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Impacts of demographic, contextual and interaction effects on thermal sensation—Evidence from a global database

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Abstract

Previous studies have demonstrated that non-thermal factors may affect occupants' thermal response in the indoor environment. The effects of demographic and contextual factors on thermal perception have been extensively studied, yet in previous studies, confounding variables have not been commonly controlled; it is also not known how these factors interact with each other. The current study leverages on the largest global thermal comfort database to date and explores the impacts of available demographic and contextual factors, including gender, ventilation mode, building typology, season and climate, on occupants' thermal sensation, along with their two-way and three-way interaction effects. Results indicate that all tested demographic and contextual factors except ventilation mode significantly affect occupants' thermal sensation. Under the same indoor environmental and outdoor climatic conditions, males perceive the environment as being significantly warmer than females in all contexts; males' thermal sensitivity is also consistently lower than females'. Thermal sensations in multifamily housing are significantly lower and closer to neutral than in office buildings under the same exposure conditions, yet it is likely to be the combined effects of building typology and ventilation mode. All else being equal, occupants in office buildings have less seasonal variation in thermal sensation than classrooms and multifamily housing. Residents in a warmer climate deem the same indoor thermal environment significantly cooler than residents in a cooler climate; this climatic adaptation is more pronounced in females than in males. Occupants' sensitivity to indoor air temperature, humidity and air movement significantly vary between different ventilation modes under different seasons.

Key words: Demographic factors; Contextual factors; Interaction effects; Thermal sensation; ASHRAE Global Thermal Comfort Database II

1. Introduction

Previous research literature has revealed that human response to conditions inside buildings may be affected by a wide range of non-thermal factors that are not accounted for in the classic heat-balance comfort models. A recent study [1] has pointed out that the accuracy of PMV-PPD model in predicting subjects' thermal sensation is only 34%. The remaining 66% of residual diversity in human thermal sensation may derive from many non-thermal factors. These include demographics factors, e.g. gender, age, body composition, and socio-economic status; contextual factors, e.g. building design, building typology, season, and climate; environmental interactions, e.g. lighting, acoustics, and indoor air quality; and cognition factors, e.g. attitude, preference and expectations [2–6]. Studying the impacts of these factors not only contributes to our knowledge of how occupants interact with their built environment, but also provides guidance for the design, operation and management of buildings to ensure occupant health, comfort and wellbeing, while at the same time optimising energy use.

Understanding the causes of individual difference in human thermal perception has gained popularity in recent comfort studies. Several researchers have conducted comprehensive reviews related to this topic, e.g. Frontczak and Wargocki [7], Mishra and Ramgopal [8], Rupp et al. [9], Wang et al. [10], and Schweiker et al. [11]. Based on the current state of knowledge, the underlying mechanisms and contributions of some factors to differences in thermal perception, e.g. thermal adaptation and personal control, are better understood than other factors, e.g. gender and age. Schweiker et al. [11] also pointed out the need in studying interaction effects between different diversity-driving factors, both physiological and psychological, for establishing a holistic picture. The current study leverages on the largest global thermal comfort database to date, and explores the effects of available demographic, contextual factors and their interaction effects on building occupants' thermal sensation in the indoor environment, hoping to contribute to the current understanding of drivers of diversity in human thermal perception.

1.1 Demographic factor

A large amount of laboratory and field research effort has been applied to gender differences in thermal perception [7,12–22]. Previous studies demonstrate that morphological differences between sexes, e.g. higher surface-to-volume ratio, different body composition, and lower metabolic rate for females, are likely to cause differences in thermoregulation and thermal perception between males and females [8,23]. Most studies reported that females are more sensitive to, and less satisfied with cold exposures than their male counterparts, yet there was no significant difference in the neutral temperature¹ between sexes [10,11,24]. However, Wang et al. [10] point out that the gender difference mainly derives from the lower thermal insulation of clothing (*clo* value) and lower metabolic rate of females, and thus might lose its influence once metabolic rate or anthropometric data are controlled in the multiple regression model [25].

Berglund and Gonzalez [26] defined thermal sensitivity as $\Delta TSV/\Delta T$ where ΔTSV means change of thermal sensation vote (TSV) on the ASHRAE 7-point scale and ΔT means change of operative temperature of the environment. Regarding gender differences in thermal sensitivity, several studies [22,27–29] indicated that women were more sensitive to temperature variations than men. Zhang et al. [17], however, did not find any significant difference in thermal sensitivity between sexes.

1.2 Contextual Factors

1.2.1 Ventilation mode

There has been a growing interest in comparing occupants' thermal sensation and thermal comfort in buildings with different ventilation modes, especially with the advent of mixed-mode (MM) or hybrid approaches to building ventilation [30–35]. Previous studies revealed that, apart from reducing cooling and heating energy, MM ventilation also has the advantage of providing higher levels of thermal comfort and occupant satisfaction [32,36–38]. Some recent studies in MM buildings suggested that the building ventilation mode, *ceteris paribus*, influences building occupants' thermal sensation [34,39–41]. Several studies have compared occupants' thermal sensation in air-conditioned (AC), naturally-ventilated (NV) and MM buildings, however did not identify whether this difference was caused by variations in indoor temperatures resulting from the different ventilation modes, or simply the ventilation mode itself. For example, Lau et al. [37] compared thermal perceptions in air-conditioned (AC), naturally-ventilated (NV) and MM learning spaces in Singapore, and found that the mean thermal sensation in AC space was significantly lower than that in NV and MM spaces [37]. De Vecchi et al. [32], however, reported similar thermal sensation and acceptability levels in AC and MM buildings with roughly equivalent indoor Standard Effective Temperatures (SET)².

¹ The ambient temperature found by statistical analysis to most frequently coincide with the “neutral” rating on the thermal sensation scale is referred to as the sample's “neutrality” or “neutral temperature” [42].

² SET is defined as the equivalent air temperature of an isothermal environment at 50% RH in which a subject, wearing clothing standardized for the activity concerned, has the same skin temperature t_{sk} and thermoregulatory strain (skin wettedness w) as in the actual environment [78].

Previous studies found that thermal sensitivity in NV buildings was generally lower than in AC buildings [37,39,42–44]. Lau et al. [37] reported similar thermal sensitivity differences between NV and MM buildings, however no statistical test has been carried out to test the significance. Previous literature also demonstrated that there was a significant positive correlation between thermal sensation and humidity (vapour pressure) [45–47], and negative correlation between thermal sensation and air speed [12,17]. The interaction effects between sensitivity to humidity and air movement, and ventilation strategy have not been studied.

There are limited studies focusing on the interaction effect between ventilation strategy and gender. Muzi et al. [48] found a large gender difference in AC office buildings, but no difference in NV buildings. Maykot et al. [19] compared thermal perception of different genders in AC and MM buildings in Brazil, concluding that there were significant differences between males' and females' thermal sensation and thermal preference under similar thermal conditions; in AC buildings and MM buildings operated in NV mode, significant differences were also found for thermal sensation between different genders.

1.2.2 Building typology

In thermal comfort field studies, offices attracted the most research attention; classrooms and residential buildings are also extensively investigated. However, few studies have compared occupants' thermal sensation in different building typologies possibly due to the differences in thermal environments, building occupants and so on. Oseland [49] compared 30 UK participants' thermal sensation in their offices and homes, and concluded that participants felt warmer in their homes than in offices even though the indoor climate, activity levels and clothing insulation were identical. Karjalainen's survey [50] showed that even the least satisfied group in home environment is more comfortable than the most satisfied group in offices. Mishra and Ramgopal have concluded that it is the *adaptive opportunity* in different building typologies that lead to different thermal sensation and comfort levels even under the same thermal environment and "people vote closer to comfort if they are given more adaptive opportunities and they are more comfortable in places familiar to them" [8].

1.2.3 Seasonal and climatic adaptation

Adaptation is defined as "changes that reduce the physiological strain produced by stressful components of the total environment" [51]. Seasonal and climatic adaptation are both an acclimatization process, a subcategory within phenotypic adaptation [11]. Acclimatization refers to "the adaptive changes within an organism occurring in response to its natural climate" and can occur in both a short term and a long term. Repeated cold exposure results in an enhancement of cold-induced thermogenesis for human bodies, whereas repeated warm exposure facilitates more efficient heat loss. This adaptation is conducive to human survival by increasing the ability to tolerate stress, or by elevating the margin for safety during stress loading [52].

