Dynamic evaluation method for assessing households' thermal sensation using parametric statistical analysis: A longitudinal field study in the South-eastern Mediterranean climate

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Abstract. Climate change is causing a wide range of impacts, including more frequent and brutal climate events, such as long-term heatwaves while compound effects of extreme weather events can dramatically disrupt indoor thermal conditions, causing increased mortality risks, especially for vulnerable populations with health conditions. Comfort standards do not give clear guidelines to determine the minimum or ideal range of continuous measurements, considering the climate change projections to determine neutral thermal comfort thresholds in 2030s, 2050s and 2080s. The aim of this study is to evaluate the predictive skills of existing long-term thermal comfort indices from the ASHRAE RP-884-II database and to propose new indices based on continuous, in-situ physical environmental measurements and subjective evaluations of social householders in naturally ventilated multi-family houses in the South-eastern Mediterranean basin. A meta-analysis of ASHRAE Global Thermal Comfort Database II showed that the acceptable temperatures extend across a wide range of conditions and vary depending on building type and climate. The results revealed that the Predicted Mean Vote (PMV) is the upper limit in ASHRAE standard-55's 0.5 clothing value (*clo*) summer comfort zone stretches all the way to 27°C at 50% relative humidity with air speeds below 0.2 m/s. The results prove that the neutral mid-point of the summer comfort zone is at about 25.5°C regardless the neutral temperature was 28.5°C, and the upper limit of the comfort range in warm indoor air temperature conditions was 31.5°C in the South-eastern Mediterranean region. Our analysis reappraises the scope of applicability of the adaptive comfort standard, assess potential regional differences by considering the detrimental impact of climate change in adaptive thermal comfort responses, and propose mitigation strategies to adaptive comfort theory, the adaptive comfort model and standard and sustainable building design. Finally, we suggest that building operations should better regulate occupant's psychological behaviour to adapt to warmer indoor conditions by implementing adaptive comfort algorithms to optimise occupants' thermal comfort against the warming climate conditions. This could lead to improving energy performance of naturally ventilated buildings without sacrificing the occupant comfort.

Keywords. Adaptive model, ASHRAE database, Climate change, Thermal comfort, Thermal history
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1. Introduction

1.1 Knowledge Gap

The provision of thermal comfort for building occupants stands out as one of the largest end-uses of energy in the built environment, bearing significant responsibility for greenhouse emissions (GHG) and their destabilising effects on our global climate system. One of the more common architectural answers to these challenges is climate-responsive or passive design of buildings where natural ventilation (NV) is substituted for mechanical conditioning to deliver comfortable indoor environments while at the same time minimising the energy demand for heating, ventilation, and air-conditioning (HVAC).

In light of the changing landscape of adaptive thermal comfort research over the last two decades, and the release of the ASHRAE Global Thermal Comfort Database II - into the public domain, a follow-up analysis of the adaptive concept seems timely. The availability of a large volume of new data from diverse climatic and regional contexts provides an opportunity to revisit the original ASHRAE 55 adaptive comfort standard. Typical of that era is the 'neutral' adaptive thermal comfort model developed for detailed and more reliable (evidence-based) thermal comfort studies that would go on to form the ASHRAE RP-884 database, from which the first adaptive thermal comfort standard.

Comfort standards do not give clear guidance to determine the minimum or ideal range of continuous in-situ physical measurements of indoor environment conditions of buildings. Long-term assessment criteria found in ISO 7730 (ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) indices and local thermal comfort criteria), EN 16798 (energy performance of buildings - ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics) and ASHRAE 55 Standard simply state that the environmental monitoring (EM) period should be representative of the in-vivo experience of longitudinal field studies. Given that most of the existing indices found in current international comfort standards do not correlate well with long-term thermal satisfaction, there is a need to propose new thermal comfort thresholds for benchmarking criteria that better forecast occupants' evaluations of indoor environments.

