

Article

Occupants' Thermal Sensation in Mixed-Mode Buildings: The Contribution of Thermal Disposition to Interindividual Variability

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Abstract

Interindividual differences in thermal perception remain an important challenge for thermal comfort assessment, particularly in mixed-mode buildings. This study investigates interindividual variability in thermal sensation in a mixed-mode office building in southern Brazil, focusing on the explanatory contribution of thermal disposition. A secondary analysis was conducted using longitudinal field data comprising 2741 questionnaire responses from 159 participants. Indoor air and globe temperatures, relative humidity, and air velocity were monitored, and operative temperature was derived from these measurements. Linear mixed-effects models with participant-specific random intercepts were used to account for repeated observations. Operative temperature, thermal disposition, gender, building operation mode, and body mass index were progressively included as explanatory variables. Adding operative temperature to the baseline model significantly improved model fit (p -value < 0.001) and was positively associated with thermal sensation (fixed-effect coefficient $\beta = 0.157$, p -value < 0.001). Adding thermal disposition further improved model fit ($p < 0.001$), with this specification presenting the lowest Bayesian Information Criterion among the hierarchical models. Occupants classified as heat-sensitive according to their self-reported thermal disposition reported higher thermal sensation votes under comparable operative temperatures. Gender and building operation mode were also significant, whereas body mass index was not. Overall, thermal disposition contributed additional explanatory information on interindividual variability in thermal sensation.

Keywords: occupant-centred comfort; individual variability; linear mixed-effects models; thermal sensation; mixed-mode buildings



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1. Introduction

Occupants exposed to similar indoor thermal conditions frequently report different thermal sensations, indicating that thermal perception cannot be fully explained by environmental variables alone [1–3]. Although operative temperature is a major determinant of thermal sensation, considerable variability remains among individuals subjected to comparable thermal exposures. This heterogeneity reflects interactions between environmental exposure and physiological, psychological, demographic and contextual factors. Previous thermal experiences, expectations, behavioural opportunities, and perceived control may therefore contribute to differences in how occupants interpret the same thermal

environment [4–6]. Thermal comfort responses may vary substantially among individuals exposed to comparable environmental conditions [3]. This persistent interindividual variability highlights the importance of analytical approaches capable of distinguishing population-level relationships from systematic differences among occupants.

This individual variability becomes particularly relevant in buildings that allow occupants to actively modify their thermal environment [7]. In mixed-mode buildings, where natural ventilation and air-conditioning coexist, occupants can respond to their thermal preferences by operating windows, fans, or mechanical cooling systems [8,9]. Exposure to different operating modes may also involve different adaptive opportunities, thermal histories, expectations, and levels of perceived control [10,11]. Here, thermal history refers to an occupant's previous and repeated exposure to different thermal environments and conditioning modes, which may influence adaptation, expectations, and thermal tolerance. This differs from thermal disposition, which represents a general self-characterisation of being more sensitive to heat, cold, both, or neither relative to others. Therefore, mixed-mode buildings provide a particularly relevant context for investigating how environmental, individual, and operational factors jointly shape thermal sensation.

Statistical and mathematical thermal comfort models are widely used to estimate occupants' thermal responses and comfort conditions. Adaptive models, for instance, establish relationships between outdoor climatic conditions and indoor comfort temperatures based on occupants' responses under real building conditions [1]. Although these approaches have substantially advanced thermal comfort prediction, they are primarily designed to represent average responses at the population level. Consequently, the thermal responses and comfort requirements of individual occupants may differ from the population-level conditions represented by these models, particularly when occupants with different personal characteristics, thermal histories, and adaptive experiences are exposed to comparable indoor conditions [12]. Recent studies have also addressed uncertainty in thermal comfort prediction through probabilistic approaches, highlighting the influence of variations in microclimatic conditions and heat-transfer parameters on predicted thermal responses [13].

The adaptive Predicted Mean Vote (aPMV) model, for example, extends the conventional PMV framework by introducing an adaptive coefficient to account for occupants' adaptation to their thermal environment [14]. In this context, conventional Predicted Mean Vote/Predicted Percentage of Dissatisfied (PMV/PPD) approaches are discussed as a reference population-level heat-balance framework, whereas aPMV illustrates how adaptive influences can be incorporated into such models. However, neither PMV/PPD nor aPMV is applied in the present analysis; their relevance here is to contextualise modelling approaches that account for adaptation, while the present study focuses on persistent interindividual variability associated with thermal disposition. The Adaptive Thermal Heat Balance (ATHB) framework similarly integrates adaptive processes into heat-balance modelling through adjustments to parameters such as clothing insulation and metabolic rate [15].

Recent research has also considered a broader range of thermal comfort assessment criteria and building-performance metrics. Reviews of occupant comfort assessment have highlighted the use of PMV/PPD, adaptive approaches, and other thermal comfort indicators, while also emphasizing the relevance of integrating environmental and personal factors in comfort assessment [16]. In simulation-based building-performance studies, Thermal Comfort Percentage (TCP) has been used to quantify the proportion of time during which thermal conditions satisfy defined comfort criteria and has been incorporated alongside energy and daylight metrics in multi-objective assessments [17]. Other recent studies have similarly integrated thermal comfort with additional indoor environmental performance criteria in building-design optimization [18]. These approaches address

building-level or aggregated comfort performance, whereas the present study focuses on repeated individual Thermal Sensation Vote (TSV) responses and interindividual variability under measured indoor conditions.

These developments demonstrate increasing recognition that occupants' thermal responses cannot be fully represented by environmental conditions alone. Nevertheless, substantial interindividual differences may persist even among occupants exposed to comparable thermal environments, indicating that adaptation-based adjustments do not necessarily capture the full extent of individual heterogeneity [19]. This reinforces the need for analytical approaches capable of explicitly modelling differences among occupants and assessing the contribution of individual characteristics to thermal sensation. Accounting for interindividual differences is particularly important in longitudinal field studies involving repeated measurements from the same occupants, as observations are nested within individuals and may therefore exhibit intra-individual correlation [19]. Mixed-effects modelling approaches provide an appropriate framework for accounting for the hierarchical structure of thermal comfort data and distinguishing population-level associations from participant-specific variability [20]. It should be noted that no outdoor- or indoor-based adaptive comfort model was applied in the analysis shown herein. Adaptive models are discussed here only as theoretical context for approaches that incorporate occupant adaptation, whereas the present study focuses on interindividual variability using measured indoor operative temperature and individual and operational factors within a mixed-effects modelling framework.