Many previous studies have investigated the effects of seasonal variations on occupants' comfort or neutral temperatures and found that they were higher in warmer seasons compared to cooler seasons [53–55]; also this seasonal variation was more prominent in NV buildings than in AC buildings [56,57]. However, there are other studies reporting trivial difference in neutral temperature between summer and winter [20,56,58]. Limited studies have examined seasonal variations on thermal sensation and also yielded conflicting results. Yao et al. [59] and Liu et al. [60] both reported significant seasonal variations in occupants' thermal sensation in NV buildings. Conversely, Zhang et al. [61] compared thermal responses in both NV and AC conditions and confirmed the existence of seasonal acclimatization, yet concluded that it did not have a significant impact on thermal sensation or thermal comfort.

Studies regarding effects of climatic adaptation on occupants' thermal perception mainly focused on comfort or neutral temperatures. Generally, these studies found that comfort or neutral temperature in warmer climates was higher than that in cooler climates [7,42,57,62–64]; AC buildings from different regions and climates did not report as prominent differences in neutral temperature as in NV buildings [42,65]. Lau et al. [37] reported a significant negative correlation between neutral temperature and the latitude of the studied site in non-AC buildings. Conversely, Manu [43] concluded that outdoor temperature had very little effect on indoor thermal comfort in AC buildings; Fanger [12] and Zhang et al. [61] both concluded that climate differences did not have any significant impact on occupants' thermal sensation or thermal comfort.

1.3 Scopes and aims of this research

Previous literature has investigated various demographic and contextual factors, and their effects on thermal sensation and comfort. However, due to relatively small sample sizes, unique contexts and limited scopes of individual studies, most investigations only tested one or two factors in isolation. It was thus impossible to explore how these effects interact with other influencing factors of thermal comfort. For example, previous studies have not looked at how thermal sensitivity, humidity sensitivity and air movement sensitivity vary between different ventilation modes, building typologies or seasons. In addition, due to limited factors tested in previous studies, confounding variables have not been commonly controlled, which may have partially contributed to the contradictory results being reported in the literature. With the newly released ASHRAE Global Thermal Comfort Database II [66], which represents the largest database of its kind, it is possible to test a range of demographic and contextual factors simultaneously having thermal environmental parameters controlled; it is also possible to explore how these factors jointly affect building occupants' thermal sensation vote (TSV). Specifically, this study aims to:

- Examine main effects of gender, ventilation mode, building typology, season and monthly outdoor air temperature on occupants' thermal sensation;
- Test the interaction effects between the above demographic and contextual factors;
- Test if occupants' sensitivity to indoor air temperature, vapour pressure, and air speed is affected by demographic and contextual factors.

2. Methodology

2.1 ASHRAE Global Thermal Comfort Database II

ASHRAE Global Thermal Comfort Database II [66], is an online, open-source database containing objective indoor climatic field observations with corresponding “right-here-right-now” subjective evaluations by the building occupants. The field studies in the database are distributed across six continents. (shown in Figure 1).

Figure 1 Locations of the field studies in ASHRAE Global Thermal Comfort Database II [66]

The database includes basic information such as occupancy type, geographical location, climate, season and year of measurement, and heating/cooling strategy; personal information about the participants, such as sex, age, height, weight, clothing value, and metabolic rate; indoor physical measurements including various types of temperatures, relative humidity, air velocity; actual and predicted thermal comfort indexes such as thermal sensation, thermal acceptability, Thermal Preference (TP), thermal comfort, Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Standard Effective Temperature (SET); types of indoor environment controls available, such as blinds, fans, operable windows, doors, heaters, etc.; outdoor meteorological information represented by monthly average temperatures. A detailed description of the database can be found in Földvary Licina et al.[66].

2.2 Exclusion criteria of the dataset

The dataset for the current study was compiled by extracting data for different “continents” in the ASHRAE Global Thermal Comfort Database II website³—Asia, Europe, Oceania, North America, South America and Africa, yielding 107,583 total records from 98 cities in 28 countries across 16 Koppen climate types [1]. Due to large number of missing recordings on key variables of interest, the current analysis was confined to a subset. The following exclusion criteria applied when determining the final dataset for the current analysis:

- The original database has four categories of ventilation modes (cooling strategies as in [66]: AC, mechanically ventilated, NV and MM) and five categories of building typologies (classroom, multifamily housing, office, senior centre and others). Records with mechanically ventilated cooling

³ <http://www.comfortdatabase.com>.

strategy and building typologies of senior centre and others were excluded in the current study due to their scarcity in the database;

- For multilevel linear regression of occupants' TSV, only records with complete sets of dependent and independent variables (deemed as valid cases) were included in the model (see Table 1 for sample sizes);
- Based on the 30/30 rule of sufficient sample size for MLM [67] which recommends a minimum of 30 groups with at least 30 members in each group, records were excluded from the database if the number of valid cases for a specific city was less than 30.
- Univariate and multivariate outliers are removed based on Raudenbush & Bryk [68]'s recommendation.

Table 1. Composition of the data in the current analysis.

Table 1 shows the structure of the data in the current analysis. After applying the above preclusions, the final dataset for TSV regression contained 18,966 survey responses nested within 39 cities nested within 14 climate zones based on the Köppen climate classification [69]. The largest within-city sample size is 1,913 and the smallest is 32 with an average city size of 486. The largest within-climate sample size is 4,458 and the smallest is 96 with an average climate zone size of 1,355.

2.3 Statistical Analysis

2.3.1 Multilevel Linear Models (MLM)

As shown in Table 1, the current dataset displays a hierarchical structure—individual surveys were clustered within cities, which were in turn clustered within countries and/or different climate zones. Survey responses from the same hierarchical level (same city/ country/ climate zone) are likely to be more correlated than from different hierarchical levels (different cities/countries/climate zones). For this reason, we adopted multilevel linear models (MLM) [70,71], a hierarchical linear regression model with a dependent variable defined at the lowest (usually the individual) level, and explanatory variables at all existing levels [67]. Multilevel linear models have been adopted extensively in social and medical research studies where data are often collected from different geographical and/or organizational contexts. It is particularly relevant in cross-cultural research studies involving international datasets with a nesting of data [72]. MLM has also been applied to recent thermal comfort and environmental psychology studies with hierarchical data structure [17,73–76].

In a multilevel model, responses from a subject are thought to be the sum of fixed and random effects. An effect in an experiment is said to be a *fixed effect* if all possible treatment conditions that a researcher is interested in are present in the experiment; if the experiment contains only a random sample of possible treatment conditions, it is called a *random effect* [70]. The main difference between multilevel models and ordinary regression is that parameters in the latter generally are fixed values estimated from the sample (fixed effects) while parameters in the former are allowed to vary (random effects). Fixed effects affect the population mean whereas the random effects contribute only to the *covariance structure* of the data. The covariance structure specifies the form of the variance–covariance matrix (a matrix in which the diagonal elements are variances and the off-diagonal elements are covariances) [70]. Multilevel models permit the modelling of the variance-covariance matrix from the data directly so that the normal requirement of homogeneity of variance across the whole dataset can be relaxed [71]. In this study, although the fixed effect is the only research interest, the covariance structure of the data was adjusted to achieve the best fit of the model. To assess the model fit, $-2LL$ (minus twice the log-likelihood) was compared. The smaller the $-2LL$, the better the model fit to the data [70].

During the process of developing multilevel linear models for TSV, two possible 3-Level hierarchical structures (individual-city-climate zone and individual-city-country) and one 2-Level structure (individual-city) were tested. The goodness-of-fit measures and covariance parameters demonstrated that a 3-level MLM did not improve the model fit over that of a 2-Level structure, meaning that there is no significant between-climate zone/ between-country variances in thermal sensation but significant between-city variances, consequently the

2-Level structure of individual-city was adopted in this study. The *intra-class correlation*⁴ at the “city” level is 10.7%, meaning that 10.7% of the variance in TSV is attributable to the second-level of hierarchy (city).

2.3.2 Dependent and independent variables

In the original database [66], Thermal Sensation Vote (TSV) was registered on the ASHRAE 7-point scale (-3 for cold, 0 for neutral and +3 for hot). Although it is essentially an ordinal variable, thermal comfort research community has usually regarded it as a continuous variable (e.g.[17,42,73,77,78]), thus a multilevel linear regression was applied.

Independent variables were selected following precedents in the literature [12,17] on potential influencing parameters for TSV—air temperature, vapour pressure, air velocity, clothing insulation, Metabolic rate, gender, building typology, ventilation mode, season, and outdoor monthly average temperature. The two-way and occasional three-way interaction items between independent variables were also tested in MLM to examine the interaction effects. It is worth of mentioning that even though operative temperature is a better comfort predictor than air temperature because it combines the effect of thermal radiation, it was not as commonly recorded in the database as air temperature. Consequently, air temperature was selected as the independent variable instead to maximise the sample size. In the original database, relative humidity was recorded. Given that it was correlated with air temperature that causes multicollinearity, vapour pressure was then computed and served as an independent variable in the MLM. The inclusion of vapour pressure as an independent variable in modelling thermal sensation is also seen in previous literature [17,78,79].