None of the previous studies in the literature review demonstrated clear impacts of thermal history and expectations on thermal comfort in buildings that are shared by multiple occupants who have grown up in diverse climate conditions. Whilst the general adaptive principle has been repeatedly demonstrated across diverse settings world-wide, region-specific adaptive models are not universally applicable. ASHRAE's Standard 55 adaptive thermal comfort model and the European Union counterpart of EN 15251 were transformative because of their generalisability, the empirical basis of which was vastly more comprehensive than anything preceding the development of 'neutral' adaptive thermal comfort for each region across the world.

1.2 Study Focus

This study will leverage the largest global thermal comfort database to date, and explore the effects of available demographic, contextual factors and their interaction effects on building occupants' thermal sensation in the indoor environment, aiming to contribute to the current understanding of drivers of diversity in human thermal perception. The aim of this study is to reappraise the scope of applicability of the adaptive comfort standard, assess potential regional differences in adaptive comfort responses, and propose nudges to adaptive comfort theory, the adaptive comfort model and standard, and building design and operational conventions.

In the interest of nudging on current understanding of adaptive theory, the existing adaptive comfort model, and the application of adaptive principles to building operational strategies, the objectives of this study are as follows:

- To assess differences in adaptive comfort principles across broad regions of the world;
- To provide an evidence-based methodological workflow to extend the limits of applicability of the adaptive comfort model beyond naturally ventilated buildings as currently specified in ASHRAE Standard 55-2021;
- To develop the potential for nudging building optimisation strategies to incorporate adaptive comfort theory as an energy-reduction strategy.

This study addresses the following research questions: "Is there any relationship between thermal comfort perception and long-term thermal history in environments accommodating occupants with diverse climatic backgrounds?" and "How does the occupant's climatic background (long-term thermal history) influence their in-the-moment thermal comfort assessments inside their condominiums in different climate characteristics worldwide?".

2. Literature Review

This section reviews previous scholars' thermal comfort assessment criteria to provide thorough guidance for the development of "neutral" adaptive thermal comfort thresholds in the South-eastern Mediterranean climate of Cyprus. Scholars have applied and developed different methods of design to measure occupants' thermal sensation in order to identify their PMV, but none of these scholars have clarified the differences between the selection of thermal sensation as either an ordinal or continuous variable type, or they haven't accurately undertaken parametric statistical analysis in the building engineering field.

In the present study, throughout the development stages of the statistical analysis, it was found that the differences between ordinal and continuous variable types of thermal sensation should be addressed. This is supported by the conventional methods of design applied by previous studies on thermal comfort, as listed in **Tab. 1**.

Tab. 1 - Worldwide Studies on Thermal Comfort Assessment.

References	Sample Size	Statistical Method	Thermal Comfort Assessment
Rupp *et al.* (2021) [1]	Data extracted from the ASHRAE Global Thermal Comfort Database II (n = 107,583).	Regression coefficient	Griffiths constant/occupant's thermal sensitivity theorem applied.
Wang *et al.* (2018) [2]	Three different experiments were conducted in the climate chamber by using a discrete scale of 2 votes per subject, a discrete scale of 5 votes per subject, and a continuous scale for thermal sensation and satisfaction with 5 votes per subject.	- Frequency statistics - Normalised standard uncertainty - Descriptive statistics - Box plot distribution - Bar chart distribution	Humphreys and Nicol's (2002) theorem was applied by investigating subject respondents' PMV and PPD.
Haldi and Robinson (2008) [3]	- A dataset of some 5,908 entries from 60 participants was used. - The dataset was built on a comprehensive longitudinal field survey conducted during the warm summer of 2006.	- Histograms were used for the distribution of temperature measurements in the database. - Logistic regression techniques were used. - G-statistics differences were reported by using Nagelkerke's statistical tradition.	Nicol and Humphreys's (2004) theorem was applied to assess occupants' thermal comfort votes.
Haghighat and Donnini (1998) [4]	A total of 877 subjects participated in the questionnaire survey during the summer and winter of 1996.	- Descriptive statistics - Pearson's correlation coefficient - Bar chart diagram distribution	ASHRAE Standard 62-89R and ASHRAE Standard 55-92 were used for the benchmarking criteria.
Brager *et al.* (2004) [5]	A total of 1,000 survey responses were integrated into the dataset.	- Descriptive statistics - Scatter plot diagrams - Bar chart distribution - Linear regression analysis - Histograms	ASHRAE RP-884 and ASHRAE RP-1161 datasets were used for the benchmarking criteria.