Among the individual factors that may contribute to thermal heterogeneity, thermal disposition is particularly relevant. In this study, thermal disposition refers to an occupant's general self-assessment of being more sensitive to heat, cold, both, or neither relative to other occupants exposed to comparable conditions [21,22]. It should not be interpreted as a direct measure of physiological thermal sensitivity. In this manuscript, thermal sensitivity refers broadly to an individual's responsiveness to thermal stimuli and is not directly measured. Thermal sensation refers to the momentary perception of the thermal environment, assessed on the seven-point scale from -3 (cold) to $+3$ (hot), whereas thermal preference refers to the occupant's desired direction of thermal change at a given moment. Thermal disposition, in contrast, represents a general self-characterisation of being more sensitive to heat, cold, both, or neither relative to other occupants.

Because both thermal disposition and thermal sensation are self-reported constructs related to thermal perception, some conceptual overlap between them may exist. However, they represent different levels of assessment: thermal disposition reflects a general self-characterisation of the individual, whereas thermal sensation represents a momentary evaluation of the thermal environment under the specific conditions prevailing at each observation. Accordingly, the relationship investigated herein should be interpreted as an association between general self-perceived thermal disposition and repeated thermal sensation responses, rather than as evidence of a distinct physiological sensitivity to heat or cold.

Within this framework, thermal disposition may provide additional explanatory value for understanding persistent differences in thermal sensation that cannot be captured by environmental variables alone. Other individual characteristics, including gender and anthropometric factors such as Body Mass Index (BMI), have also been associated with differences in thermal perception and physiological responses, although their effects may vary according to environmental exposure and study context [19,23].

Empirical evidence from both field and controlled studies has shown systematic differences in thermal sensation and preference according to thermal disposition [24,25]. Studies conducted in Brazilian office buildings have similarly identified differences in

thermal sensation among self-reported thermal disposition groups under comparable environmental exposures [25]. However, previous research has primarily established associations between thermal disposition and thermal responses. It remains less understood whether thermal disposition provides additional explanatory information beyond operative temperature and whether this association persists when repeated observations and other individual and contextual factors are simultaneously considered.

Accordingly, the novelty of this study lies not in introducing thermal disposition as a new concept, but in evaluating its incremental explanatory contribution within a hierarchical mixed-effects modelling framework applied as a secondary analysis of an existing longitudinal field dataset. Operative temperature, thermal disposition, gender, building operation mode, and BMI were progressively incorporated while accounting for repeated observations and participant-specific variability. The study therefore aims to evaluate the contribution of thermal disposition to interindividual variability in thermal sensation and to determine whether its association with thermal sensation persists after demographic, operational, and anthropometric factors are considered.

2. Materials and Methods

This study is based on a pre-existing longitudinal field dataset and is therefore structured as a secondary analysis. To ensure that the analysis can be understood independently, the main characteristics of the original field campaign, data-collection protocol, participants, environmental measurements, and questionnaire procedure are described below. Previous publications based on the same field campaign are cited only to provide additional methodological background [25]; all information required to understand the data collection and analytical procedures used in this study is provided herein.

In summary, the methodological workflow of the study comprised: (i) longitudinal field data collection through repeated electronic questionnaires and simultaneous environmental measurements; (ii) temporal matching of the one-minute environmental records to each questionnaire response; (iii) screening of responses and preparation of the analytical dataset; and (iv) hierarchical linear mixed-effects modelling, followed by model comparison and interpretation of the results.

2.1. Study Context and Building Characteristics

This study is based on field data collected in the municipality of Florianópolis, southern Brazil (27.59° S, 48.54° W), which has a humid subtropical climate characterised by hot summers and mild winters. Mean annual air temperature reaches 20.7 °C, with average highs exceeding 28.0 °C and average lows near 16.5 °C [26,27].

The research was conducted in a rectangular office building with an approximate floor-plan area of 3090 m², distributed over five floors and one basement, with its main façade oriented to the south. The building has a reinforced-concrete structure and glazed façades composed of clear glass with an applied metallic film. The glazing is recessed from the façade, providing partial external shading. The office spaces are predominantly characterised by open-plan layouts with internal partitions and a ceiling height of approximately 2.6 m. The building accommodates approximately 250 occupants and is typically occupied between 8:00 a.m. and 6:00 p.m.

The office spaces analysed support mixed-mode operation through user-operable windows and individually controlled split-type air-conditioning systems. Portable fans were also available, providing occupants with additional opportunities to modify their immediate thermal environment according to individual preferences.

As this study is based on a secondary analysis of a pre-existing field campaign, original visual records of the building spaces and field survey setup were not available for systematic inclusion in this article.

2.2. Field Measurements and Data Collection

Measurements and data collection were carried out between April 2015 and February 2016, covering all four climatic seasons. The field studies were conducted during regular working hours, with data-collection sessions beginning at approximately 9:00 a.m. and 2:00 p.m. Indoor environmental variables and occupants' subjective responses were collected simultaneously. Subjective evaluations were obtained through electronic questionnaires administered on occupants' personal computers. At the scheduled times, the questionnaire application automatically opened a window containing the corresponding set of questions. Each session comprised six successive questionnaire rounds administered at approximately 20-min intervals, resulting in approximately 200 min of data collection per monitoring day.

The electronic questionnaire collected personal and anthropometric characteristics, including weight, height, age, gender, clothing, length of employment, and activity level. Information regarding individual habits and preferences, physical condition, preferences for natural or mechanical conditioning, and thermal history was also obtained. Real-time subjective assessments included thermal sensation, thermal preference, thermal acceptability, thermal comfort, and perceptions related to air movement and humidity. Thermal sensation was assessed using the standardized seven-point TSV scale, ranging from -3 to $+3$, with the categories defined as -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), $+1$ (slightly warm), $+2$ (warm), and $+3$ (hot), in accordance with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 [2]. TSV is a dimensionless ordinal response scale and therefore has no physical unit.

Indoor environmental variables, including air temperature, globe temperature, relative humidity, and air velocity, were monitored. During the 2015–2016 monitoring period considered in this study, four microclimatic stations equipped with dry-bulb temperature sensors, omnidirectional thermo-anemometers, capacitive relative humidity sensors, and 15-cm-diameter globe thermometers were used. ISO 7726 [28] was adopted as the reference for the measurement of the physical environmental variables and for the calculation procedures applied to the measured data. Sensors were installed 0.6 m above the floor—roughly abdomen height for a seated occupant—and logged readings every minute. For each questionnaire response, environmental measurements were matched to the corresponding observation time using the one-minute records collected by the microclimatic stations. Mean Radiant Temperature (MRT) was estimated from globe temperature readings following the ISO 7726 [28] calculation procedure. Measurement accuracy was reported as ± 0.1 °C for air temperature, ± 0.2 °C for globe temperature, $\pm 3.0\%$ for relative humidity, and ± 0.03 m/s for air velocity in the documentation of the original field campaign. Manufacturer and model information, complete measurement ranges, and original calibration records for the instruments were not available in the documentation accessible for this secondary analysis; therefore, only specifications that could be reliably verified from the original field documentation are reported. Operative temperature was subsequently calculated from air temperature and MRT following ISO 7726 [28] and considering the measured air velocity conditions.