Development of MLM was divided into two stages; first, to fit a basic multilevel model containing the universally accepted predictors, i.e. the classic comfort vectors of air temperature, vapour pressure, air velocity, clothing insulation, and metabolic rate [79], along with significant random effects; second, to add demographic and contextual variables—gender, ventilation mode, season, outdoor monthly average temperature and possible interaction items into the basic multilevel model. The coding for categorical independent variables is shown in Table 2. Age was not tested in the MLM due to numerous missing values in the database [66]. In order to test the effect of local climate on thermal perception, *monthly outdoor temperature* was added as an independent variable, which serves as a characteristic of the specific “city” and a Level-2 variable. Due to high frequency of missing values in the original database, we manually input most of the data by looking up the archival weather data and averaging the three monthly mean temperatures in the specified season of the year for the specified city. Most historical weather data were sourced from UK Met Office Hadley Centre Observations datasets⁵ [80]. There were also a few archival weather data obtained from *Weather Underground* website⁶.

Table 2 Coding for categorical independent variables in the MLM

In the MLM, some predictors were centred by their grand mean values. Subtracting a mean from each predictor score—that is “centring” it, changes a raw score to a deviation score. One major justification for doing this is to prevent multicollinearity [70], such as the possible correlation between indoor temperature and outdoor temperature in NV buildings. Also centring can facilitate interpretation when there is no meaning to a value of zero on a predictor [81]. In the MLM, air temperature, vapour pressure, metabolic rate and monthly outdoor temperature were all centred by their respective grand means (shown in Table 3).

Multilevel linear modelling of participants’ TSV was implemented by SPSS Mixed Linear Models (Version 25). Whenever a *post-hoc* analysis was needed for multiple comparisons, a *Sidak* adjustment was performed. All statistical significance level was set to be $p < 0.05$.

⁴ The *intra-class correlation* is an explicit measure of the dependence of errors because it compares differences between groups to individual differences within groups. The larger the intra-class correlation, the greater the violation of independence of errors.

⁵ <https://www.metoffice.gov.uk/hadobs/crutem4/data/download.html>

⁶ <https://www.wunderground.com/history/>

3. Results

3.1 Descriptive statistics

Table 3 presents a statistical summary of the dataset, demonstrating the grand mean values, standard deviations, minimum and maximum values of the continuous independent variables and the dependent variable for the multilevel linear regression of TSV.

Table 3 Descriptive statistics for continuous independent variables and the dependent variable

Figure 2 plots the mean thermal sensation grouped by different building typologies, ventilation modes, and genders. In classrooms, occupants' mean thermal sensation is colder than neutral in AC mode compared to warmer-than-neutral TSV in NV and MM modes; NV is the only ventilation mode available in the dataset for multifamily housing and the mean TSV is about neutral; office buildings observe neutral TSV in AC and MM modes while warmer-than-neutral TSV in NV mode. Gender difference seems to be consistent in that males' mean TSV is generally closer to neutral than females'.

Figure 2 Mean Thermal Sensation grouped by different building typologies, ventilation modes, and genders (error bars indicate 95% confidence interval)

Figure 3 plots the mean thermal sensation grouped by different building typologies, seasons, and genders. Naturally-ventilated multifamily housing observes the most seasonal variations in mean TSV, with warmer-than-neutral mean TSV in springs and summers, and cooler-than-neutral mean TSV in autumns and winters; office buildings, on the contrary, display the least seasonal variation with the mean TSV in all seasons close to neutral; TSV variations in classrooms fall in those between multifamily housing and offices.

Figure 3 Mean Thermal Sensation grouped by different building typologies, seasons, and genders (error bars indicate 95% confidence interval)

3.2 Basic multilevel linear models (MLM) for Thermal Sensation Vote (TSV)

Table 4 demonstrates the parameter estimates for the basic MLM for TSV. The first half of the table displays fixed effect coefficients and the second half displays random effect coefficients. For fixed effects which affect the population mean, air temperature, air velocity, metabolic rate and vapour pressure are significant predictors of thermal sensation ($p < 0.001$ for the first three predictors and $p = 0.05$ for vapour pressure), whereas clothing insulation ($p = 0.45$) is not significant. Air temperature and metabolic rate are positively correlated with TSV while air velocity and vapour pressure are negatively correlated with TSV. Regarding random coefficients, we assume both a random intercepts model and a random slopes model. Random intercepts model assumes the intercepts in the different contexts to be normally distributed around the overall model; similarly, random slopes model assumes the slopes to be normally distributed around the overall slope fitted when ignoring the hierarchical structure [70]. Table 4 reports significant intercept variance and slope variances across the city level (Level 2). Significant variability in the intercept means that under the same air temperature, air velocity, metabolic rate and vapour pressure, occupants' thermal sensation would still be significantly different for people from different cities ($p < 0.001$). Table 4 also reveals that slopes of four predictors (air temperature, vapour pressure, air velocity and clothing insulation) have significant variability ($p < 0.01$, $p < 0.01$, $p < 0.05$ and $p < 0.01$ respectively) across cities. The variances tell us how much the slopes vary around a single slope fitted to the entire dataset (i.e., ignoring the cities that participants come from), confirming that the regression coefficients (slopes) for the four predictors are significantly different between different cities. The interaction between air temperature and vapour pressure also displays significant slope variance ($p < 0.05$) across different cities. The goodness-of-fit measures and significant random coefficients on the "city" level both justify the use of a two-level structure (individual responses clustered within cities) for the MLM.

Table 4 Parameter estimates, standard errors and significance levels for variables tested in the basic MLM

3.3 Multilevel models for testing demographic, contextual and interaction effects

After setting up the basic MLM, we continued to add more predictors into the model in order to test the effects of demographic, contextual factors on thermal sensation. Apart from the main effects, we also tested the two-way interaction effects within these variables as well as the interaction effects between these variables and the three most important environmental parameters, i.e. air temperature, vapour pressure and air speed.

3.3.1 Effects of gender on thermal sensation

Table 5 lists the results of main and interaction effects of gender on TSV. Controlling the significant environmental, demographic and contextual factors, occupants' thermal sensation is significantly different between males and females ($p < 0.01$), and males tend to perceive the same thermal environment 0.10 unit warmer than their female counterparts. Thermal sensitivity (interaction item between gender and air temperature) is also highly significantly different between different genders ($p < 0.001$)—thermal sensitivity of males (0.322) is significantly lower than that of females (0.352), meaning that it takes males 3.1 °C higher or lower air temperature to change one unit of their thermal sensation vote compared to 2.8 °C of air temperature for females. The relationship between TSV and vapour pressure, TSV and air speed do not vary significantly between sexes.

Table 5 The effect of gender and interaction effects on TSV

3.3.2 Effects of ventilation mode on thermal sensation

Table 6 summarizes the effects of ventilation mode and interaction items on thermal sensation. Ventilation mode is not a significant predictor for thermal sensation; yet, the relationship between TSV and air temperature (thermal sensitivity), TSV and vapour pressure, TSV and air speed have detected significant differences between ventilation modes ($p < 0.001$ for all three interaction items). Gender difference in thermal sensation is not affected by ventilation mode. Results are reported in detail for significant interaction effects.

Table 6 The effect of ventilation mode and interaction effects on TSV

Table 7 demonstrates the parameter estimates of significant interaction items between ventilation mode and environmental parameters for TSV. Since females, MM, office and winter serve as the reference group, the estimates listed in Table 7 are the differences in female subjects' thermal sensation in office buildings with other ventilation modes and with mixed-mode during winter. The regression coefficient for air temperature (thermal sensitivity) is 0.345 in MM mode ($p < 0.001$), and thermal sensitivity in AC mode is significantly (0.098) higher than that in MM mode ($p < 0.001$), while not significantly different between NV and MM mode ($p = 0.67$). In MM mode, the regression coefficient of vapour pressure is not significant ($p = 0.13$), indicating no significant association between TSV and vapour pressure in MM buildings in winter; nonetheless in NV mode, vapour pressure is significantly negatively correlated with TSV (regression coefficient -0.347, $p < 0.01$), meaning that holding other variables fixed in NV buildings, TSV decreases when humidity increases from its mean value 1.6 kPa. Given that winter is the reference season in MLM and no significant gender difference is observed in humidity sensitivity, the above finding reveals that higher humidity, ceteris paribus, results in significant cooler thermal sensation in NV office buildings in winter, but no significant association with thermal sensation in AC or MM office buildings. In MM mode, the regression coefficient of air speed is -1.047 ($p < 0.05$), indicating a negative association between TSV and air speed in MM office buildings in winter. Multiple pairwise comparisons demonstrate that occupants' sensitivity to air movement is significantly higher in AC office buildings than in MM office buildings in winter ($p < 0.05$), while no difference exists between air movement sensitivity in NV and MM office buildings ($p = 0.94$). To sum up, during winter season, females' sensitivity to air temperature is significantly higher in AC office buildings than in MM buildings, but no difference exists

between NV and MM office buildings; high humidity results in significantly lower thermal sensation for all occupants in NV office buildings than in AC and MM office buildings in winter; occupants are more sensitive to air movement in AC office buildings than MM office buildings in winter.

