occupants stating otherwise. Similarly, the Msida parish church also had a high percentage of votes for 'no suggestion' (66.7%) followed by fewer votes for 'heaters' (13.3%), 'close windows/doors' (13.3%) and 'dehumidifier' (6.7%), as shown in Column 3 of Table 3. This result confirms that the Msida parish church is also overall thermally comfortable, with minimal non-invasive intervention, such as closing windows/doors proving sufficient.

The St Venera parish church had the lowest 'no suggestion' voting (31.7%) out of the contemporary churches. Moreover, 33.3% of its occupants selected 'close windows/doors'. This correlates with the high percentage achieved for 'too much air movement' as a result of the missing *antiporta*, conceivably further aggravating the cold ambience of the church, for which 20% of the occupants voted as 'cold ambience'. Coherently, 26.6% of the occupants selected 'heaters' to rectify.

The results for the Fgura parish church were similar to those of the St Venera parish church, with an increase in votes for 'no suggestion' (46.7%) and 'heaters' (50%). This may be attributed to the fact that there is a significantly higher percentage of indoor relative humidity and a low indoor temperature, hence creating an overall colder environment.

Table 3. Showing the different suggestions in the different parish churches in both summer and winter.

Season	Suggestions	Parish Church				
		Balzan	Sliema	Msida	St Venera	Fgura
Summer	Curtains/blinds	0	1	0	22	1
	Air-conditioner	9	22	15	11	30
	Open windows/doors	0	0	9	0	0
	Fans	2	9	17	6	17
	No suggestion	49	28	19	21	12
Winter	Heaters	23	11	8	16	30
	Curtains/blinds	2	0	0	0	2
	Dehumidifier	20	2	4	4	0
	Close windows/doors	15	2	8	20	0
	No suggestion	0	45	40	19	28

$$X^2(16) = 178.98, p < 0.001 \text{ (Summer)} \quad (13)$$

$$X^2(16) = 177.83, p < 0.001 \text{ (Winter)} \quad (14)$$

where the number in brackets is the degrees of freedom ($df = (\text{Rows} - 1) \times (\text{Columns} - 1)$) and the value for $X^2(df)$ is the chi-squared value.

4. Conclusions

Results attained through mathematical statistics from thermal sensation surveys, recorded indoor temperature and relative humidity conclude that a significant correlation exists between the actual thermal comfort levels measured according to EN 16798-1 standard and that expected by the occupants in most of the parish churches under evaluation for both summer and winter.

Baroque churches were found to be overall more thermally comfortable than the contemporary churches in both summer and winter due to their differences in construction methodology and building envelope. Moreover, the difference between indoor radiant and air temperatures was found to be insignificant.

With regards to physiological factors taken into consideration, results show that females tend to feel more thermally comfortable than males in warmer climates and that older generations tend to feel more thermally comfortable in warmer rather than colder environments.

A number of parishioners recommended mechanical means of air-conditioning to improve the thermal ambience in both summer and winter. The use of a combination of natural and mechanical ventilation may improve the adaptation conditions of occupants. However, though a hybrid system could be considered, one must be concerned about the consequences of this decision, such as energy costs, its effect on building material and artefacts and its carbon footprint. It is understandable that today's comfort expectations have increased significantly; however, it must also be appreciated that the use of places of worship is mainly intermittent and air-conditioning systems may not always be justified.

The use of passive measures through better use of operable apertures and shading was also strongly highlighted by parishioners. These mainly referred to feasible options to optimise on orientation in controlling solar gains, natural ventilation and the effective use of the building envelope to decrease extreme internal temperatures. Based on the human interaction with the built environment, these suggested passive measures, which have the potential to satisfy comfort expectations and are critical to achieving a lifetime of thermal comfort, should first be considered prior to any mechanical means.

This true understanding of occupants' thermal comfort requirements provides unprecedented first-hand information about occupants' diversities of thermal sensations and dynamic behaviour adaptations to the intricate environment within churches. Analysis of

the sources of discomfort and suggestions made by the occupants' revealed how passive design solutions help enhance indoor thermal conditions, within issues portrayed, while reducing energy demands and eventually carbon emissions. This information provides assurance for optimised decision-making methods, used to generate accurate solutions for policy-makers, architects and engineers, with an understanding of practical applications of passive measures for places of worship.

Limitations

Whilst these RBs served as typical buildings to represent differences between Baroque and contemporary parish churches, it is pertinent to point out that the outcome might not be applicable to all parish churches on the Maltese islands.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

RB	Reference Building
TSS	Thermal Sensation Survey
CTS	Current Thermal State

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