Many scholars have debated the identification of accurate statistical analysis criteria for the convention of the initial thermal comfort assessment scale that was developed by Bedford in 1936. This assessment used a 7-point Likert scale and was later applied and proved by Fanger in the 1970s; it has since become the widely used conventional method of design, and was applied, among others, by Griffiths in the 1990s. Its scale was also made popular by Nicol in the 2000s and since then many top-notch scholars in thermal comfort research, such as Brager in 2008, de Dear in 2010 and Parkinson in 2016, have continued developing this reliable thermal comfort assessment criterion based on the conventional methods of design applied and developed by previous scholars.

De Dear in 2010 and Parkinson in 2016, as well as their colleagues in thermal comfort studies, established the ASHRAE Global Thermal Comfort Databases I and II. This open-source international global database allows researchers to identify the appropriate method of thermal comfort assessment criteria for their studies (i.e. using thermal sensation as either an ordinal or continuous variable).

Rupp *et al.* published an article in 2021 entitled "The Impact of Occupants' Thermal Sensitivity on the Adaptive Thermal Comfort Model". In this paper, 107,583 samples were extracted from the ASHRAE Global Thermal Comfort Database II to conduct a regression analysis using a p-value of < 0.001 to determine the significance factor within the variables. Rupp *et al.* (2021) used the [-3, +3] thermal comfort assessment criteria as a continuous variable to run statistical analysis with in-situ measurements (i.e. indoor operative temperature and indoor air temperature) [1].

Wang *et al.* (2018) stress that the use of different measurement criteria in thermal comfort studies has led to misunderstandings when interpreting the findings in accordance with statistical conventions [2]. To avoid any further misunderstanding by the scholars who are not experts in thermal comfort studies, Wang *et al.* (2018) recommend the most appropriate thermal sensation assessment criteria as shown in **Fig. 1**.

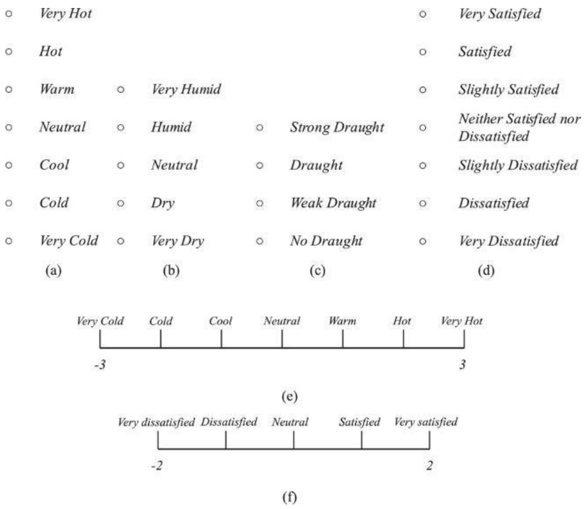

Fig. 1 - Thermal sensation scale on the questionnaire. (a) 7-point discrete thermal sensation scale; (b) 5-point discrete humidity sensation scale; (c) 4-point discrete draught sensation scale; (d) 7-point discrete thermal sensation scale; (e) 7-point continuous thermal sensation scale; (f) 5-point continuous thermal sensation scale. Source: Wang *et al.* (2018)

Wang *et al.* (2018) used a climate chamber to control thermal variables and determine the most appropriate design for their thermal sensation scale. They provide a list of the acceptable variable types to be used when assessing any type of variable related to thermal comfort studies, which is shown in **Tab. 2**.

