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ABSTRACT
Different thermal demands and preferences between individuals lead to a low occupant satisfaction rate, despite the high energy consumption by HVAC system. This study aims to quantify the difference in thermal demands, and to compare the influential factors which might lead to those differences. With the recently released ASHRAE Database, we quantitatively answered the following two research questions: which factors would lead to marked individual difference, and what the magnitude of this difference is. Linear regression has been applied to describe the macro-trend of how people feel thermally under different temperatures. Three types of factors which might lead to different thermal demands have been studied and compared in this study, i.e. individual factors, building characteristics and geographical factors. It was found that the local climate has the most marked impact on the *neutral temperature*, with an effect size of 3.5 °C; followed by country, HVAC operation mode and body build, which lead to a difference of more than 1 °C. In terms of the *thermal sensitivity*, building type and local climate are the most influential factors. Subjects in residential buildings or coming from *Dry* climate zone could accept 2.5 °C wider temperature range than those in office, education buildings or from *Continental* climate zone. The findings of this research could help thermal comfort researchers and designers to identify influential factors that might lead to individual difference, and could shed light on the feature selection for the development of personal comfort models.

Key words:
Thermal comfort; Individual difference; Group difference; Adaptive thermal comfort; ASHRAE Global Thermal Comfort Database

1. Introduction

Among all the building energy consumption sources, heating, ventilation and air conditioning (HVAC) systems accounts for as high as 30% to 50% [1], [2], [3]. However, field studies showed that occupants are not always satisfied with their indoor thermal environment [4], [5]. A major reason behind this problem is people respond differently to the same built environment [6] and have diversified thermal comfort preferences given the same ambient thermal environment [7], which could not be satisfied by a 'one-fits-all' centralized HVAC system without personal adaptation.

The major topic of this study is individual difference[1], which is defined as the different thermal preference between individuals

[1] Some literatures call it inter-individual difference. To keep the term consistence, we use individual difference throughout this study

given the same ambient thermal environment. We care about individual differences because for the purpose of HVAC control, it would be problematic or at least more complicated if some people prefer warmer while others prefer cooler given the same indoor temperature. To address individual thermal comfort demands more efficiently and to achieve higher satisfaction rate in buildings [8], it is important to quantify the magnitude of this difference and what is the source of this difference (sex, age, building type and etc.).

1.1 Diversified thermal comfort demands

Occupants' diversified thermal demands might be driven by many factors. Fanger's heat-balance based PMV-PPD model considered two personal comfort factors, e.g. the clothing insulation and metabolic rate [9]. The uncertainty in these two parameters can cause large PMV ranges [10], [11]. As an example of clothing difference, Fountain et al. [12] found that different dress code in each sex could lead to different temperature preference because females had less clothing insulation (e.g. bare legs in a dress) than their male counterparts (business suit). Regarding the metabolic rate, DeGroot and Kenney pointed out that seniors prefer a higher temperature as the older people's metabolic rate is significantly lower than the youth [13].

As another theoretical framework, the adaptive thermal comfort model ascribes diversified thermal demands to different adaptive aspects such as thermal experiences, expectations [14], [15] as well as drinking hot/cold drinks etc. [16]. In terms of thermal experience, Lee et al. found that people coming from tropical area are less sensitive in hot exposure compared with their counterparts coming from temperate climate region [17]. Thermal expectation is more related to psychological issues. As ANSI/ASHRAE Standard 55 [18] states 'thermal comfort is a condition of mind', how the thermal environment is expected by occupants would also affect their satisfaction levels.

Both the PMV and the adaptive comfort model are averaged model based on a group of people, they may fail to predict individual comfort if large individual difference exists or some hard-to-measure inputs unknown (such as clothing, and metabolic rate). Cheung et al. [19] found that the accuracy of PMV in predicting observed thermal sensation was only 34%. To address the commonly existed personal comfort difference, Kim et al. [20] advocated moving from averaged comfort model toward personalized models. Zhang et al. [21] proposed personal comfort systems to satisfy individual comfort requirements. All these efforts showed that addressing individual comfort difference is important to achieve high satisfaction.