2.3. Participants and Analytical Dataset

The analytical dataset comprised 2741 valid questionnaire responses from 159 participants, with repeated observations collected from the same occupants throughout the field campaign. Because participants could respond during multiple questionnaire rounds and

monitoring sessions, each participant contributed multiple observations over time. Participants contributed an average of 17.2 valid observations, with a median of 18 observations per participant and a range of 5 to 46 observations. Questionnaire responses were included in the analytical dataset when complete information was available for thermal sensation and the explanatory variables required for the corresponding model. The number of observations varied among participants, resulting in an unbalanced longitudinal dataset. This repeated-measures structure was explicitly considered in the subsequent statistical analysis by treating participant identification as a grouping factor in the mixed-effects models.

Thermal disposition was assessed through a self-reported questionnaire item asking participants to compare their self-perceived thermal responsiveness with that of their coworkers. The question was: “Compared with your coworkers, do you consider yourself to be:”, with four response options: (1) “more sensitive to cold”, (2) “more sensitive to heat”, (3) “sensitive to both heat and cold”, and (4) “little or not sensitive to either”. Each participant was assigned directly to the thermal disposition group corresponding to the selected response; no statistical cut-off, clustering procedure, or derived score was used. The item was included in the first questionnaire round of a field-study session and could therefore be answered on more than one occasion by the same participant over the monitoring period. For participants with repeated responses, the reported category remained consistent across assessments, and thermal disposition was therefore treated as a participant-level characteristic. This classification follows the procedure adopted by Rupp et al. [25] and is consistent with previous research treating thermal disposition as a subjective self-characterisation of thermal sensitivity [22].

Although based on a single self-reported item, thermal disposition was intended to represent participants’ general self-perceived thermal disposition rather than a physiological or psychometric measure. The consistency of repeated responses provides additional support for the stability of this self-classification over the monitoring period. The measure may reflect perceptual and psychological dimensions related to expectations, previous experiences, and comparisons with other occupants [29,30]. In contrast to the momentary TSV collected under specific environmental conditions, thermal disposition was used as a general occupant-level explanatory characteristic to investigate whether this self-perception was systematically associated with repeated thermal sensation responses.

The analytical framework considered TSV as the response variable. Operative temperature and building operation mode were treated as observation-level variables, whereas thermal disposition, gender, and BMI were treated as participant-level characteristics. Building operation mode was classified as natural ventilation or air-conditioning according to the prevailing conditioning mode at the time of each questionnaire response. Participant identification was included as the grouping factor to account for repeated observations and persistent interindividual differences in thermal sensation.

Additional variables recorded during the field campaign, including clothing insulation, metabolic rate, relative humidity, and air velocity, were retained to characterise the occupants and indoor thermal conditions but were not included as predictors in the pre-defined hierarchical modelling sequence. Clothing insulation and metabolic rate showed relatively limited variability in this predominantly sedentary office population, while relative humidity and air velocity were retained as environmental descriptors.

2.4. Statistical Analysis

Descriptive statistics were initially used to characterise the analytical dataset, including means, standard deviations, and minimum and maximum values for the environmental and personal variables considered. To account for the repeated-measures structure of the dataset and investigate interindividual variability in thermal sensation, linear mixed-effects

models were fitted in Python (version 3.12.4) [31] using the MixedLM implementation of the statsmodels package (version 0.14.2) and estimated by Maximum Likelihood (ML), with participant identification specified as the grouping factor.

The mixed-effects modelling approach combines fixed and random effects and is particularly suitable for repeated-measures data. Fixed effects were used to estimate population-level associations between TSV and the explanatory variables, whereas random effects accounted for participant-specific variability not explained by these predictors. Because repeated responses from the same participant are not statistically independent, participant identification was specified as the grouping factor, with a participant-specific random intercept allowing each individual to have a different baseline level of thermal sensation. This structure accounts for within-participant correlation while estimating population-level associations. Although TSV was measured on a seven-point ordinal scale ranging from -3 to $+3$, it was treated as approximately continuous, assuming approximately equal spacing between adjacent response categories.

Conceptually, the model uses the explanatory variables included in each specification—such as operative temperature, thermal disposition, gender, building operation mode, and BMI—as inputs to estimate the TSV for each observation. The estimated response combines the population-level contribution of the fixed effects with a participant-specific random deviation, thereby accounting for both the explanatory variables and persistent differences among individuals. Equation (1) presents the general formulation of the linear mixed-effects model used in this study.

$$Y_{ij} = \beta_0 + \sum_{k=1}^p (\beta_k X_{kij}) + u_{0j} + \varepsilon_{ij} \quad (1)$$

where:

Y_{ij} is the TSV response for observation i from participant j ;

β_0 is the population-level fixed intercept;

u_{0j} is the participant-specific random intercept, representing the deviation of participant j from the population-level intercept;

X_{kij} is the value of explanatory variable k for observation i from participant j ;

β_k is the population-level fixed-effect coefficient associated with explanatory variable k ;

p is the total number of explanatory variables included in the model;

ε_{ij} is the residual error associated with observation i from participant j .

Accordingly, Equation (1) represents the general mixed-effects structure used throughout the analysis, while the explanatory variables represented by X_{kij} varied according to the hierarchical model specification described below.

The models were constructed hierarchically through the progressive inclusion of explanatory variables to evaluate their incremental contribution to model performance [32]. The baseline model included a fixed intercept and a participant-specific random intercept, with no explanatory predictors. Operative temperature was subsequently introduced as the primary environmental predictor, followed by thermal disposition, gender, building operation mode, and BMI. This sequential modelling strategy enabled the additional explanatory contribution of each variable to be evaluated relative to the preceding model. The order of predictor inclusion was defined a priori according to the analytical objectives of the study, with operative temperature representing the baseline environmental contribution and thermal disposition subsequently introduced as the primary individual factor of interest. Gender, operation mode, and BMI were then added to evaluate whether additional demographic, operational, and anthropometric information further improved model performance (Table 1).

Table 1. Hierarchical structure and progressive inclusion of explanatory variables in the linear mixed-effects models.