Table 7 Estimate of significant interaction items between ventilation mode and environmental parameters for TSV (females, MM, office and winter serve as the reference)

3.3.3 Effects of building typologies on thermal sensation

Table 8 summarizes the effects of building typology and interaction items on thermal sensation. Again, building typology is not a significant predictor for thermal sensation; yet, the relationship between TSV and vapour pressure observes a significant difference ($p < 0.05$) between building typologies. There is also a significant interaction effect between building typology and ventilation mode on thermal sensation ($p < 0.05$). On the contrary, Occupants' sensitivity to air temperature or air speed does not vary between building typology; gender difference in TSV is not affected by building typology either. Results are reported in detail for significant interaction effects.

Table 8 The effect of building typology and interaction effects on TSV

Figure 4 illustrates the effect of building typology, holding all continuous predictors fixed at their respective mean values. Multiple pairwise comparisons reveal that all else being equal, thermal sensation is significantly lower in multifamily housing than in office buildings ($p < 0.01$). This result agrees with previous finding that people tend to be more thermally satisfied with their homes than with their offices even though the thermal environment is essentially the same [8,49,50].

Figure 4 Estimated means of TSV in different building typologies (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Table 9 reports significant interaction effect between building typology and environmental parameters on thermal sensation. Parameters in Table 9 are differences between classroom, multifamily housing and office for female occupants in mixed-mode buildings during winter. As mentioned in Table 7, females' sensitivity to vapour pressure is not significantly associated with TSV in MM office buildings in winter. Table 9 reveals that in multifamily houses, vapour pressure is negatively correlated with TSV during winter (regression coefficient -0.48, $p < 0.05$). Given that all multifamily houses are naturally ventilated, this finding agrees with the previous finding regarding relationship between TSV and vapour pressure in NV buildings in Table 7. Females' sensitivity to vapour pressure in classrooms with mixed mode ventilation during winter is not different from that in office building counterparts ($p = 0.53$). Interaction effects between building typology and ventilation mode will be interpreted in the Discussion section.

Table 9 Estimate of significant interaction items between building typology and environmental parameters for TSV (females, MM, office and winter serve as the reference)

3.3.4 Effects of season and local climate on thermal sensation

Table 10 summarizes the effects of season, local climate and interaction effects on TSV. Occupants' thermal sensation varies significantly between different seasons ($p < 0.01$). The relationship between TSV and air temperature, TSV and air speed are significantly affected by different seasons ($p < 0.01$ and $p < 0.001$ respectively). There is also a significant interaction effect between season and building typology ($p < 0.01$). Monthly outdoor temperature is a highly significant predictor of occupants' thermal sensation ($p < 0.001$). However, this local climatic impact significantly differs between genders ($p < 0.05$). Results are reported in detail for each significant effect.

Table 10 Effects of season, climate and interaction effects on TSV

Figure 5 plots the estimated means of TSV for different seasons, holding all continuous predictors fixed at their respective mean values. Multiple pairwise comparisons reveal that thermal sensation is significantly lower in winter than in spring ($p < 0.01$), summer ($p < 0.01$) and autumn ($p < 0.05$), all else being equal.

Figure 5 Estimated means of TSV in different seasons (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Table 11 reports significant season (interaction) effect and local climate effect (main and interaction) on thermal sensation. The regression coefficient of air temperature (thermal sensitivity) for females in MM office buildings during winter is significantly higher than in spring ($p < 0.01$) and summer ($p < 0.05$). The regression coefficient of air velocity for occupants in MM office buildings during winter is -1.047 ($p < 0.05$). Table 11 reveals that occupants do not perceive the air movement differently between spring and winter, or between autumn and winter; yet there is a significant difference in air movement perception between summer and winter ($p < 0.05$). In summer, the regression coefficient of air speed is positive (0.794) in MM office buildings, but negative in all other seasons. The interaction effect between season and building typology will be interpreted in the Discussion Section. Monthly outdoor temperature is significantly negatively correlated with TSV ($p < 0.001$), with a regression coefficient of -0.038 for females in MM office buildings in winter, meaning that if all else being equal, occupants in the location where the monthly outdoor temperature is higher than the average value 22.1 °C would result in highly significantly lower thermal sensation ($p < 0.001$); and vice versa. Apart from the main effect, there is also a highly significant gender difference in the climatic impact ($p < 0.001$)—the above-mentioned climatic impact on thermal sensation is significantly lower in male occupants than in females.

Table 11 Estimate of significant season and local climate effects on TSV (females, MM, office and winter serve as the reference)

To summarize, both season and local climate are effective moderators of building occupants' thermal sensation. People generally feel warmer during warmer seasons and cooler in cooler seasons, even though the indoor thermal environment is essentially the same. Residents in a warmer climate may deem the same thermal environment to be significantly cooler than residents in a cooler climate.

4. Discussions

The complete multilevel linear regression model for thermal sensation reveals that indoor air temperature, vapour pressure, and air speed are all significantly correlated with occupants' thermal sensation, which agrees with classic thermal comfort literature (e.g. [12,45,46,79]), although the regression coefficients of air temperature, vapour pressure and air speed all vary significantly between different ventilation modes. Table 8 and 10 reveals that there are significant interaction effects between ventilation mode and building typology ($p < 0.05$), and between season and building typology ($p < 0.05$). In this section, these interaction effects are further explored and interpreted.

4.1 Sensitivity to air temperature, humidity and air movement in different ventilation modes during various seasons

Table 6 reveals that occupants' sensitivity to air temperature, humidity and air movement is significantly affected by different ventilation modes. To fully understand these interaction effects and further examine how the relationship between thermal sensation and air temperature, humidity and air movement varies between ventilation modes and seasons, three-way interaction items (environmental parameters $\times$ ventilation mode $\times$ season) are added to the multilevel model individually. For thermal sensitivity, the interaction item is not significant, yet the pairwise comparisons demonstrate that during summer, occupants' thermal sensitivity in AC

office buildings is significantly higher than that in MM office buildings ($p < 0.05$); the same can be said in winter ($p < 0.001$), as already shown in Table 7. No difference is observed in occupants' thermal sensitivity between AC and MM office buildings in spring or autumn. Likewise, no difference exists between NV and MM office buildings for all seasons. Males' thermal sensitivity is consistently lower than females' in all contexts ($p < 0.001$). These findings generally agree with the previous literature that occupants display higher thermal sensitivity in AC buildings than in NV buildings [42–44], however confine it to thermally demanding seasons.

Regarding occupants' sensitivity to humidity, the three-way interaction item is highly significant ($p < 0.001$). Multiple pairwise comparisons demonstrate that in AC office buildings, occupants' thermal sensation is significantly positively correlated with humidity in all seasons ($p < 0.01$), with the highest sensitivity occurred in summer ($p < 0.01$); in NV office buildings, occupants' thermal sensation is negatively correlated with humidity in winter and spring ($p < 0.001$), but no significant correlation is observed in summer or autumn; in MM office buildings, occupants' thermal sensation is significantly negatively correlated with humidity in autumn only ($p < 0.01$), while no significant correlation exists in other seasons. The above findings may seem inconsistent at first glance yet can generally fit into the existing thermal comfort theory. It is known that high humidity exacerbates warm sensation in high temperatures and cold sensation in low temperatures; within a comfortable temperature range, people can well tolerate a large range of humidity levels. This explains the negative correlation between TSV and humidity in NV and MM buildings during cooler seasons since the indoor temperature in these buildings may be much lower than in AC buildings. However, in warmer seasons, occupants' thermal sensation and humidity may be positively correlated or not correlated depending on the indoor temperatures. There is no gender difference in terms of sensitivity to humidity.

Regarding occupants' sensitivity to air movement, the three-way interaction item is significant at $p < 0.01$. Multiple pairwise comparisons reveal that in general, occupants in AC office buildings have the highest sensitivity towards air movement among all ventilation modes in spring, autumn and winter, where more air movement results in lower thermal sensation; in summer, however, the association between air movement and thermal sensation is weak for all ventilation modes.