The first step to develop a personal comfort model to predict individual thermal demands is to select proper features which might influence occupants' thermal comfort behaviors and expectations. Sex is widely considered as an influential factor for thermal comfort, and has been frequently analyzed in previous studies [22], [23], [24], [25]. After reviewing dozens of scientific literatures on this topic, Karjalainen [26] found females are more likely than males to express thermal dissatisfaction, but there is no significant difference in neutral temperatures between the genders. Another influential factor is age [23], [27], [28]. Wang et al.'s review [29] found there is no consistent conclusion on whether the age has statistically significant influence on thermal comfort. Other factors have been studied in previous studies include economic conditions [28], thermal history [30], physical disabilities [31], fitness [32], [33], and climate zone and country [34].

However, a major constraint of existing studies is each study focus on only one or a few influential factors. Because different researches applied different statistical models/tests, and utilized different datasets, it is difficult and unconvincing to compare between studies on which factors are more important and should be included in personal comfort models. Therefore, despite the abundant studies on this topic, it is still necessary to re-examine this research question, and compare the effect size of different potential factors with a consistent statistical method on a uniform dataset.

1.2 Objectives and contributions

Comfort is subjective and shaped by a number of sociological and psychological factors, but there are macro-trends. For example, people might feel differently given the same ambient temperature, but they tend to feel hotter when the temperature increases. The goal of this study is to identify those macro-trends for different groups of people with similar characteristics, and to quantify the inter-group difference of those trends. We used a linear regression model - between the ambient temperature and Thermal Sensation (TS) - to simplify and describe the macro-trend of how people feel thermally under different temperatures. There is a clear implication of the regression coefficients: the *intercept* corresponds to the *neutral temperature*, while the *slope* corresponds to the *thermal sensitivity*, both of which are of special interests in this study.

To be more specific, this paper aims to answer two critical questions in thermal comfort field: 1) how much the individual difference could be; and 2) where does the difference come from. Factors which might lead to different thermal preference are classified into three categories: individual factors, building characteristics and geographical factors, as illustrated in Figure 1.

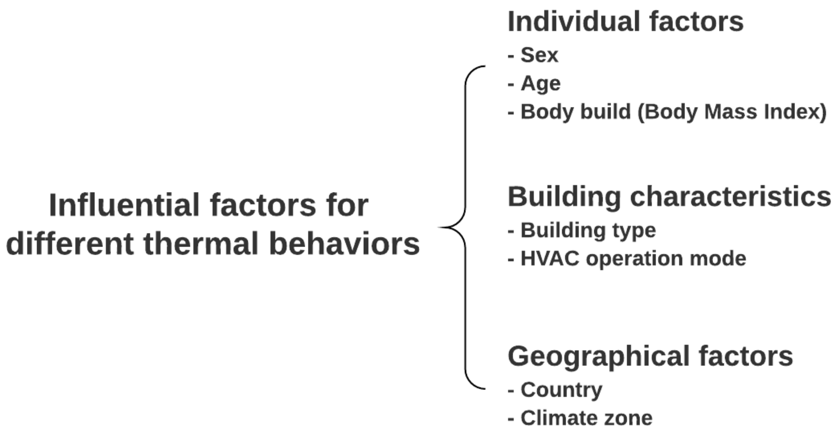


Figure 1: Factors for individual difference to be studied

Despite the fact that there already exist many studies on this topic, revisiting this research question with the recently released ASHRAE Database [35] could bring the following extra benefits and contributions. First, the sample size is critical to statistical analysis. The large sample size of the ASHRAE Database would result in a reliable and robust result. Second, previous studies usually focus on one or two factors leading to individual difference. It is hard to compare the effect size of different factors as different studies use different data sets. The ASHRAE Database provides a unique opportunity to examine and compare different factors with a uniform single dataset. Third, previous studies mainly focus on individual factors, for example sex, since it is challenging to recruit subjects coming from different climate zones and cultural backgrounds for either chamber experiments or field studies. As an international cooperative effort, ASHRAE Database provides us the chance to study on all the three types of factors listed in Figure 1.