Model	Fixed Effects Included *	Main Purpose
1	None	Baseline interindividual variability
2	Operative temperature	Environmental contribution
3	Operative temperature and thermal disposition	Additional contribution of thermal disposition
4	Operative temperature, thermal disposition and gender	Additional demographic contribution
5	Operative temperature, thermal disposition, gender and mode of operation	Additional operational contribution
6	Operative temperature, thermal disposition, gender, mode of operation and BMI	Additional anthropometric contribution

* All models included a fixed intercept and a participant-specific random intercept.

Multicollinearity among the explanatory variables included in the full model was assessed using Variance Inflation Factors (VIFs). VIF values below 5.0 were considered indicative of the absence of problematic multicollinearity.

The models were estimated using Maximum Likelihood (ML), and a significance level of 5.0% was adopted for the evaluation of fixed-effect coefficients. The progressive sequence of nested models was examined to evaluate changes in model performance following the inclusion of each additional predictor. ANOVA-based model comparisons were performed to assess whether each successive model provided a statistically significant improvement in fit relative to the preceding model. In addition, the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were used to compare model performance while accounting for model complexity, with lower values indicating a better balance between goodness of fit and model complexity. Because AIC and BIC may favour different levels of model complexity, BIC was adopted as the primary criterion for identifying the preferred model specification, given its stronger penalty for additional parameters and its suitability for explanatory modelling in this study.

As an additional analysis of participant-specific variability, Model 6 was re-estimated with participant-specific random intercepts and random slopes for operative temperature. Operative temperature was mean-centred at 24.12 °C so that the random intercept represented thermal sensation under average thermal conditions. The model was estimated using ML, and random-effects variance components, intercept–slope covariance and correlation, log-likelihood, AIC, BIC, and convergence diagnostics were examined. This specification allowed interindividual variability to be evaluated not only in thermal sensation levels but also in responsiveness to changes in operative temperature. The random-slope specification was compared with the corresponding random-intercept model using AIC and BIC, with both models fitted to the same analytical sample and using the same fixed-effects structure. Finally, an interaction between mean-centred operative temperature and thermal disposition was added to the random-slope model to assess whether thermal disposition groups differed in their responsiveness to changes in operative temperature. The interaction model was compared with the corresponding main-effects model using a likelihood-ratio test, AIC, and BIC.

3. Results and Discussions

The analyses were based on 2741 valid responses from 159 participants, classified according to their thermal disposition as: sensitive to cold, sensitive to heat, sensitive to both, or little or not sensitive to either.

3.1. Indoor Thermal Conditions and Participants' Characteristics

In the analysis of environmental variables, air temperature, MRT, operative temperature, air velocity, and relative humidity were considered, collected across all four seasons. Descriptive statistics for these variables, disaggregated by the building's two operating modes, are summarised in Table 2. The values represent the mean across all monitored zones, and measurement uncertainties follow the tolerances established by ISO 7726 [28].

Table 2. Indoor environmental variables recorded under each operating mode (mean $\pm$ standard deviation).

Environmental Variables	Under Air-Conditioning	Under Natural Ventilation
Air temperature ($^{\circ}\text{C}$)	23.95 ± 1.29	24.07 ± 1.26
MRT ($^{\circ}\text{C}$)	24.20 ± 1.16	24.20 ± 1.16
Operative temperature ($^{\circ}\text{C}$)	24.02 ± 1.20	24.20 ± 1.18
Air velocity (m/s)	0.12 ± 0.08	0.11 ± 0.07
Relative humidity (%)	59.81 ± 8.61	67.47 ± 8.42

The distribution of indoor operative temperature was analysed to characterise the thermal environment observed throughout the monitoring campaign and to provide contextual information on seasonal variability and the adaptive opportunities available in the mixed-mode building (Figure 1). Because data collection extended across the four seasons, the analysis captured the range of indoor operative temperatures typical of humid subtropical climates, which may influence occupants' adaptive behaviour and expectations regarding thermal comfort.

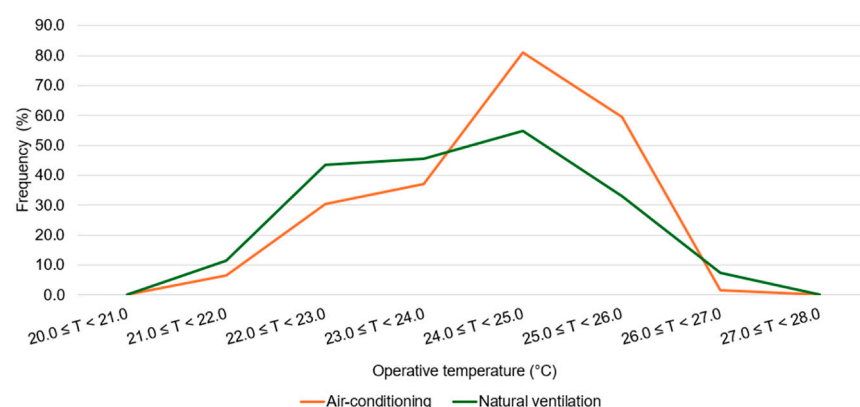


Figure 1. Frequency distribution of operative temperature across the observations under natural ventilation and air-conditioning modes.

The results indicate that the building presented very similar average thermal conditions under both operating modes. Thermal variables, including air temperature, MRT, and operative temperature, remained within close ranges, with mean values around 24.0°C , associated with low air velocities. This suggests a relatively homogeneous and thermally stable indoor environment. The main difference observed between operating modes was

relative humidity, which showed higher values during natural ventilation and lower values under air-conditioning use, reflecting the dehumidification effect of mechanical systems.

Age, height, weight, and BMI were summarized at the participant level using individual mean values for repeated records. Descriptive statistics were then calculated separately for men and women, with each participant contributing once (Table 3).

Table 3. Descriptive statistics of participants' anthropometric and personal characteristics according to gender (mean $\pm$ standard deviation).

Anthropometric Variables	Females	Males
Age (years)	35.87 $\pm$ 8.99	39.39 $\pm$ 9.02
Height (m)	1.63 $\pm$ 0.08	1.76 $\pm$ 0.07
Weight (kg)	63.65 $\pm$ 12.87	82.13 $\pm$ 12.86
BMI	24.10 $\pm$ 3.13	26.49 $\pm$ 3.14
Clothing (clo)	0.70 $\pm$ 0.12	0.65 $\pm$ 0.12
Metabolism (met)	1.19 $\pm$ 0.13	1.17 $\pm$ 0.13

Overall, anthropometric differences were observed between men and women. On average, men presented higher age, height, weight, and BMI compared to women. Clothing insulation was slightly higher among women, while mean metabolic rate values were similar between genders. These anthropometric differences may influence thermal perception and should be considered in the interpretation of the results.