4.2 Interaction effects between ventilation mode, building typology and season

Figure 6 illustrates the adjusted mean values of TSV under different building typologies and ventilation modes, having all continuous variables fixed at their respective mean values. The MLM reveals that there are significant differences in these mean values ($p < 0.05$). Previous analysis demonstrates a significant effect of building typology ($p < 0.05$), with the TSV in multifamily housing significantly lower than in offices, all else being equal, and an insignificant effect of ventilation strategy. Due to the fact that NV is the only ventilation strategy used in multifamily housing in the whole dataset, it is not possible to tell if the low TSV in residential buildings are associated with ventilation mode (NV) or building typology (multifamily housing), or the joint effects of both. Nevertheless, considering the previous finding that the amount of adaptive opportunities (including opening and closing windows and doors), occupants' sense of belonging and control promote their thermal satisfaction in residential buildings [14,49], it is likely that both building typology and ventilation mode are associated with the near-neutral thermal sensation in homes.

Figure 6 Estimated means of TSV in different building typologies and ventilation modes (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Figure 5 previously illustrates a consistent seasonal effect on TSV, with significantly lower thermal sensation observed in winter than in three other seasons. Mixed models also reveal that there is a significant interaction effect between season and building typology ($p < 0.05$), meaning that seasonal variations of thermal sensation significantly vary between different building typologies. Figure 7 illustrates the adjusted mean values of TSV for different building typologies and seasons. Obviously, office buildings display the least seasonal variation in occupants' thermal sensation among three ventilation modes, with warmer-than-neutral TSV values all year round; multifamily housing observes warmer-than-neutral TSV in spring, whereas cooler-than-neutral TSV

values in summer, autumn and winter; classrooms report positive TSV values in all seasons but winter. This finding is reasonable since offices are the most tightly controlled among all three building typologies; even naturally-ventilated offices generally have narrower temperature ranges than in NV classrooms and houses. In Australia most offices implement a "22 °C scenario" all year round [82,83]. However, contradictory to some previous studies (such as [61]), the current study found that even tightly-controlled office buildings have significant seasonal variations in thermal sensation, although not as pronounced as in multifamily housing and classrooms.

Figure 7 Estimated means of TSV in different building typologies and seasons (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

This study is not without limitations. Although almost always an improvement compared to classical regression [84], multilevel modelling is much more complex to implement and interpret; also, the situation with power and sample size is complicated. In general, a larger sample size is needed if more levels are introduced into the model and more parameters need to be estimated [84]. The dataset used in this analysis has tested many variables including two-way and three-way interactions items, thus may not have large enough samples to detect all significant interaction effects, even though it complies with the general 30/30 rule-of-thumb. Due to large amount of missing values in the original database, some important demographic and contextual factors that may influence thermal sensation, such as occupants' age, body mass index, environmental control options, could not be included in the MLM. In addition, there are also other non-thermal factors, such as ethnicity, educational background, socio-economic status, and environmental awareness, which may affect thermal perception but have not been recorded in the database and are therefore beyond the scope of this analysis. Several previous researches have demonstrated a significant bifurcation of thermal perception in MM buildings when they switch between AC and NV mode [34,40], thus suggesting separate thermal comfort models for each operation stage. Since modes of operation were not recorded for MM buildings in the database, this type of analysis was unachievable with current data resources [66].

5. Conclusions

This study tests the effects of demographic, contextual factors and their interaction effects on building occupants' thermal sensation in studies conducted in 39 cities from 14 climate zones worldwide. Specifically, main and interaction effects of gender, ventilation mode, building typology, season and climate were tested in the multilevel linear model after controlling indoor thermal environments. The following conclusions can be drawn:

- Gender displays significant main and interaction effects on thermal sensation. Females perceive the same thermal environment significantly cooler than their male counterparts in all contexts. Thermal sensitivity is also consistently higher in females; sensitivity to humidity and air movement does not vary between sexes.
- Building ventilation mode does not significantly affect thermal sensation, yet building occupants' sensitivity to air temperature, humidity and air movement significantly vary between different ventilation modes.
- Building typology observes both significant main and interaction effects. All else being equal, occupants have significantly lower and closer-to-neutral thermal sensation in multifamily housing than in offices. However, since all multifamily houses available to this study are naturally ventilated, the above result is likely to be the combined effects of building typology and ventilation mode.
- Season displays significant main and interaction effects on thermal sensation. Under the same thermal environment, occupants have consistently lower thermal sensation during winter in all contexts. Occupants in office buildings have the least seasonal variation in thermal sensation among all building typologies.

- The local climate significantly affects thermal sensation. Given the same indoor thermal environment, occupants from warmer climates tend to feel significantly cooler than their counterparts in cooler climates in all contexts, suggesting a long-term acclimatization effect. Interestingly, this climatic adaptation is consistently more pronounced in females than in males.
- Occupants' thermal sensitivity in AC office buildings is significantly higher than that in MM office buildings during summer and winter. Sensitivity towards air movement in AC offices is significantly higher than in NV and MM offices during all seasons but summer. In AC offices, thermal sensation is positively correlated with indoor humidity level in all seasons, whereas in NV offices, thermal sensation is negatively correlated with humidity in winter and spring, but no correlation is observed in summer and autumn.

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References

- [1] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, *Build. Environ.* 153 (2019) 205–217. doi:https://doi.org/10.1016/j.buildenv.2019.01.055.
- [2] D.A. McIntyre, Chamber studies—reductio ad absurdum?, *Energy Build.* 5 (1982) 89–96. doi:https://doi.org/10.1016/0378-7788(82)90003-2.
- [3] N. V. Baker, Thermal comfort evaluation for passive cooling-A PASCOOL task, in: *Sol. Energy Archit. Plan.*, H S Stephens & Associates, Florence, 1993.
- [4] N.A. Oseland, A comparison of the predicted and reported thermal sensation vote in homes during winter and summer, *Energy Build.* 21 (1994) 45–54. doi:10.1016/0378-7788(94)90015-9.
- [5] N. Baker, M. Standeven, Comfort criteria for passively cooled buildings a pascool task, *Renew. Energy.* 5 (1994) 977–984. doi:https://doi.org/10.1016/0960-1481(94)90120-1.
- [6] G.S. Brager, R.J. De Dear, Thermal adaptation in the built environment : a literature review, *Energy Build.* 27 (1998) 83–96.
- [7] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, *Build. Environ.* 46 (2011) 922–937. doi:10.1016/j.buildenv.2010.10.021.
- [8] A.K. Mishra, M. Ramgopal, Field studies on human thermal comfort — An overview, *Build. Environ.* 64 (2013) 94–106. doi:https://doi.org/10.1016/j.buildenv.2013.02.015.
- [9] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, *Energy Build.* 105 (2015) 178–205. doi:10.1016/j.enbuild.2015.07.047.
- [10] Z. Wang, R. de Dear, M. Luo, B. Lin, Y. He, A. Ghahramani, Y. Zhu, Individual difference in thermal comfort: A literature review, *Build. Environ.* 138 (2018) 181–193. doi:https://doi.org/10.1016/j.buildenv.2018.04.040.
- [11] M. Schweiker, G.M. Huebner, B.R.M. Kingma, R. Kramer, H. Pallubinsky, Drivers of diversity in human thermal perception - A review for holistic comfort models, *Temp. (Austin, Tex.).* 5 (2018) 308–342. doi:10.1080/23328940.2018.1534490.
- [12] P.O. Fanger, Thermal comfort. Analysis and applications in environmental engineering., Danish Technical Press, Copenhagen, 1970. <http://www.cabdirect.org/abstracts/19722700268.html%5Cnpapers2://publication/uuid/5CE163C3-F9AC-4937-A143-1238F1D806C5>.
- [13] T.M. Erlandson, K. Cena, R. de Dear, Gender differences and non-thermal factors in thermal comfort of office occupants in a hot-arid climate, in: Y. Tochihara, T.B.T.-E.E.B.S. Ohnaka (Eds.), *Environ. Ergon.*, Elsevier, 2005: pp. 263–268. doi:https://doi.org/10.1016/S1572-347X(05)80043-6.
- [14] M. Indraganti, K.D. Rao, Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations, *Energy Build.* 42 (2010) 273–281. doi:https://doi.org/10.1016/j.enbuild.2009.09.003.
- [15] H. Liu, Y. Wu, D. Lei, B. Li, Gender differences in physiological and psychological responses to the thermal environment with varying clothing ensembles, *Build. Environ.* 141 (2018) 45–54.