2. Method

2.1. Statistical approach

Before studying individual difference in detail, it is necessary to clearly define what is individual difference in this study. Thermal environment is determined by the air temperature, radiant temperature, air velocity and humidity. In this study, we only considered the first two factors by using the operative temperature. The other two factors - air velocity and humidity – were ignored for two reasons. The major reason is very few data points in ASHRAE Database have recorded air velocity and humidity. To make sure the sample size is big enough, we ignored these two factors. Second, temperature has been found to have a stronger effect on thermal comfort than air velocity and humidity. Therefore, we are interested in the difference in *neutral temperature* and *thermal sensitivity* between groups of people with different features. As shown in Figure 2, the *neutral temperature* refers to the temperature corresponding to a neutral thermal sensation vote (TS=0), which is indicated by the intercept term of Equation 1 (β_0 and $\beta_1 * Factor$). The *neutral temperature* might not always necessarily be the preferred temperature in any scenario. For example, Humphreys and Nicol found when the outdoor temperature was high, the preferred temperature tended to be slightly cooler than the *neutral temperature* [36]. However, the *neutral temperature* corresponds to a moderate heat balance and is widely used as an important thermal metrics in laboratory and field studies. The *thermal sensitivity*[2] in this study is defined as the value of temperature change that would lead to a unit thermal sensation vote change, which is indicated by the slope term of Equation 1 (β_2 and $\beta_3 * Factor$). A larger temperature change for a unit thermal sensation vote change means that subjects are not sensitive to temperature deviations. As the thermal comfort zone in ANSI/ASHRAE Standard 55 [18] corresponds to a unit scale ranging from -0.5 to 0.5, a larger value of the slope indicates a wider temperature range is acceptable by the occupants.

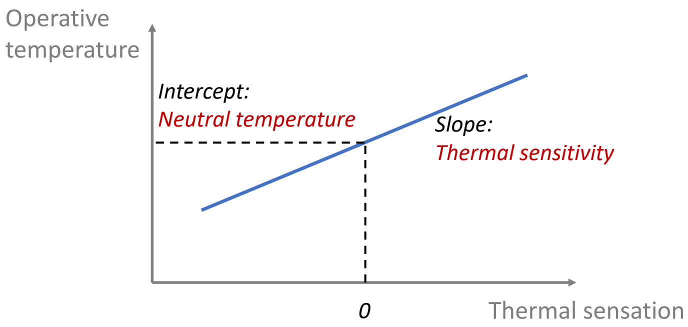


Figure 2: Individual difference of interest in this study

As explained above, the intercept and slope of Equation 1 has the physical implication of the *neutral temperature* and *thermal sensitivity* respectively. The statistical significance of β_1 and β_3 (associated with each factor) indicated whether the factor studied would result in different *neutral temperatures* and *thermal sensitivities* or not. As the regression is applied to a group of people with similar characteristics, the regressed *neutral temperature* and *thermal sensitivity* represents an 'average' person of a specific group, rather than an individual. It is worthy to point out the thermal sensitivity defined in this study ($\beta_2 + \beta_3 * factor$) is the reciprocal of the Griffiths Constant [37].

$Temp \sim \beta_0 + \beta_1 Factor + (\beta_2 + \beta_3 * factor) * TS$ Equation 1

In this study, we are interested in not only whether the difference is statistically significant, but also the effect size of the difference. In statistics, an effect size is a quantitative measure of the magnitude of a phenomenon, which could be correlation between two variables, the regression coefficient in a regression, the mean difference, and etc. As the focus of current research is whether the factors listed in Figure 1 would lead to different *neutral temperature* and *thermal sensitivity*, the effect size in this study is defined as the mean difference in *neutral temperature* and *thermal sensitivity* of different group of occupants, to be more specific, the regressed value of β_1 (effect size of *neutral temperature*) and β_3 (effect size of *thermal sensitivity*).

In this study, we studied the influence of potential factors one by one using Equation 1, rather than applying the multivariate regression to study all factors with one regression. The major reason is to complete the regression we could only use a subset of data that have recorded the factor/factors to be studied. If we studied too many factors in one multivariate regression, the sub-set of data that could be used has a very small sample size. For example, 34598 sets of data could be used for the regression to study the influence of *Sex*, but only 20632 sets of data are usable if we want to study *sex* and *age* together with a multivariate regression.