3.2. Thermal Disposition Groups and Distribution of Responses

A total of 84 men and 75 women participated in the study. Based on their self-reported thermal disposition, 22 participants were classified as little or not sensitive to either heat or cold, 34 as sensitive to both heat and cold, 60 as sensitive to heat, and 43 as sensitive to cold. The distribution according to gender is shown in Figure 2 and Table 4. Males predominated in the heat-sensitive group, whereas females predominated in the cold-sensitive group; this unequal distribution should be considered when interpreting the respective contributions of gender and thermal disposition.

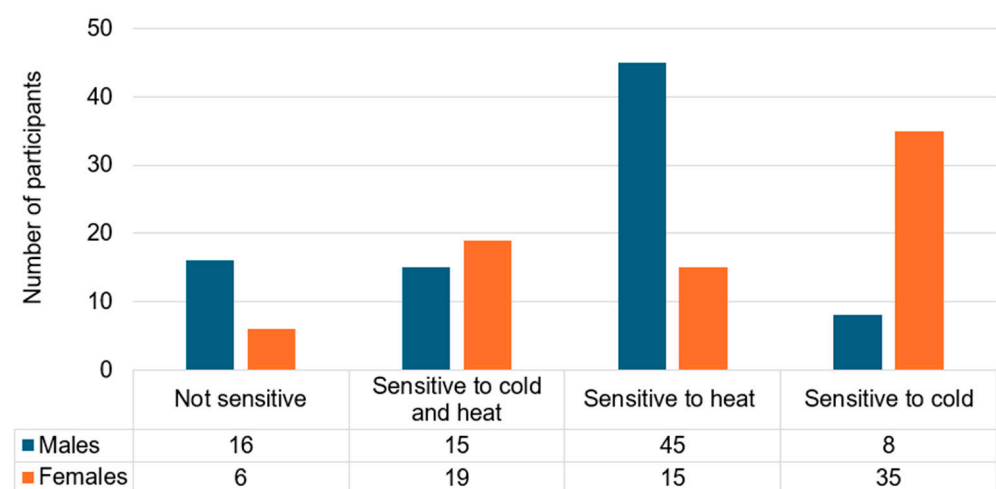
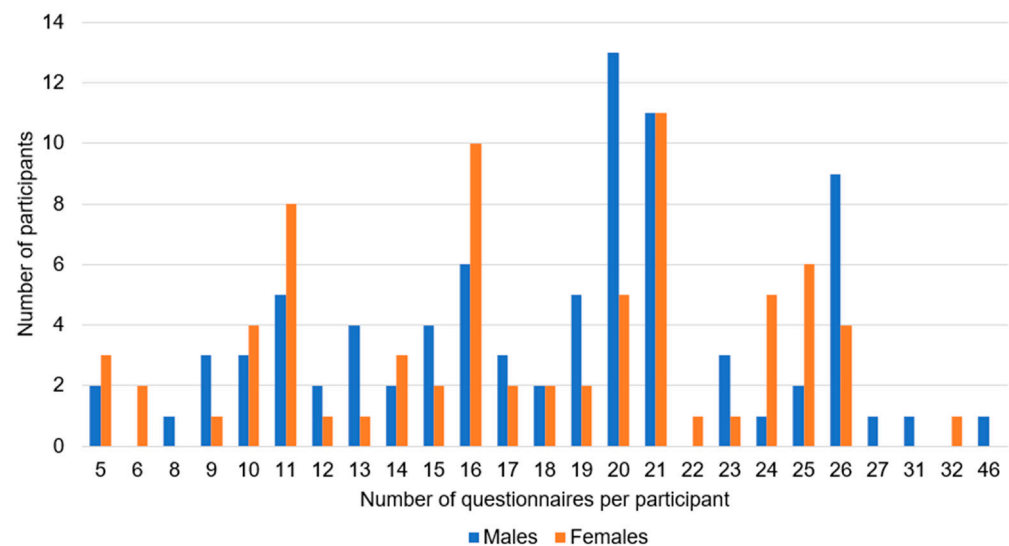


Figure 2. Number of participants across thermal disposition groups according to self-reported thermal disposition.

Table 4. Distribution of participants according to thermal disposition and gender, expressed as absolute frequencies and percentages of participants within each thermal disposition group.

Thermal Disposition	Males	Females	Total of Participants
Not sensitive	72.7%	27.3%	22
Sensitive to both heat and cold	44.1%	55.9%	34
Sensitive to heat	75.0%	25.0%	60
Sensitive to cold	18.6%	81.4%	43
Total	52.8%	47.2%	159

Since individual participants were able to respond to more than one questionnaire over the course of the monitoring period, the resulting dataset contains repeated measures per subject. The number of questionnaire responses varied among participants. Figure 3 shows this distribution, stratified by gender.

**Figure 3.** Distribution of participants according to the number of questionnaire responses completed during the field campaign, stratified by gender.

3.3. Linear Mixed-Effects Model Analysis

Considering the repeated data collection throughout the day and the expected interindividual variability in thermal perception, linear mixed-effects models were adopted. This approach allows for the simultaneous estimation of the average effects of explanatory variables (fixed effects) and individual variability among participants (random effects), while also accounting for the correlation between repeated responses from the same individual. TSV was defined as the dependent variable, with a random intercept specified for each participant to capture individual differences in baseline thermal sensation.

The models were constructed hierarchically, resulting in six specifications with the progressive inclusion of the independent variables: operative temperature, thermal disposition, gender, mode of operation, and BMI. The null model, comprising only a fixed intercept and a participant-specific random intercept, estimated an overall mean thermal sensation of 0.055. Between-participant variability was observed (random-intercept variance = 0.148), indicating systematic differences in baseline thermal sensation among occupants. The residual variance was 0.391, representing the remaining within-observation variability not accounted for by the model.

Considering that one unit on this scale corresponds to roughly 3.0 °C in typical office environments, individual differences in preferred temperature may reach approximately 3.0 °C [33]. Furthermore, evidence shows that intraindividual variability is also on the order of one scale unit, indicating that the same individual may exhibit relevant perceptual variations over time [34].

The inclusion of operative temperature resulted in a significant improvement in model fit (Figure 4). This variable showed a positive and highly significant effect on thermal sensation ($\beta = 0.157$; $p < 0.001$), indicating that increases in operative temperature are consistently associated with higher reported thermal sensation among occupants. Nevertheless, the persistence of substantial interindividual variance suggests that additional individual factors influence thermal perception beyond environmental conditions alone.