Tab. 2 - Variables for Thermal Comfort Assessment.

Subjective thermal indicators	**Points on rating scale**	**Subjective rating scale**
Thermal sensation	Fig.2 (a)	Discrete
Humidity sensation	Fig.2 (b)	Discrete
Draught sensation	Fig.2 (c)	Discrete
Thermal satisfaction	Fig.2 (d)	Discrete
Thermal sensation	Fig.2 (a)	Discrete
Thermal satisfaction	Fig.2 (d)	Discrete
Thermal sensation	Fig.2 (e)	Continuous
Humidity sensation	Fig.2 (b)	Discrete
Draught sensation	Fig.2 (c)	Discrete
Thermal satisfaction	Fig.2 (f)	Continuous
Source: Adapted from Wang *et al.* (2018)		

Haldi and Robinson (2008) conducted a longitudinal field survey to assess occupants' thermal comfort [3]. They conducted a multiple logistic regression analysis to identify neutral adaptive thermal comfort; the assessment criteria were presented by using the thermal scale band [-3, +3]. Another pilot study was conducted by Haghighat and Donnini (1998) to investigate the psycho-social factors affecting occupants' thermal sensation by using in-situ measurements of indoor air environment conditions [4]. They used descriptive statistics to report the monitored indoor air environment conditions by using the continuous variable type. Haghighat and Donnini also used Pearson's correlation analysis to measure occupants' thermal sensation and the measured/recorded variables for their statistical analysis. In their study, occupants' thermal sensation was coded by using the conventional tradition of [-3, +3] parameters. Additionally, Haghighat and Donnini (1998) presented the questionnaire survey items set out as ordinal variables in bar chart formatting to demonstrate the survey findings according to their research hypothesis.

Brager *et al.* (2004) conducted a longitudinal survey by using a sample size of 105 for the warm season and 93 for the cool season to assess occupants' thermal sensation [5]. By using this method, they were following a similar method of design to that developed by Haghighat and Donnini (1998) to report on-site measurement findings by using the EM dataset as a continuous variable and occupants' thermal sensation votes coded as a continuous variable ranging between -3 and +3 for accuracy in their linear regression analysis.

The present study follows the conventional method of design that was developed and conducted by previous scholars. To identify the neutral adaptive thermal comfort thresholds in the South-eastern Mediterranean climate of Cyprus, it codes thermal sensation as [-3, +3] and conducts a Pearson's correlation analysis. The following section presents the stages of data collection undertaken to assess domestic energy use and occupants' thermal comfort in this longitudinal field study.

3. Materials and Methods

This section presents the research methodology by explaining the rationale of the research hypotheses, aims and objectives. It illustrates the case study and explains the research design model adopted to approach the research problem. It also explains the selection criteria of base-case representative residential tower blocks (RTBs) and presents the data collection methods used, the field work procedures and the data analysis and interpretation. The present study fully explains the mixed methods research design approach through three different sets of methods developed before stating some limitations of the study.

The outdoor air temperature (OAT) and relative humidity (RH) levels of the environmental conditions were monitored between July 28 and September 3, 2018 to assess the overheating risk issues of the flats interviewed and measured in this research context. This monitoring period overlapped with the 2018 heatwave period, during which the Meteorological Office of Cyprus recorded the highest temperatures across Europe since 1976 [6]. The outdoor thermal conditions, including the outdoor air temperature, relative humidity and heat stress index, were monitored by a Wireless Vintage Pro 2 weather station from Davis Instruments. The monitoring of OAT and RH levels in the case study provides an in-depth understanding of the indoor environment conditions and validates the results from a simulation analysis of the occupied spaces in which the measured rooms reported relatively high indoor temperatures inappropriate for their occupants' thermal comfort [7].