Another simplification we made here is we used linear regression (Equation 1) to describe the macro-trend of how people feel thermally under different temperatures, though in practice the relation between thermal sensation and operative temperature might be non-linear. There are two reasons behind this simplification. First, the regressed intercept and slope of linear

[2] In some other studies, thermal sensitivity is defined as thermal sensation change/divided by temperature change, which is different to the definition of this study.

regression have clear physical implications. Second, the focus of this study is to quantify the different thermal behaviors of different groups. Using a more complicated models (like quadratic) would introduce more coefficients, and distract us from the key research question we are trying to answer.

To find the values of *neutral temperature* and *thermal sensitivity*, we regressed Equation 1 using the dataset, where the factor of a variable is 0/1 coded, i.e. either 0 or 1, termed as the integer encoding. This method is straightforward for binary variables, for instance sex, the male is coded as 0 and the female as 1. However, for a category with more than 2 variables, such as building type (office, classroom and residential building), it causes confusion because the integers hint a natural ordinal relationship between each variable which does not exist between office, classroom and residential (see Table 1a). One-hot encoding is widely used to encode categorical variables where no ordinal relationship exists. One-hot encoding approach (see Table 1b) assigns 0 or 1 to each variable therefore can avoid the misrepresentation of the ordinal relationship introduced by the integer encoding. This study adopted the one-hot encoding approach. One-hot encoding actually conducted a pair-wise comparison between different groups of samples, in the building type case, it compares office with classroom, office with residential, and classroom with residential respectively.

Table 1 Integer encoding vs. One-hot encoding

Categorical variable	*Building type*
Office	0
Classroom	1
Residential	2

(a) Integer encoding

Categorical variable	*Building type_Office*	*Building type_Classroom*	*Building type_Residential*
Office	1	0	0
Classroom	0	1	0
Residential	0	0	1

(b) One-hot encoding (used in this research)

Another point needs to be discussed in the method section is how we do the grouping. Some groupings are straightforward, such as the grouping the building type into office, classroom and residential. Other groupings might be trickier. There are two principles when we group the occupants. First, the grouping needs to make sense, which ideally should be supported by reference, such as the definition of overweight and underweight. Second, the sample sizes of different groups should be as balanced as possible. If the sample size of one group is much smaller than others, that group might be integrated into other groups to avoid unbalanced sample size.

2.2. ASHRAE Global Thermal Comfort Database

This study applies the statistical analysis mentioned above to the ASHRAE Global Thermal Comfort Database. The ASHRAE Thermal Comfort Database, as an international collaboration led by University of California at Berkeley and University of Sydney, aims to advance thermal comfort studies by integrating and harmonizing the abundant data from worldwide thermal comfort studies [35]. Several criteria on the data selection have been proposed by the research team to guarantee the data quality [35], including: 1) data should come from field tests rather than chamber experiments; 2) both physical indoor climatic observations and 'right-now-right-here' subjective evaluations should be measured; 3) raw data rather than processed should be provided.

Till now, there are two ASHRAE Thermal Comfort Databases available. The Database I was released in late 1990s, recording 25,616 sets of measurements from field studies [38]. The Database II was released very recently in 2018, including 81,967 datasets [35]. In this study, we used data from both Databases, a total of 107,583 observations for the following statistical analysis. To avoid confusion, we use the term *ASHRAE Global Thermal Comfort Database* or *database* to refer to the database with 107,583 observations, without distinguishing Database I or Database II.

ASHRAE Global Thermal Comfort Database recorded 68 attributes, covering subjective thermal comfort vote, objective physical measurement, building characteristics, demographic information of subjects, and local climate/weather condition. The large sample size and abundant attributes of ASHRAE Database, which is really rare in thermal comfort studies, provides a unique chance to leverage the emerging technique of advanced data analytics to address inquiries about thermal comfort studies.

Since the data contributors had different research interests and only measured part of the parameters that we are planning to analyze. For instance, the thermal sensation is recorded in almost every data points (104,454), while the operative temperature is recorded only in 58,025 data points. The "missing" rate is high for the occupant-related attributes such as sex, height, weight, as shown in Table 2. Despite of the relatively high missing rate in some attributes, the data available is still large due to the large overall sample size of the database, compared with existing studies.