- doi:<https://doi.org/10.1016/j.buildenv.2018.05.040>.
- [16] K.C. Parsons, The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort, *Energy Build.* 34 (2002) 593–599. doi:[https://doi.org/10.1016/S0378-7788\(02\)00009-9](https://doi.org/10.1016/S0378-7788(02)00009-9).
 - [17] F. Zhang, R. de Dear, C. Candido, Thermal comfort during temperature cycles induced by direct load control strategies of peak electricity demand management, *Build. Environ.* 103 (2016) 9–20. <http://dx.doi.org/10.1016/j.buildenv.2016.03.020>.
 - [18] J. Kim, R. de Dear, C. Cândido, H. Zhang, E. Arens, Gender differences in office occupant perception of indoor environmental quality (IEQ), *Build. Environ.* 70 (2013) 245–256. doi:10.1016/j.buildenv.2013.08.022.
 - [19] J.K. Maykot, R.F. Rupp, E. Ghisi, Assessment of gender on requirements for thermal comfort in office buildings located in the Brazilian humid subtropical climate, *Energy Build.* 158 (2018) 1170–1183. doi:10.1016/J.ENBUILD.2017.11.036.
 - [20] R. De Dear, M.E. Fountain, Field Experiments On Occupant Comfort and Office Thermal Environments In a Hot-Humid Climate, *ASHRAE Trans.* 100 (1994) 457–474. [http://www.cbe.berkeley.edu/research/other-papers/de Dear - Fountain 1994 Field experiments on occupant comfort and office thermal environments in a hot-humid climate.pdf](http://www.cbe.berkeley.edu/research/other-papers/de%20Dear%20-%20Fountain%201994%20Field%20experiments%20on%20occupant%20comfort%20and%20office%20thermal%20environments%20in%20a%20hot-humid%20climate.pdf).
 - [21] T.H. Karyono, Report on thermal comfort and building energy studies in Jakarta—Indonesia, *Build. Environ.* 35 (2000) 77–90. doi:[https://doi.org/10.1016/S0360-1323\(98\)00066-3](https://doi.org/10.1016/S0360-1323(98)00066-3).
 - [22] Z. Wang, A field study of the thermal comfort in residential buildings in Harbin, *Build. Environ.* (2006). doi:10.1016/j.buildenv.2005.04.020.
 - [23] D. Shipworth, G. Huebner, M. Schweiker, B.R. Kingma, Diversity in Thermal Sensation: drivers of variance and methodological artefacts, in: L. Brotas, S. Roaf, F. Nicol, M. Humphreys (Eds.), *Proc. 9th Wind. Conf. Mak. Comf. Relev., Network for Comfort and Energy Use in Buildings*, Windsor, UK, 2016: pp. 56–72.
 - [24] S. Karjalainen, Thermal comfort and gender: a literature review, *Indoor Air.* 22 (2012) 96–109. doi:10.1111/j.1600-0668.2011.00747.x.
 - [25] G. Havenith, H. van Middendorp, The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress, *Eur. J. Appl. Physiol. Occup. Physiol.* 61 (1990) 419–427. doi:10.1007/BF00236062.
 - [26] L.G. Berglund, R.R. Gonzalez, Application of acceptable temperature drifts to built environments as a mode of energy conservation, *ASHRAE Trans.* 84 (1978) 110–121.
 - [27] R.L. Hwang, T.P. Lin, N.J. Kuo, Field experiments on thermal comfort in campus classrooms in Taiwan, *Energy Build.* 38 (2006) 53–62. doi:10.1016/j.enbuild.2005.05.001.
 - [28] C. Peng, Survey of thermal comfort in residential buildings under natural conditions in hot humid and cold wet seasons in Nanjing, *Front. Archit. Civ. Eng. China.* 4 (2010) 503–511. doi:10.1007/s11709-010-0095-1.
 - [29] T.T. Chow, K.F. Fong, B. Givoni, Z. Lin, A.L.S. Chan, Thermal sensation of Hong Kong people with increased air speed, temperature and humidity in air-conditioned environment, *Build. Environ.* 45 (2010) 2177–2183. doi:10.1016/j.buildenv.2010.03.016.
 - [30] G.S. Brager, Mixed-mode cooling, *ASHRAE J.* 48 (2006) 30.
 - [31] M. Takasu, R. Ooka, H.B. Rijal, M. Indraganti, M.K. Singh, Study on adaptive thermal comfort in Japanese offices under various operation modes, *Build. Environ.* 118 (2017) 273–288. doi:10.1016/j.buildenv.2017.02.023.
 - [32] R. De Vecchi, C. Candido, R. de Dear, R. Lamberts, Thermal comfort in office buildings: Findings from a field study in mixed-mode and fully-air conditioning environments under humid subtropical conditions, *Build. Environ.* 123 (2017) 672–683. doi:10.1016/J.BUILDENV.2017.07.029.
 - [33] J. Kim, R. De Dear, Impact of different building ventilation modes on occupant expectations of the main IEQ factors, *Build. Environ.* 57 (2012) 184–193. doi:10.1016/j.buildenv.2012.05.003.
 - [34] M.P. Deuble, R.J. de Dear, Mixed-mode buildings: A double standard in occupants' comfort expectations, *Build. Environ.* 54 (2012) 53–60. doi:<https://doi.org/10.1016/j.buildenv.2012.01.021>.
 - [35] S. Drake, R. De Dear, A. Alessi, M. Deuble, Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices, *Archit. Sci. Rev.* 53 (2010) 297–306. doi:10.3763/asre.2010.0021.
 - [36] G. Brager, L. Baker, Occupant satisfaction in mixed-mode buildings, *Build. Res. Inf.* 37 (2009) 369–380. <https://doi.org/10.1080/09613210902899785>.
 - [37] S.S.Y. Lau, J. Zhang, Y. Tao, A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus, *Build. Environ.* 148 (2019) 579–599. doi:10.1016/J.BUILDENV.2018.11.032.
 - [38] S.A. Damiati, S.A. Zaki, H.B. Rijal, S. Wonorahardjo, Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season, *Build. Environ.*

- 109 (2016) 208–223. doi:<https://doi.org/10.1016/j.buildenv.2016.09.024>.
- [39] M. Luo, B. Cao, J. Damiens, B. Lin, Y. Zhu, Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate, *Build. Environ.* 88 (2015) 46–54. doi:<https://doi.org/10.1016/j.buildenv.2014.06.019>.
- [40] R.F. Rupp, R. de Dear, E. Ghisi, Field study of mixed-mode office buildings in Southern Brazil using an adaptive thermal comfort framework, *Energy Build.* 158 (2018) 1475–1486. doi:10.1016/j.enbuild.2017.11.047.
- [41] M. Khoshbakht, Z. Gou, F. Zhang, A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies, *Energy Build.* 196 (2019) 194–205. doi:<https://doi.org/10.1016/j.enbuild.2019.05.030>.
- [42] R.J. De Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, *ASHRAE Trans.* 104 (1998) 1–18. http://repositories.cdlib.org/cedr/cbe/ieq/deDear1998_ThermComPref.
- [43] S. Manu, Y. Shukla, R. Rawal, L.E. Thomas, R. de Dear, Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC), *Build. Environ.* 98 (2016) 55–70. doi:<https://doi.org/10.1016/j.buildenv.2015.12.019>.
- [44] W. Yang, G. Zhang, Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China, *Int. J. Biometeorol.* 52 (2008) 385–398. doi:10.1007/s00484-007-0133-4.
- [45] F.H. Rohles Jr., R.G. Nevins, The Nature of Thermal Comfort for Sedentary Man, *ASHRAE Trans.*, 77 (1971) 239–247. <http://ci.nii.ac.jp/naid/10006771877/en/> (accessed January 22, 2019).
- [46] F.H. Rohles Jr., Revised Modal Comfort Envelope. Description, Validation, and Application of a New Tool for Studying Thermal Comfort., *ASHRAE Trans.* 79 (1973) 52–59. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-0015737823&partnerID=40&md5=f127b168b927c4886aac70b34021ab96>.
- [47] M. Vellei, M. Herrera, D. Fosas, S. Natarajan, The influence of relative humidity on adaptive thermal comfort, *Build. Environ.* 124 (2017) 171–185. doi:10.1016/J.BUILDENV.2017.08.005.
- [48] G. Muzi, G. Abbritti, M.P. Accattoli, M. dell’Omo, Prevalence of irritative symptoms in a nonproblem air-conditioned office building., *Int. Arch. Occup. Environ. Health.* 71 (1998) 372–378.
- [49] N.A. Oseland, Predicted and reported thermal sensation in climate chambers, offices and homes, *Energy Build.* 23 (1995) 105–115. doi:[https://doi.org/10.1016/0378-7788\(95\)00934-5](https://doi.org/10.1016/0378-7788(95)00934-5).
- [50] S. Karjalainen, Thermal comfort and use of thermostats in Finnish homes and offices, *Build. Environ.* 44 (2009) 1237–1245. doi:<https://doi.org/10.1016/j.buildenv.2008.09.002>.
- [51] IUPS Thermal Commission, Glossary of terms for thermal physiology. Third edition. Revised by The Commission for Thermal Physiology of the International Union of Physiological Sciences., *Jpn. J. Physiol.* 51 (2001) 245–280. doi:10.1016/S0306-4565(02)00055-4.
- [52] N.A.S. Taylor, Ethnic differences in thermoregulation: Genotypic versus phenotypic heat adaptation, *J. Therm. Biol.* 31 (2006) 90–104. doi:<https://doi.org/10.1016/j.jtherbio.2005.11.007>.
- [53] K. Cena, R.J. de Dear, Field study of occupant comfort and office thermal environments in a hot, arid climate, *ASHRAE Trans.* 105 (1999) 204. <http://search.proquest.com/libraryproxy.griffith.edu.au/docview/192524560?accountid=14543>.
- [54] S. Heidari, S. Sharples, A comparative analysis of short-term and long-term thermal comfort surveys in Iran, *Energy Build.* 34 (2002) 607–614. doi:10.1016/S0378-7788(02)00011-7.
- [55] R. Becker, M. Paciuk, Thermal comfort in residential buildings – Failure to predict by Standard model, *Build. Environ.* 44 (2009) 948–960. doi:<https://doi.org/10.1016/j.buildenv.2008.06.011>.
- [56] N.A. Oseland, Thermal comfort in naturally ventilated versus air-conditioned offices, in: *Proc. 7th Int. Conf. Indoor Air Qual. Clim.*, Nagoya, Japan, 1996: pp. 215–220.
- [57] F. Nicol, M. Humphreys, Maximum temperatures in European office buildings to avoid heat discomfort, *Sol. Energy.* 81 (2007) 295–304. doi:10.1016/j.solener.2006.07.007.
- [58] A. Wagner, E. Gossauer, C. Moosmann, T. Gropp, R. Leonhart, Thermal comfort and workplace occupant satisfaction-Results of field studies in German low energy office buildings, *Energy Build.* 39 (2007) 758–769. doi:10.1016/j.enbuild.2007.02.013.
- [59] R. Yao, J. Liu, B. Li, Occupants’ adaptive responses and perception of thermal environment in naturally conditioned university classrooms, *Appl. Energy.* 87 (2010) 1015–1022. doi:<https://doi.org/10.1016/j.apenergy.2009.09.028>.
- [60] H. Liu, Y. Wu, B. Li, Y. Cheng, R. Yao, Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China, *Energy Build.* 140 (2017) 9–18. doi:<https://doi.org/10.1016/j.enbuild.2017.01.066>.
- [61] Y. Zhang, H. Chen, J. Wang, Q. Meng, Thermal comfort of people in the hot and humid area of China—impacts of season, climate, and thermal history, *Indoor Air.* 26 (2016) 820–830. doi:10.1111/ina.12256.