The indoor air temperature (IAT) was recorded using a thermometer (resolution 0.1°C), the globe temperature was recorded using a globe thermometer, which is a 15 cm diameter thin-walled copper sphere painted black (resolution 0.1°C), the relative humidity was recorded using the Heat Stress WBGT Meter model HT200 by Extech Instruments (resolution 0.1°C) and the black globe temperature (TG) was recorded. In order to validate these findings, additional spot measurements were carried out using a forward-looking infrared radiometer (FLIR) infrared thermographic camera to assess the occupants' decisions on thermal comfort preference votes (TPVs) and thermal sensation votes (TSVs) [8].

This section discusses the spaces in which the occupants mostly spent their time at home, the warmest space in summer, and the occupants' thermal comfort experience in the interviewed flats; the significant variables strongly correlate with the occupants' thermal comfort. At the same time, additional comments on several aspects of the measured IAT and RH of the households' living rooms were considered in relation to the questionnaire results. During the questionnaire survey, the households in the interviewed and measured RTBs were selected randomly, based on a door-to-door survey. Correlations among the different parameters were calculated using SPSS version 28, and the significance level of the analysis was set to both $p < 0.01$ and $p < 0.05$. This means that the statistical results were significant at the indicated p-values for the questionnaire variables. First, a descriptive analysis was used on the interview findings to report the occupants' reasons for discomfort, taking into account the building orientation and floor level differences to assess the overheating risk of the interviewed and measured flats. Then, correlation analysis methods were used on the findings to evaluate the correlations between different parameters, and for this, Pearson's rank correlation analysis (two-tailed) was conducted.

4. Analysis and Results

This section focuses on linking all the results from both the general survey and thermal comfort survey findings, on-site environmental monitoring, in-situ measurements, as well as findings from the overheating analysis, to understand the current energy performance of the flats and the thermal comfort of their occupants. The outcome of the EM carried out at the social housing development estate during the summer conditions is presented. The variables measured during the survey are discussed in order to understand the environmental conditions of measured flats for assessing their occupants' thermal comfort level and the risk of overheating experienced in summer. Furthermore, the findings of the accelerators used to measure the air temperature and relative humidity of the occupants' living room spaces are highlighted.

4.1 Questionnaire Survey Findings

Questionnaires were administered to the occupants of the measured flats. Out of 200 questionnaires distributed to the households in the 36 RTBs across the social housing development, 100 of them were successfully completed. A breakdown of the completed questionnaires shows that 36% of them were returned from south-facing blocks, 33% from northeast-facing blocks, 18% from southwest-facing blocks, 11% from southeast-facing blocks, and 4% from northwest-facing blocks. Of the households, 18% were recruited from ground floor flats, 28% were from the first floor, 19% were from the second floor, 3% were from the third floor, 23% were from the fourth floor, and 9% were from fifth-floor flats. Of the completed questionnaires, 33% male and 67% female responses were received. An analysis of age distribution votes across the interviewed households suggests that 48% of the respondents were between 55 and 65 and 65 or over, as shown in **Fig. 2** a, b and c, respectively.