Table 2: Missing rate of the variables of interest in the ASHRAE Database [35]

	Records with data available	Missing rate
Operative temperature	58,025	46%
Thermal sensation	104,454	3%
Sex	67,035	38%
Age	43,579	59%
Height & Weight	18,784	82%
Building type	103,384	4%
Country	107,583	0
Climate zone	107,583	0

3. Scale of individual difference

Before examining the influencing factors of individual difference, we quantify the magnitude of individual difference first. In Figure 3, we plotted the Standard Deviation (SD, in green) and 80% range (90% percentile – 10% percentile, in red) of thermal sensation vote (TSV) given similar indoor temperature (binned with 1 ^{o}C) of 25 studies recorded in ASHRAE Database. Please refer to [35] and the ASHRAE dataset[3] for detailed information of the each study. It could be observed that, given the same indoor temperature, occupants reported different thermal sensation. This difference is in the range of 0.5 – 2 scale in most studies. The two individual difference indicators (SD and 80% range) are highly correlated, but the relations between individual difference and ambient temperature is not consistent. In some studies (like Carlucci, 2010), higher temperature leads to a higher individual difference; while in others (like Andamon, 2006), lower temperature leads to higher individual difference. Given the 7-point Likert Scale, a standard deviation/inter-individual variety of 0.5-2 scales is not marginal and should not be ignored. Therefore, in this study, we will not only present the regressed mean, but also report the regressed standard deviation, as a metrics to quantify the differences between individuals.

[3] Link to the dataset: https://dash.berkeley.edu/stash/dataset/doi:10.6078/D1F671