- [62] J.F. Nicol, I.A. Raja, A. Allaudin, G.N. Jamy, Climatic variations in comfortable temperatures: The Pakistan projects, *Energy Build.* 30 (1999) 261–279. doi:10.1016/S0378-7788(99)00011-0.
- [63] H.B. Rijal, H. Yoshida, N. Umemiya, Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses, *Build. Environ.* 45 (2010) 2743–2753. doi:<https://doi.org/10.1016/j.buildenv.2010.06.002>.
- [64] K. Cena, R. De Dear, G. Havenith, Environmental and human factors influencing thermal comfort of office occupants in hot—humid and hot—arid climates AU - Erlandson, Tamara, *Ergonomics.* 46 (2003) 616–628. doi:10.1080/0014013031000085707.
- [65] M.A. Humphreys, Outdoor temperatures and comfort indoors, *Batim. Int. Build. Res. Pract.* 6 (1978) 92. doi:10.1080/09613217808550656.
- [66] V. Földvary Licina, T. Cheung, H. Zhang, R. de Dear, T. Parkinson, E. Arens, C. Chun, S. Schiavon, M. Luo, G. Brager, P. Li, S. Kaam, M.A. Adebamowo, M.M. Andamon, F. Babich, C. Bouden, H. Bukovianska, C. Candido, B. Cao, S. Carlucci, D.K.W. Cheong, J.-H. Choi, M. Cook, P. Cropper, M. Deuble, S. Heidari, M. Indraganti, Q. Jin, H. Kim, J. Kim, K. Konis, M.K. Singh, A. Kwok, R. Lamberts, D. Loveday, J. Langevin, S. Manu, C. Moosmann, F. Nicol, R. Ooka, N.A. Oseland, L. Pagliano, D. Petras, R. Rawal, R. Romero, H.B. Rijal, C. Sekhar, M. Schweiker, F. Tartarini, S. Tanabe, K.W. Tham, D. Teli, J. Toftum, L. Toledo, K. Tsuzuki, R. De Vecchi, A. Wagner, Z. Wang, H. Wallbaum, L. Webb, L. Yang, Y. Zhu, Y. Zhai, Y. Zhang, X. Zhou, Development of the ASHRAE Global Thermal Comfort Database II, *Build. Environ.* 142 (2018) 502–512. <https://www.sciencedirect.com/science/article/pii/S0360132318303652> (accessed October 5, 2018).
- [67] J.J. Hox, Multilevel Analysis of Grouped and Longitudinal Data, in: T.D. Little, K.U. Schnabel, J. Baumert (Eds.), *Model. Longitud. Multilevel Data Pract. Issues, Appl. Approaches Specif. Examples*, Lawrence Erlbaum Associates Publishers, Mahwah, NJ, US, 2000: pp. 15–32, 269–281. doi:10.1177/109442812003006001008.
- [68] S.W. Raudenbush, A.S. Bryk, *Hierarchical linear models: Applications and data analysis methods*, 2nd ed., SAGE Publications, Newbury Park, CA, 2002. <http://resources.library.brandeis.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=psyh&AN=1992-97494-000&site=ehost-live>.
- [69] W. Koppen, The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world, *Meteorol. Zeitschrift.* 20 (2011) 351–360. doi:10.1127/0941-2948/2011/105.
- [70] A. Field, *Discovering Statistics using IBM SPSS Statistics*, 4th Ed, SAGE Publications, 2013. <https://books.google.com.au/books?id=AlNdBAAQBAJ>.
- [71] T.A.B. Snijders, R.J. Bosker, *Multilevel analysis: An introduction to basic and advanced multilevel modeling*, 2nd ed., SAGE Publications Inc, London, 2012. doi:10.1007/s00374-009-0409-4.
- [72] J. Lorah, Effect size measures for multilevel models: definition, interpretation, and TIMSS example, *Large-Scale Assessments Educ.* 6 (2018) 8. doi:10.1186/s40536-018-0061-2.
- [73] J. Kolarik, J. Toftum, B.W. Olesen, A. Shitzer, Occupant responses and office work performance in environments with moderately drifting operative temperatures (RP-1269), *HVAC R Res.* 15 (2009) 931–960. <http://www.tandfonline.com.ezproxy2.library.usyd.edu.au/doi/ref/10.1080/10789669.2009.10390873#tabModule>.
- [74] P. Barrett, F. Davies, Y. Zhang, L. Barrett, The impact of classroom design on pupils’ learning: Final results of a holistic, multi-level analysis, *Build. Environ.* 89 (2015) 118–133. doi:<https://doi.org/10.1016/j.buildenv.2015.02.013>.
- [75] F. Zhang, R. de Dear, University students’ cognitive performance under temperature cycles induced by direct load control events, *Indoor Air.* 27 (2017) 78–93. <https://doi.org/10.1111/ina.12296>.
- [76] F. Zhang, R. de Dear, Application of Taguchi method in optimising thermal comfort and cognitive performance during direct load control events, *Build. Environ.* 111 (2017) 160–168. <http://dx.doi.org/10.1016/j.buildenv.2016.11.012>.
- [77] R. de Dear, J. Kim, C. Candido, M. Deuble, Adaptive thermal comfort in Australian school classrooms, *Build. Res. Inf.* 43 (2015) 383–398. doi:10.1080/09613218.2015.991627.
- [78] ASHRAE, 2017 ASHRAE handbook: Fundamentals (SI), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2017. <http://app.knovel.com/hotlink/toc/id:kpASHRAEB2/ashrae-handbook-fundamentals/ashrae-handbook-fundamentals>.
- [79] T. Erlandson, K. Cena, R. De Dear, G. Havenith, Environmental and human factors influencing thermal comfort of office occupants in hot—humid and hot—arid climates, *Ergonomics.* 46 (2003) 616–628. doi:10.1080/0014013031000085707.
- [80] P.D. Jones, D.H. Lister, T.J. Osborn, C. Harpham, M. Salmon, C.P. Morice, Hemispheric and large-

- scale land-surface air temperature variations: An extensive revision and an update to 2010, *J. Geophys. Res. Atmos.* 117 (2012) D05127. doi:10.1029/2011JD017139.
- [81] B.G. Tabachnick, L.S. Fidell, *Using multivariate statistics*, 5th ed, Pearson Education, Limited, Boston, MA, 2013.
- [82] F. Zhang, S. Haddad, B. Nakisa, M.N. Rastgoo, C. Candido, D. Tjondronegoro, R. de Dear, The effects of higher temperature setpoints during summer on office workers' cognitive load and thermal comfort, *Build. Environ.* 123 (2017) 176–188. doi:<https://doi.org/10.1016/j.buildenv.2017.06.048>.
- [83] F. Zhang, R. de Dear, P. Hancock, Effects of moderate thermal environments on cognitive performance: A multidisciplinary review, *Appl. Energy*. 236 (2019) 760–777. doi:10.1016/J.APENERGY.2018.12.005.
- [84] A. Gelman, Multilevel (Hierarchical) Modeling: What It Can and Cannot Do, *Technometrics*. 48 (2006) 432–435. <http://www.jstor.org/stable/25471214>.