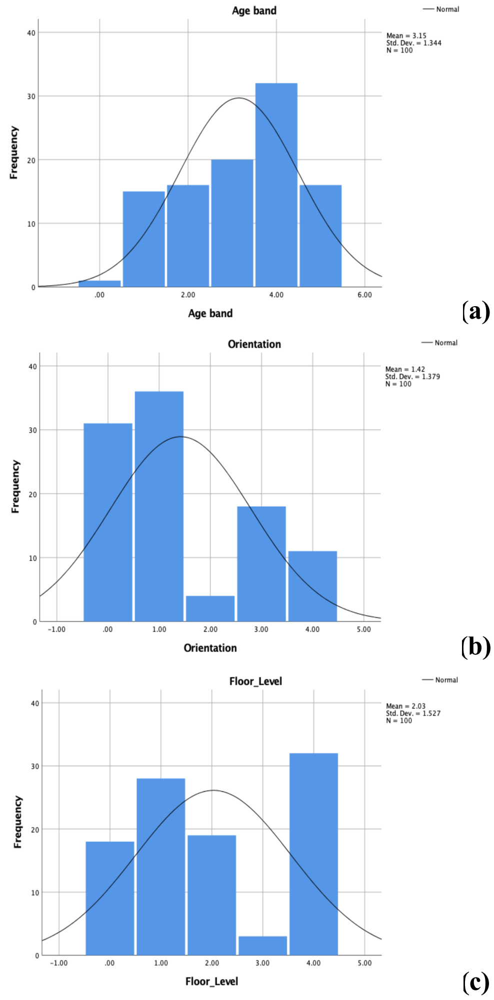

Fig. 2 - (a) frequency distribution of the households' age

groups; (b) frequency distribution of the households' age band, taking into consideration the RTBs' orientation; (c) frequency distribution of the households' age band, taking into consideration the flats' floor level differences; the households' age band scale runs from 0 "20–25" to 5 "65 or over;" the recruited households from different orientations with the age band scale runs from 0 "northeast" to 4 "southeast;" the recruited households from the floor level differences with the age band scale runs from 0 "ground" to 4 "fourth". **Tab. 3** highlights the frequency and percentage of age distribution from the questionnaires from the households.

Tab. 3 - Age distribution of the thermal comfort survey questionnaires returned from the RTBs.

	Age frequency distribution					
Orientation	**20-25**	**25-35**	**35-45**	**45-55**	**55-65**	**65 or over**
Northeast	1	8	4	4	9	5
South	0	6	8	9	6	7
Northwest	0	0	0	0	3	1
Southwest	0	0	2	4	10	2
Southeast	0	1	2	3	4	1
Total	1	15	16	20	32	16

Floor level	**20-25**	**25-35**	**35-45**	**45-55**	**55-65**	**65 or over**
Ground	0	1	2	2	10	3
First	1	2	3	7	9	6
Second	0	4	5	3	3	4
Third	0	1	1	0	0	1
Fourth	0	7	5	8	10	2
Total	1	15	16	20	32	16

The distribution of occupancy type and responses indicate 84% ownership status and 16% private tenancy status. These response rates according to the different tenure types indicate that ownership status may influence the occupants' perceptions of the thermal environment. The occupancy duration of the residents in the interviewed flats indicates that 14% of the households have been living in their flats between 2 and 5 years while the majority of the residents in the development have been living there for more than 10 years as of the time of the survey. The responses also indicate that the southwest-facing block, number 21, which was built in phase two in the 1990s, has the highest density of occupants per household in the RTBs. This may be a result of the location of the block and the tenancy status available in the interviewed flats as most of the residents in number 21 were either private housing owners or private renters.

This section presents the second phase of the questionnaire in line with the interpretation of the general survey findings that emerged from the first phase of the study. The main survey results are discussed, focusing on the topics presented in **Tab. 4**. From the survey findings, the mean average age of the households was 51.37 years old; the oldest surveyed household member was 84 years old and the youngest was 23 years old. In addition, the number of rooms examined in the residences ranged between 2 and 5 rooms; most of the households participating in the survey had 5 rooms, which they mostly occupied on weekdays and at weekends. In the 20 blocks examined, there were five-storey buildings and 15 four-storey buildings; 32 flats were located on the ground floor, 32 flats were on the fourth floor (top floor flats), and 40 flats were on the fifth floor (top floor flats). Finally, a noteworthy result emerging from the survey is that most of the flats do not have any form of insulation.

In this survey, the households' types of heating and cooling systems were examined. Most of the households were using combinations of heating and cooling systems to achieve better thermal conditions in their properties [9]. Furthermore, they preferred to use each available system based on their needs to improve their thermal comfort and achieve maximum energy savings. Therefore, it was found that there were a lot of adaptive solutions developed by the elderly households in their properties to withstand the cold winters and extremely hot summers in these inefficiently built RTBs in this particular Mediterranean climate.