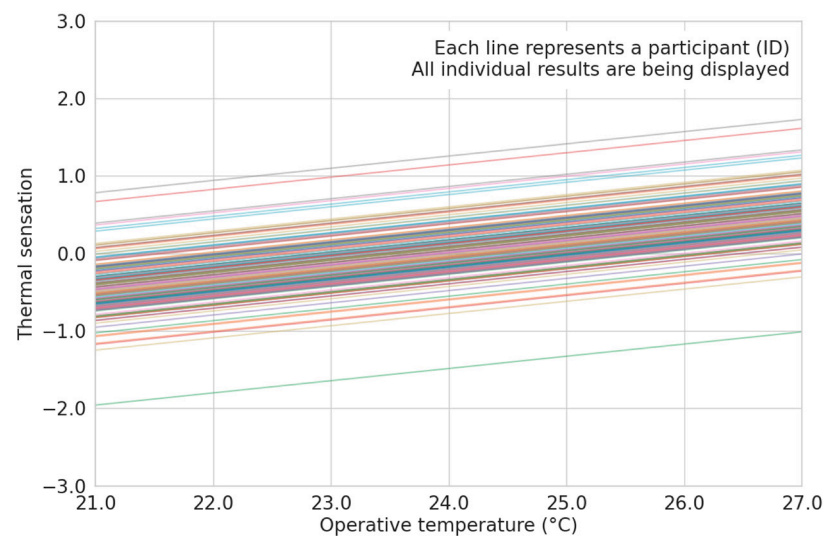


Figure 4. Participant-specific predicted thermal sensation as a function of operative temperature based on the random-intercept linear mixed-effects model.

With the inclusion of thermal disposition, operative temperature remained a significant predictor ($\beta = 0.159$; $p < 0.001$). However, clear differences were observed among thermal disposition groups (Figure 5). Occupants classified as heat-sensitive according to their self-reported thermal disposition reported significantly warmer thermal sensations than the other groups (β ranging from 0.29 to 0.37; $p \leq 0.001$) under comparable environmental conditions. In contrast, occupants classified as cold-sensitive reported lower thermal sensation only in comparison with the non-sensitive group, with this difference losing statistical significance when compared with the group sensitive to both heat and cold. No statistically significant differences were observed between occupants classified as non-sensitive and those classified as sensitive to both heat and cold. These group differences should be interpreted as associations between general self-reported thermal disposition and repeated thermal sensation responses, rather than as evidence of distinct physiological sensitivity to heat or cold. The random-intercept variance remained close to 0.10, indicating that between-participant variability persisted after accounting for operative temperature and thermal disposition. Because Figure 5 is based on the random-intercept specification, participant-specific differences are expressed as vertical shifts in predicted thermal sensation, while the operative-temperature slope is common across participants. The figure is therefore intended primarily to illustrate interindividual differences in thermal sensation levels rather than differences in responsiveness to operative temperature.

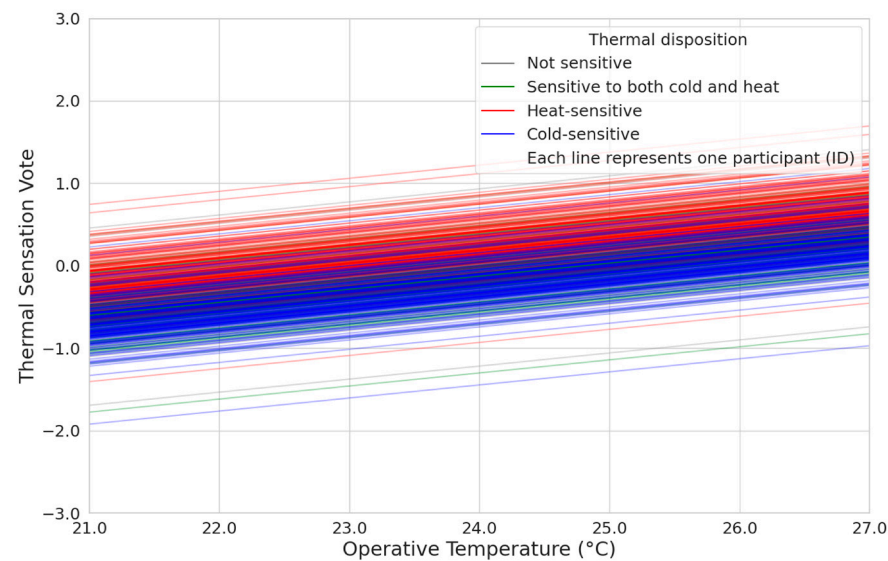


Figure 5. Participant-specific predicted thermal sensation as a function of operative temperature across thermal disposition groups based on the random-intercept linear mixed-effects model. Individual lines illustrate participant-specific differences in predicted thermal sensation levels.

Similar results were reported by Hwang and Chen [35], who used logistic regression to model thermal preference as a function of operative temperature. They observed similar preferred temperatures among groups, but differences in the width of the acceptable temperature range. A narrower comfort zone was interpreted as an indicator of greater thermal sensitivity. Analogously, herein, differences among thermal disposition groups were expressed as systematic differences in reported thermal sensation under comparable operative temperatures.

The inclusion of gender in the model did not alter the effect of operative temperature, which remained positive and highly significant ($\beta = 0.160$; $p < 0.001$). Among the thermal disposition groups, only occupants classified as heat-sensitive continued to report significantly higher thermal sensation compared to the reference group. Gender proved to be a relevant variable, with male occupants reporting, on average, higher thermal sensation than female occupants ($\beta = 0.145$; $p = 0.023$). This effect remained stable regardless of the reference category adopted. The association observed between gender and thermal disposition should also be considered when interpreting their respective model coefficients, as the unequal distribution of men and women across thermal disposition groups may result in partially overlapping explanatory contributions. Male participants were predominant in the heat-sensitive group, whereas female participants were predominant in the cold-sensitive group. Although the VIF values did not indicate problematic multicollinearity, the unequal distribution of gender across thermal disposition groups should be considered when interpreting their respective coefficients.

To examine whether the association between thermal disposition and thermal sensation differed according to gender, an additional model including a thermal disposition $\times$ gender interaction was fitted. The interaction did not improve model fit compared with Model 4 (likelihood-ratio statistic = 0.578, $df = 3$, $p = 0.902$), and AIC and BIC were higher. None of the interaction terms was significant (all $p \geq 0.632$). Thus, there was no evidence that the association between thermal disposition and thermal sensation differed according to gender.

Lan et al. [36] found that women's comfort temperature was 1.0 °C higher than that of men. They also identified greater physiological sensitivity to cold among women, whereas men appeared to be more sensitive to heat. Similarly, Liu et al. [37] found that women were

more sensitive to colder thermal environments and reported colder thermal sensations than men under comparable cold conditions. In turn, Hashiguchi et al. [38] reported that women had greater sensitivity and lower thermal satisfaction at the beginning of exposure ($p < 0.05$), although this difference decreased over time, suggesting a possible adaptation effect.