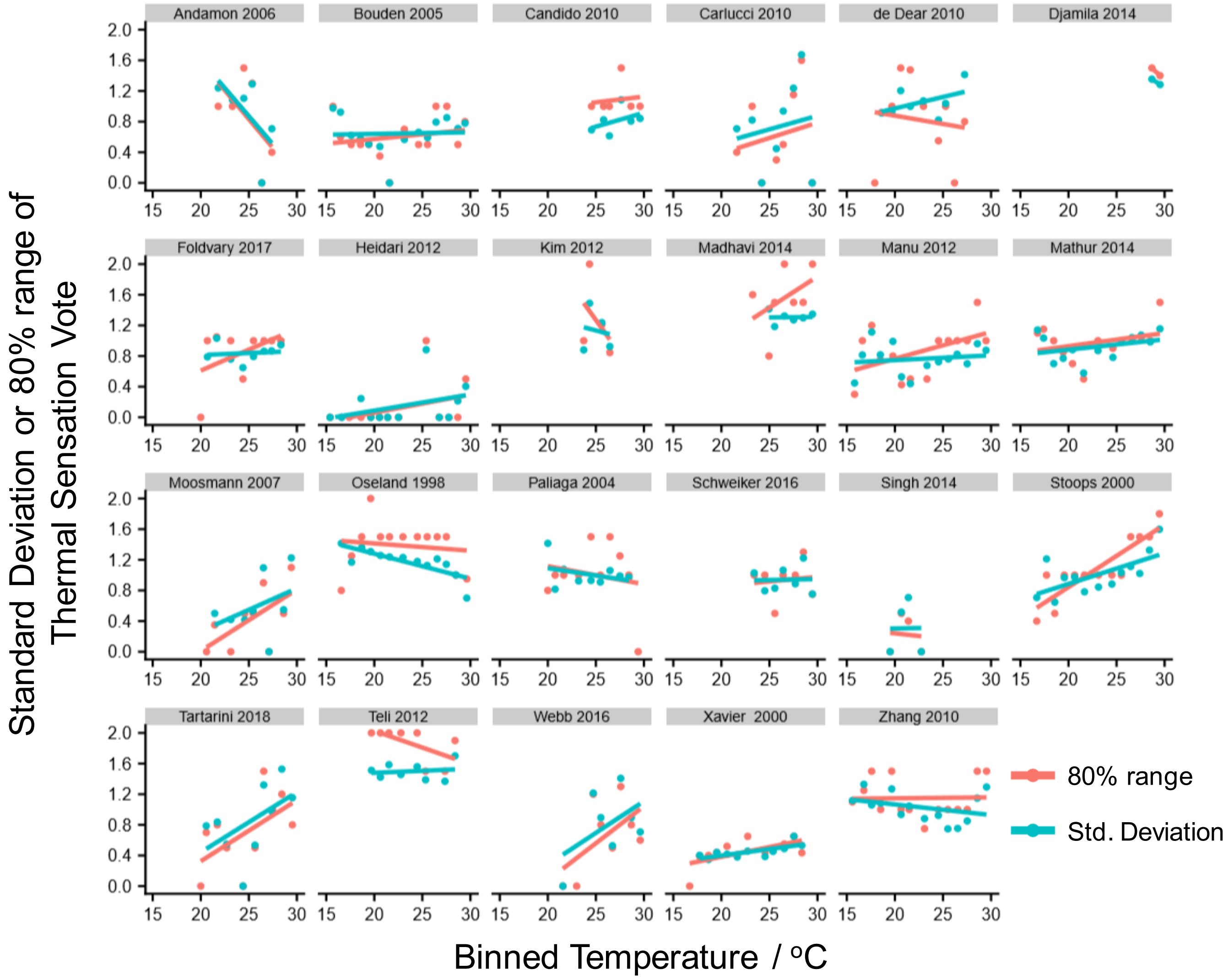


Figure 3. Scale of individual difference: Standard Deviation and 80% range of Thermal Sensation Vote given similar indoor temperature of each study

4. Individual factors

In this section, we tested whether individual factors, including sex, age and body build, lead to statistically significant difference in terms of *neutral temperature* and *thermal sensitivity*.

4.1 Sex

ASHRAE Global Thermal Comfort Database provides a balanced distribution in terms of males and females. Among the 34,598 datasets which include thermal sensation, operative temperature and sex, 47.3% are females and 52.7% are males. The regression result is shown in Table 3 and Figure 4. To examine the difference between male and female, we care about not only the statistical significance, but also the size effect, as Schiavon and Altomonte suggested [39],

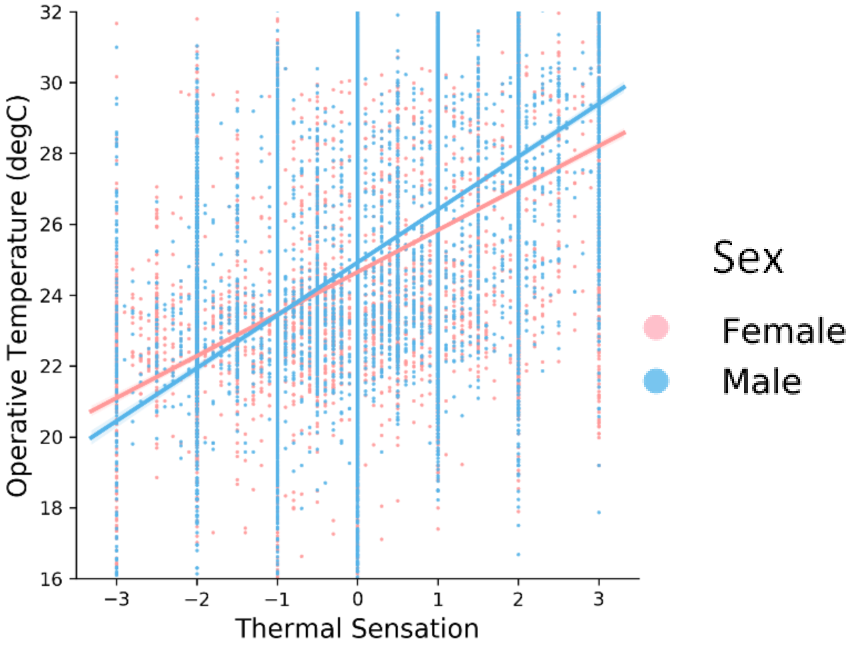


Figure 4: Individual difference from sex (sample size =34,598), the translucent bands in the both figures refer to the confidence interval of the regressed estimates