In the general survey findings, it emerged that in the heating season, most of the households used heating systems that were gas cylinder domestic appliances (frequency = 32), wall-mounted air-conditioning systems (frequency = 7) and wood-burning stoves (frequency = 5). From these results, it can be seen that gas cylinder heaters proved to be the most commonly used energy to supplement the main heating system in most of the flats; these are used because they are a high-temperature and affordable heat source, but they are not fuel-efficient or low-carbon heating systems. In addition, wood-burning stoves as well as wood and oil biomass heating with other systems (wall-mounted air-conditioning systems, wood burners, oil-fired heaters etc.) were used in all but 21% of the households, where portable electrical heaters were the main heating system.

In the cooling season, the most commonly used cooling systems were portable fans (frequency = 28) and wall-mounted air-conditioning systems (frequency = 18); in two of the flats examined, there were no cooling systems used, either due to economic reasons or because the occupants stated that they did not need them (e.g. they spent more time sitting on the balcony or on an outdoor patio in the ground floor flats). It is worth noting that these social housing blocks are located in a densely built city centre, indicating the possibility of a different thermal experience in the cooling season for the elderly people and the homes with young children present. In addition, 39% of the households preferred to use both wall-mounted air-conditioning systems and portable fans for cooling purposes while in the rest of the homes, air conditioning with or without fans was used.

4.2 Relationships for the Identification of Thermal Comfort

Cross tabulations using chi-square analysis explored the reasons for thermal discomfort in respect to the household age, the orientation of the RTBs and the different floor levels in each occupied space based on the collected data from the respondents. This analysis was conducted because socio-demographic characteristics have been shown to be a significant factor in people's behaviour in any setting. Considering the age band in this cross tabulation analysis was necessary because nearly half (48%) of the households were in the 55–65 and 65-years-of-age and older age groups, it is important to consider the impact of age on thermal comfort in these measured flats.

In conjunction with households' socio-demographic analysis, the different RTB orientations and floor levels were taken into consideration. The results of interviews highlight that 24% of the occupants complained about high humidity in the southwest-facing RTBs in summer, and 17% complained about incoming sun. This indicated that the occupants may have experienced thermally uncomfortable conditions due to the high outdoor-air temperatures and humid conditions in this south-eastern Mediterranean climate. This became clear when the study determined that there were negative relationships between the occupants' reasons for thermal discomfort and the different floor levels for their respective flats, as shown in **Tab. 4**.

Tab. 4 - Relationships between reasons for thermal discomfort and household age band, RTB orientation, and floor level.

Research Question and Variables	Measure	Discomfort	Age Band	Orientation	Floor Level
Q 35: How would you best describe the source of this discomfort?	Cramer's V	1	0,203	0,405**	0,233
	Significance	—	0,416	<0,001	0,062
Age Band	Cramer's V	0,203	1	0,229	0,211
	Significance	0,416	—	0,202	0,347
Orientation	Cramer's V	0,405**	0,229	1	0,197
	Significance	<0,001	0,202	—	0,234
Floor Level	Cramer's V	0,233	0,211	0,197	1
	Significance	0,062	0,347	0,234	—

Household age band scale ran from 0 (20–25) to 5 (65 and over)
RTB orientation: 0 (north-east), 1 (south), 2 (north-west), 3 (south-west), and 4 (south-east)
Different floor levels: 0 (ground), 1 (first), 2 (second), 3 (third), 4 (fourth) and 5 (fifth)
Age band scale ran from 0 (20–25) to 5 (65 and over)
Reasons for thermal discomfort – Floor level, χ^2 (9) = 16,26, p = 0,062, Cramer's V = 0,233
Reasons for thermal discomfort – Orientation, χ^2 (9) = 49,33, p = 0,000, Cramer's V = 0,405
Reasons for thermal discomfort – Age bands, χ^2 (12) = 12,38, p = 0,416, Cramer's V = 0,203
Age bands – Floor level, χ^2 (12) = 13,31, p = 0,347, Cramer's V = 0,211
Age bands – Orientation, χ^2 (12) = 15,77, p = 0,202, Cramer's V = 0,229
Orientation – Floor level, χ^2(9) = 11,65, p = 0,234, Cramer's V = 0,197