With the inclusion of building operation mode, operative temperature continued to show a positive and significant effect ($\beta = 0.165$; $p < 0.001$). The heat-sensitive group remained associated with higher thermal sensation ($\beta = 0.272$; $p = 0.002$), while the other thermal disposition groups did not present statistically significant differences. Gender maintained a statistically significant effect, with female occupants reporting lower thermal sensation than male occupants ($\beta = -0.152$; $p = 0.016$). After accounting for operative temperature and the individual characteristics included in the model, observations collected under natural ventilation were associated with higher TSV than those collected under air-conditioning ($\beta = 0.071$; $p = 0.010$). Previous evidence demonstrates that thermal history significantly influences heat tolerance. Busch [39] identified differences of up to 3.0 °C in the upper comfort limit between individuals accustomed to natural ventilation and those used to air-conditioning, with the latter being less tolerant to heat. Complementarily, Yu et al. [40], in a climate chamber study, showed that frequent exposure to air-conditioning may reduce physiological thermoregulatory capacity, resulting in greater perception of discomfort under heat stress.

Finally, the inclusion of BMI did not substantially alter the results. Operative temperature remained positively and significantly associated with thermal sensation, whereas BMI was not statistically significant, indicating that BMI did not provide a statistically significant additional contribution to explaining thermal sensation after accounting for the other variables included in the model. Occupants classified as heat-sensitive continued to report significantly higher thermal sensation, whereas the other thermal disposition groups did not differ significantly from the reference category. Gender and operation mode maintained significant effects, with women reporting lower thermal sensation than men and observations under natural ventilation being associated with higher TSV. Complete coefficient estimates, standard errors, 95% confidence intervals, and p -values for all hierarchical model specifications are provided in Supplementary Tables S1–S5. Complete fixed-effect estimates and variance components for the fully adjusted Model 6 are shown in Table 5.

Table 5. Fixed-effect estimates, standard errors, 95% confidence intervals, p -values, and variance components for the fully adjusted linear mixed-effects Model 6 of thermal sensation.

Predictor	β	SE	95% CI	p
Intercept	−4.242	0.341	[−4.909; −3.574]	<0.001
Operative temperature	0.165	0.012	[0.142; 0.189]	<0.001
Sensitive to both heat and cold	−0.039	0.096	[−0.22; 0.150]	0.689
Sensitive to heat	0.269	0.086	[0.100; 0.438]	0.002
Sensitive to cold	−0.142	0.098	[−0.334; 0.050]	0.146
Male	0.138	0.064	[0.013; 0.263]	0.030
Air-conditioning	−0.073	0.028	[−0.128; −0.019]	0.008
BMI	0.009	0.007	[−0.005; 0.022]	0.208

Reference categories were little or not thermally sensitive for thermal disposition, female for gender, and natural ventilation for operation mode. Variance components: participant-level random-intercept variance = 0.094; residual variance = 0.391.

Field studies conducted in office buildings in southern Brazil [41,42] indicated that BMI significantly influences thermal sensation, clothing habits, and comfort temperature. It was observed that individuals with BMI ≤ 25.0 kg/m² presented a comfort temperature 0.4 °C higher ($p < 0.001$) than those with higher BMI. Similarly, Indraganti et al. [43] also identified a significant association between BMI and thermal comfort, finding that overweight individuals (BMI > 25.0 kg/m²) had a comfort temperature 0.7 °C lower ($p < 0.001$) than underweight individuals (BMI < 18.5 kg/m²), reinforcing the influence of anthropometric characteristics on thermal perception. The absence of a significant BMI effect in the present sample may reflect the relatively narrow range of BMI variation observed among participants, or partial overlap with variance already captured by gender, given the known association between BMI and body composition differences across genders.

The random-intercept variance decreased from 0.148 in the null model to approximately 0.10 after the inclusion of operative temperature and thermal disposition, remaining relatively stable at approximately 0.094 to 0.099 in the subsequent models. This reduction indicates that the fixed effects accounted for part of the between-participant variability, although participant-specific differences in thermal sensation remained. The residual variance remained relatively stable across the adjusted models. No evidence of problematic multicollinearity was observed among the explanatory variables included in Model 6, with VIF values ranging from 1.03 to 2.53.

After completing the construction and analysis of the hierarchical models, changes in model fit were evaluated using ANOVA tests, p -values, and information criteria (AIC and BIC). Table 6 shows these model comparisons and the incremental contribution of the explanatory variables across the hierarchical sequence.

Table 6. Model comparison statistics for the linear mixed-effects models of thermal sensation.

Model	ANOVA	p	AIC	BIC
1	-	-	5701.04	5718.79
2	172.365	<0.001	5530.68	5554.34
3	49.873	<0.001	5486.8	5528.22
4	5.146	0.023	5483.66	5530.99
5	6.652	0.0099	5479.01	5532.25
6	1.582	0.2084	5479.42	5538.59

Regarding the ANOVA-based comparisons between nested models and p -values, Model 2 showed a significant improvement compared to Model 1, indicating that the inclusion of operative temperature contributed to explaining variability in individuals' thermal sensation. Subsequently, the comparison between Model 3 and Model 2 also demonstrated a statistically significant improvement, evidencing that the inclusion of thermal disposition enhanced model fit. The introduction of gender in Model 4 resulted in a further statistically significant improvement compared to Model 3, although with smaller magnitude than in the previous steps. Finally, Model 5, which incorporated the building operation mode, also showed a statistically significant improvement over Model 4. However, the addition of BMI in Model 6 did not result in a statistically significant gain compared to Model 5, suggesting that this variable does not contribute to explaining thermal sensation within the adjusted model context.

The analysis of information criteria partially reinforces the findings of the statistical tests. A progressive reduction in AIC was observed as variables were added, indicating improved model fit up to Model 5. However, when BMI was included, the AIC did not show meaningful change. The BIC reached its lowest value in Model 3, indicating that

this specification was favoured by BIC because of its balance between model fit and model complexity. Model 5 presented the lowest AIC and incorporated significant contributions from operative temperature, thermal disposition, gender, and operation mode.

The fully adjusted model was subsequently re-estimated allowing both the intercept and the operative-temperature slope to vary across participants. The random-slope specification showed between-participant variability in both thermal sensation levels and responsiveness to changes in operative temperature, while the intercept–slope association was weakly positive. The model converged successfully without convergence warnings, and the estimated random-effects covariance matrix was positive definite. Detailed random-effects estimates and model-fit statistics are shown in Table 7.

Table 7. Random-effects estimates and model-fit statistics for the fully adjusted random-slope model.