Table 1. Composition of the data in the current analysis.

Categorical Variables	N	Percentage
<i>Genders</i>		
Male	9,537	50.3%
Female	9,429	49.7%
<i>Ventilation modes</i>		
AC	6,574	34.7%
NV	5,978	31.5%
MM	6,414	33.8%
<i>Building typologies</i>		
Classroom	1,824	9.6%
Multifamily housing	1,061	5.6%
Office	16,081	84.8%
<i>Seasons</i>		
Spring	2,728	14.4%
Summer	8,640	45.6%
Autumn	2,180	11.5%
Winter	5,418	28.6%
<i>Data Structure</i>		
Number of climate zones	14	
Number of cities	39	
Number of surveys	18,966	100.0%

Table 2 Coding for categorical independent variables in the MLM

Categorical Independent Variables	Coding
Gender	1=Male
	2=Female (reference group)
Ventilation mode	1=AC
	2=Nv
	3=MM (reference group)
Building typology	1=Classroom
	2=Multifamily housing
	3=Office (reference group)
Season	1=Spring
	2=Summer
	3=Autumn
	4=Winter (reference group)

Table 3 Descriptive statistics for continuous independent variables and the dependent variable

Continuous Independent variables and dependent variable	Mean	Standard Deviation	Minimum	Maximum
Air temperature (°C)	25.1	3.47	13.4	37.6
Vapour pressure (kPa)	1.6	0.63	0.1	3.8

Air velocity (m/s)	0.1	0.11	0.0	0.5
Metabolic rate (Met)	1.2	0.21	0.7	6.8
Clothing insulation (clo)	0.6	0.24	0.1	2.2
Monthly outdoor temperature (°C)	22.1	8.22	-16.3	32.3
TSV (-3 for cold, 0 for neutral, +3 for hot)	0.2	1.44	-3.0	3.0

Table 4 Parameter estimates, standard errors and significance levels for variables tested in the basic MLM

Model Term	Parameter estimate	Std. Error	Sig.
<i>Fixed Effect Coefficients</i>			
Intercept	0.50	0.13	$p < 0.001$
Centred air temperature	0.33	0.02	$p < 0.001$
Centred vapour pressure	-0.14	0.07	0.05
Air velocity	-1.01	0.23	$p < 0.001$
Clothing insulation	-0.09	0.12	0.45
Centred metabolic rate	0.44	0.07	$p < 0.001$
<i>Random Effect Coefficients</i>			
Level 1-residual	1.40	0.01	$p < 0.001$
Level 2-Intercept variance	0.54	0.15	$p < 0.001$
Level 2-Centred air temperature variance	0.01	3×10^{-3}	$p < 0.01$
Level 2- Centred vapour pressure variance	0.11	0.04	$p < 0.01$
Level 2-Air velocity variance	0.88	0.40	$p < 0.05$
Level 2-clothing insulation variance	0.39	0.11	$p < 0.01$
Level 2-Centred metabolic rate variance	0.06	0.05	0.21
Level 2- Centred air temperature $\times$ Centred vapour pressure variance	0.01	0.03	$p < 0.05$

Table 5 The effect of gender and interaction effects on TSV

Gender and interaction items	Sig.
Gender	$p < 0.01$
Gender $\times$ centred air temperature	$p < 0.001$
Gender $\times$ centred vapour pressure	NS
Gender $\times$ centred air speed	NS

(NS—not significant)

Table 6 The effect of ventilation mode and interaction effects on TSV

Ventilation mode and interaction items	Sig.
Ventilation mode	NS
Ventilation mode $\times$ centred air temperature	$p < 0.001$
Ventilation mode $\times$ centred vapour pressure	$p < 0.001$
Ventilation mode $\times$ centred air speed	$p < 0.01$
Ventilation mode $\times$ gender	NS

(NS—not significant)

Table 7 Estimate of significant interaction items between ventilation mode and environmental parameters for TSV (females, MM, office and winter serve as the reference)

Interaction items	Estimate	Standard Error	Sig.	95% Confidence Interval	
				Lower	Upper
[AC] × centred air temperature	0.098	0.021	$p < 0.001$	0.056	0.140
[NV] × centred air temperature	-0.006	0.016	0.665	-0.037	0.024
[AC] × centred vapour pressure	-0.132	0.140	0.349	-0.407	0.144
[NV] × centred vapour pressure	-0.347	0.123	$p < 0.01$	-0.588	-0.107
[AC] × centred air speed	-1.303	0.598	$p < 0.05$	-2.476	-0.130
[NV] × centred air speed	-0.040	0.541	0.941	-1.101	1.022

Table 8 The effect of building typology and interaction effects on TSV

Building typology and interaction items	Sig.
Building typology	$p < 0.05$
Building typology × centred air temperature	NS
Building typology × centred vapour pressure	$p < 0.05$
Building typology × centred air speed	NS
Building typology × gender	NS
Building typology × ventilation mode	$p < 0.05$

(NS—not significant)

Table 9 Estimate of significant interaction items between building typology and environmental parameters for TSV (females, MM, office and winter serve as the reference)

Interaction items	Estimate	Standard Error	Sig.	95% Confidence Interval	
				Lower	Upper
[Classroom] × centred vapour pressure	-0.164	0.176	0.352	-0.512	0.183
[Multifamily housing] × centred vapour pressure	-0.549	0.192	$p < 0.01$	-0.930	-0.167

Table 10 Effects of season, climate and interaction effects on TSV

Season, local climate and interaction items	Sig.
Season	$p < 0.01$
Season × centred air temperature	$p < 0.01$
Season × centred vapour pressure	NS
Season × centred air speed	$p < 0.01$
Season × gender	NS
Season × building typology	$p < 0.01$
Season × ventilation mode	NS
Centred monthly outdoor temperature	$p < 0.001$
Centred monthly outdoor temperature × centred air temperature	NS
Centred monthly outdoor temperature × centred vapour pressure	NS
Centred monthly outdoor temperature × centred air speed	NS
Centred monthly outdoor temperature × gender	$p < 0.001$
Centred monthly outdoor temperature × building typology	NS
Centred monthly outdoor temperature × ventilation mode	NS

Centred monthly outdoor temperature $\times$ season

NS

(NS—not significant)

Table 11 Estimate of significant season and local climate effects on TSV (females, MM, office and winter serve as the reference)

Main and interaction effects	Estimate	Standard Error	Sig.	95% Confidence Interval	
				Lower	Upper
[Spring] $\times$ centred air temperature	-0.051	0.016	$p < 0.01$	-0.084	-0.019
[Summer] $\times$ centred air temperature	-0.038	0.017	$p < 0.05$	-0.072	-0.004
[Autumn] $\times$ centred air temperature	-0.024	0.020	0.214	-0.063	0.014
[Spring] $\times$ centred air speed	-0.631	0.496	0.203	-1.603	0.340
[Summer] $\times$ centred air speed	1.841	0.572	$p < 0.01$	0.720	2.963
[Autumn] $\times$ centred air speed	0.368	0.607	0.544	-0.822	1.559
Centred monthly outdoor temperature	-0.038	0.007	$p < 0.001$	-0.053	-0.024
[Male] $\times$ Centred monthly outdoor temperature	0.013	0.003	$p < 0.001$	0.007	0.019

Figure 4 Estimated means of TSV in different building typologies (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Figure 5 Estimated means of TSV in different seasons (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Figure 6 Estimated means of TSV in different building typologies and ventilation modes (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Figure 7 Estimated means of TSV in different building typologies and seasons (all continuous predictors are fixed at their mean values; error bars indicate 95% confidence interval)

Highlights

- Effects of demographic and contextual factors on thermal sensation were examined.
- A subset of ASHRAE Global Thermal Comfort Dataset II were tested.
- Gender, building typology, season and climate significantly affect thermal sensation.
- Interaction effects with influencing factors of thermal comfort were also examined.