As shown in **Tab. 4**, the results indicate a moderate-strong relationship between orientation and reasons for thermal discomfort (χ^2 = 49,327, p < 0,001, Cramer's V = 0,405). A greater proportion of participants living in south-facing RTBs felt thermal discomfort due to humidity than participants living in the southwest. A greater proportion of participants living in the southwest selected incoming sun as thermal discomfort than participants living in the other areas; this was due to the poor window design in the RTBs, which prevented NV into the indoor occupied spaces. This led to a difference of 2–3°C between the ground and upper floor level flats due to a lack of NV and as a result the upper floor receives the intense horizontal radiation on the roof surfaces. Thus, it appeared that the occupants' habitual adaptive behaviour in window-opening patterns also played a crucial role in their TSV decisions. Nevertheless, reasons for thermal discomfort were not significantly related to age and floor levels. From the field survey results, it was found that the occupants were very dissatisfied with their thermal environment in summer, with the highest levels of dissatisfaction in the south- and southwest-facing RTBs. The mean distribution of votes suggests that occupants were dissatisfied with their thermal environment in the winter, at more than two-thirds (34%) of participants, indicating a slightly uncomfortable indoor environment in their flats. However, the highest level of dissatisfaction during winter was observed in the northeast-facing RTBs, particularly on the first and top floor flats, and there was a positive strong correlation found between occupancy hours and TSVs in the winter ($r = 0.540$, $p < 0.01$). Comparing overall thermal comfort in the winter and taking into consideration the RTBs' orientation differences, there was no significant correlation found, but a negative moderate correlation was found with floor level differences in summer ($r = -0.244$, $p < 0.05$) as occupants in the ground floor flats were slightly more comfortable in the indoor occupied spaces in summer than the occupants living in the top floor flats. It is noteworthy to mention that building occupants are likely to spend most of their time in the spaces that provide the best environmental living conditions [6]. From the survey results, 62% of the respondents indicated that they mostly spent their time in the living room while 69% of the respondents reported the bedroom as the warmest space across the interviewed and measured flats, with the highest number of responses coming from the south-facing RTBs, at 26%. A comparison of the findings from the surveys suggests higher thermal satisfaction of the occupants in the south-facing RTBs than the households who lived in the upper floor flats despite the higher temperatures observed in the southwest-facing RTBs. In addition, it is concluded that overheating occurs in these flats, and the occupants were thermally dissatisfied due to the higher indoor air temperatures observed in the RTBs in summer. Overall, the respondents indicated a preference to be much cooler in summer when the outdoor air temperatures increase.

5. Conclusions

The output of this work can contribute to identifying the thermally comfortable and energy efficient environmental criteria for the development of evidence-based passive cooling design strategies by selecting archetype housing stock as base-case scenario development. Furthermore, information on the thermal comfort requirements of different climatic background groups can help to suggest appropriate environmental and design solutions, which can offer a comfortable and satisfactory thermal environment. To test the research hypothesis that greater adaptive opportunities in buildings is associated with a wider range of indoor temperature (i.e. wider comfort zone), statistical analysis would be applied to the development of an adaptive model defining the comfort zone of each climatic region across the world. The results support the development of the long-term thermal history for the adaptation of human's physiological body adaptation.

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Data Access Statement: The datasets generated during and/or analysed during the current study are publicly available at - https://repository.uel.ac.uk/item/89zv1

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