Table 3: Individual difference from sex (Sample size: 34,598)

	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for females	24.65	0.03	/	0.00	24.60	24.70
β_1: Intercept difference	0.27	0.04	7.56	0.00	0.20	0.34
β_2: slope for females	1.18	0.02	/	0.00	1.15	1.22
β_3: slope difference	0.31	0.03	10.52	0.00	0.25	0.36

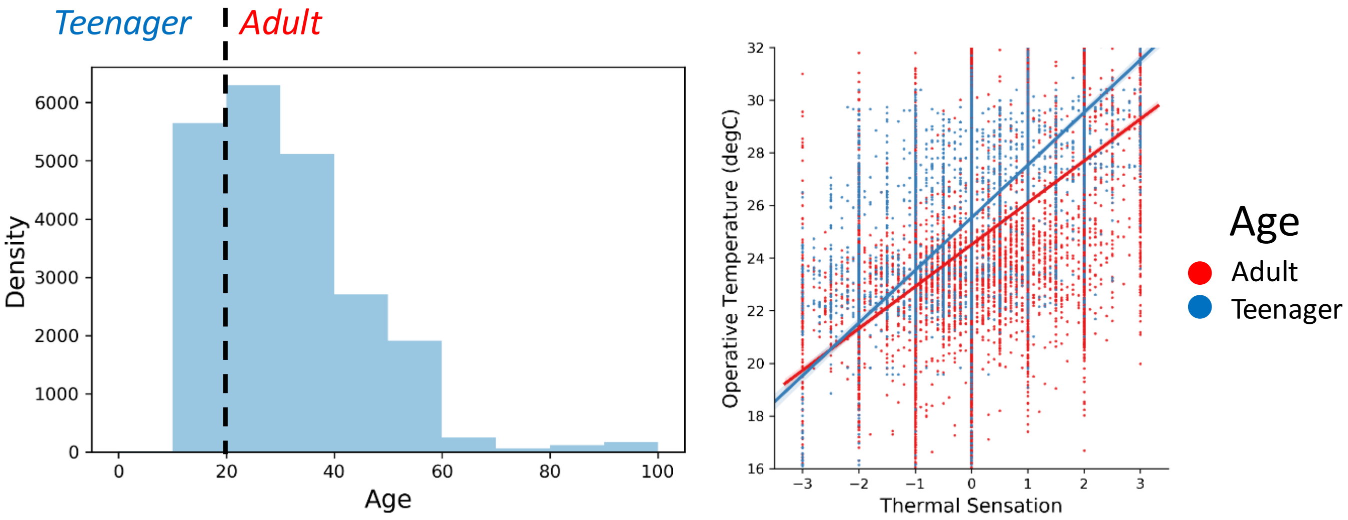
In Figure 4, each point represents a sample in the database, while the line represents the regression result for males (blue) and for females (pink). Due to the large sample size, the confidence interval of the regressed estimates, represented by the translucent bands are narrow in Figure 4, indicating that our analysis could provide reliable results with relatively small uncertainty. Table 3 compares the intercept (*neutral temperature*) and the slope (*thermal sensitivity*) of the four categories, using female as the comparison baseline; and tests whether the difference is statistically significant. As shown in Table 3, the differences in the intercept (*neutral temperature*) and the slope (*thermal sensitivity*) are all statistically significant (see column of *t-statistic* or the $P>|t|$).

In terms of the effect size, the difference in *neutral temperature* between males and females is as low as 0.27 °C (see the coefficient column of β_1, 24.65 °C for females and 24.92 °C for males), which would not make any practical difference in the building operation. In terms of *thermal sensitivity*, females are more sensitive to temperature change than males (1.18 °C/scale vs. 1.49 °C/scale, see the coefficient value of β_2 and $\beta_2 + \beta_3$). To conclude, the difference between males and females is 0.27 °C in *neutral temperature*, and 0.31 °C/scale for *thermal sensitivity*.