Statistic	Estimate
Random-intercept variance	0.088
Random-slope variance for operative temperature	0.044
Intercept–slope covariance	0.009
Intercept–slope correlation	0.147
Residual variance	0.351
Log-likelihood	−2667.657
AIC	5359.315
BIC	5430.308

The principal finding regarding thermal disposition remained consistent under the random-slope specification. Occupants classified as heat-sensitive continued to report significantly higher TSV than the reference group ($\beta = 0.281$, 95% CI: 0.114–0.448, $p = 0.001$). Operative temperature also remained positively associated with thermal sensation ($\beta = 0.161$, 95% CI: 0.118–0.203, $p < 0.001$), while male occupants reported significantly higher thermal sensation than female occupants ($\beta = 0.140$, $p = 0.030$). In contrast, building operation mode was no longer statistically significant ($\beta = -0.028$, $p = 0.335$), while BMI also remained non-significant ($\beta = 0.005$, $p = 0.463$).

Compared with the corresponding random-intercept model, the random-slope model presented substantially lower information criteria. AIC decreased from 5479.425 to 5359.315 ($\Delta\text{AIC} = -120.110$), while BIC decreased from 5538.585 to 5430.308 ($\Delta\text{BIC} = -108.277$). Thus, both criteria clearly favoured the model allowing participant-specific responses to operative temperature.

To examine whether thermal disposition groups differed in their responsiveness to changes in operative temperature, an interaction between mean-centred operative temperature and thermal disposition was added to the random-slope model. The interaction did not significantly improve model fit compared with the corresponding main-effects model (likelihood-ratio statistic = 7.059, $df = 3$, $p = 0.070$). None of the individual interaction terms was statistically significant (all $p \geq 0.201$), and their 95% confidence intervals included zero. Although AIC decreased slightly from 5359.315 to 5358.256, BIC increased from 5430.308 to 5446.997. These results did not provide statistically significant evidence that thermal disposition groups differed in their responsiveness to operative temperature; the observed group differences were therefore primarily associated with thermal sensation levels under comparable conditions.

4. Conclusions

The results of this study demonstrate that operative temperature remains a primary determinant of thermal sensation; however, environmental conditions alone do not fully explain the variability observed among occupants. The inclusion of thermal disposition significantly improved model performance and revealed systematic differences in thermal sensation among individuals exposed to comparable thermal conditions. Occupants classified as heat-sensitive according to their self-reported thermal disposition consistently reported warmer thermal sensations than the reference group, while the effects observed for the other thermal disposition groups were lower. In the hierarchical random-intercept models, gender and building operation mode were also significantly associated with thermal sensation, whereas BMI did not provide a significant additional contribution after accounting for the other variables included in the models. These findings reinforce that thermal sensation results from the combined influence of environmental, individual, and operational factors.

From a methodological perspective, the hierarchical mixed-effects modelling approach enabled the progressive contribution of different explanatory factors to be evaluated while accounting for repeated observations from the same occupants. Rather than examining thermal disposition solely through separate regression models for different occupant groups, the analytical framework adopted in this study incorporated thermal disposition alongside environmental, demographic, operational, and anthropometric factors within a unified modelling structure. The results indicate that thermal disposition provides additional explanatory information beyond operative temperature and remains relevant when other potentially influential factors are considered. Among the six prespecified hierarchical random-intercept models, the specification including operative temperature and thermal disposition presented the lowest BIC, indicating a favourable balance between explanatory improvement and model complexity within this hierarchical sequence. Separately, allowing the operative-temperature slope to vary across participants substantially improved AIC and BIC relative to the corresponding fully adjusted random-intercept model, indicating that participant-specific responsiveness to operative temperature was better represented by the random-slope structure. Importantly, the association between heat-sensitive thermal disposition and higher thermal sensation remained significant under this alternative specification, supporting the robustness of the main finding.

From a practical perspective, the findings suggest that assessments of occupants' thermal responses and building operation strategies based exclusively on population-average responses may not adequately represent the diversity of thermal requirements among occupants. The systematic differences associated with thermal disposition indicate that occupants exposed to similar indoor conditions may experience the thermal environment differently. This is particularly relevant in mixed-mode buildings, where occupants are exposed to different adaptive opportunities and operating conditions. Incorporating information on individual thermal characteristics into occupant-centred control strategies and building performance models may therefore contribute to indoor environments that better accommodate heterogeneous thermal requirements.

The findings should nevertheless be interpreted considering the study limitations. Thermal disposition was determined using a single self-reported item and should therefore be interpreted as a subjective individual characteristic rather than as an objective measure of physiological thermal sensitivity. Although repeated responses were consistent within participants, self-reported thermal disposition may not capture the full physiological or behavioural dimensions of thermal sensitivity, and some common-method overlap with self-reported TSV cannot be excluded. Future studies combining self-reported disposition with physiological or behavioural measures could provide complementary validation.

In addition, the ordinal nature of the seven-point TSV scale should be acknowledged, and future studies could examine the robustness of the findings using ordinal mixed-effects models.

The analysis was based on observational data from a single mixed-mode office building in a subtropical climate, which limits generalisation to other buildings, climates, and populations. In addition, the 2015–2016 data may not fully represent current building operation or occupant behaviour. Information on race, ethnicity, and geographical background was unavailable, and their potential contribution to interindividual variability could therefore not be assessed. Future studies should investigate thermal disposition across different climatic regions, building typologies, and occupant populations and further examine its temporal stability.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16204040/s1>, Table S1: Fixed-effect estimates, standard errors, 95% confidence intervals, and *p*-values for the linear mixed-effects model 1 of thermal sensation; Table S2: Fixed-effect estimates, standard errors, 95% confidence intervals, and *p*-values for the linear mixed-effects model 2 of thermal sensation; Table S3: Fixed-effect estimates, standard errors, 95% confidence intervals, and *p*-values for the linear mixed-effects model 3 of thermal sensation; Table S4: Fixed-effect estimates, standard errors, 95% confidence intervals, and *p*-values for the linear mixed-effects model 4 of thermal sensation; Table S5: Fixed-effect estimates, standard errors, 95% confidence intervals, and *p*-values for the linear mixed-effects model 5 of thermal sensation.

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Abbreviations

The following abbreviations are used in this manuscript:

AIC	Akaike Information Criterion
aPMV	Adaptive Predicted Mean Vote
ATHB	Adaptive Thermal Heat Balance
BIC	Bayesian Information Criterion

BMI	Body Mass Index
ML	Maximum Likelihood
MRT	Mean Radiant Temperature
VIF	Variance Inflation Factor
TCP	Thermal Comfort Percentage

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