The finding that *neutral temperatures* of males and females are similar but females are more sensitive to temperature variation is consistent with previous studies. Wang et al. reviewed 11 chamber experiments and 23 field studies that compared the preferred or neutral temperature between males and females. Among the 34 studies reviewed, only 29% found a statistically significant difference, while the remaining 71% reported either a non-significant or weak difference [29]. As for the *thermal sensitivity*, Karjalainen's literature review found females are more sensitive to and less satisfied with temperature deviations from neutral thermal environment compared with males [26].

4.2 Age

It could be observed from Figure 5(a) that the majority of subjects recorded in the ASHRAE Global Thermal Comfort Database is between 10 and 40 years old. Less than 5% of subjects are above 60 years old, which is not enough to reach a robust comparison with other age groups. Because of this, in this study, we only compared adults (age above 20) and teenagers. Among the 22,299 datasets, 25.4% are teenagers and the remaining 74.6% are adults.



(a) Age distribution (b) Regression result

Figure 5: Individual difference from age (sample size =22,299), the translucent bands in the right figure refer to the confidence interval of the regressed estimates

Table 4: Individual difference from age (Sample size: 22,299)

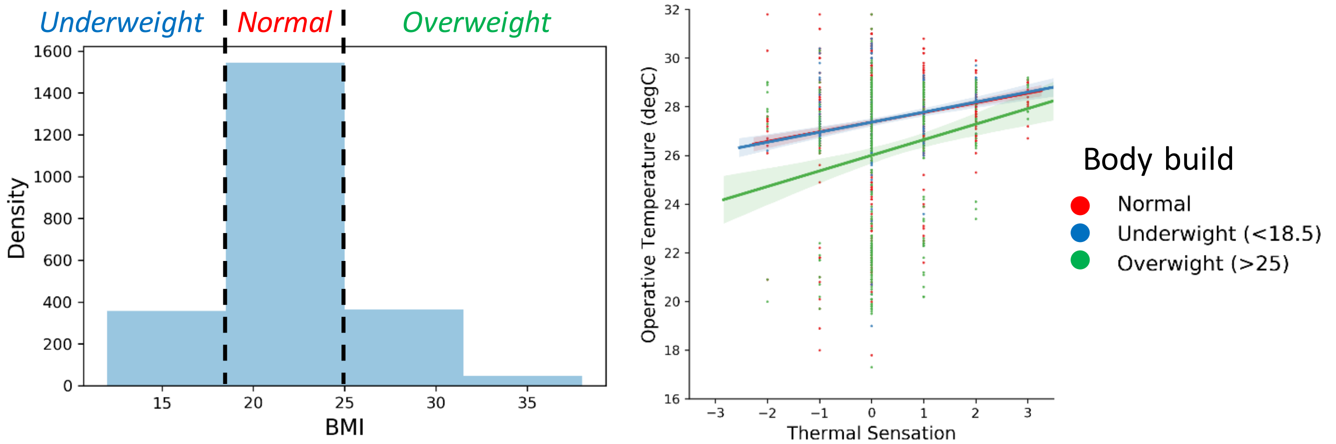
	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for adults	24.50	0.03	/	0.00	24.45	24.55
β_1: Intercept difference	1.03	0.05	18.91	0.00	0.92	1.13
β_2: slope for adults	1.59	0.02	/	0.00	1.55	1.64
β_3: slope difference	0.41	0.05	10.07	0.00	0.33	0.49

Figure 5(b) and Table 4 presents the result. The difference between adults and teenagers are significant in terms of the *neutral temperature* and *thermal sensitivity*. The *neutral temperature* difference between teenagers and adults are more marked than that between males and females. Teenagers have a 1.03 °C higher *neutral temperature* and could accept a 25.8% wider temperature variation than adults. One reason for why teenagers have a 1.03 °C higher *neutral temperature* is in the ASHRAE thermal comfort database, more than 60% of teenager samples are contributed by the study on tropical classrooms [40]. As will be discussed later, subjects from tropical areas tend to have higher *neutral temperature*. Therefore, we would argue that the conclusion that teenagers have a higher *neutral temperature* needs further verification as the samples supporting this conclusion are biased and not sufficiently representative of the whole population.

4.3 Body build

We used the Body Mass Index (BMI), defined in Equation 2, as an indicator for body build, and then classified the subjects into underweight, normal, and overweight based on the principle proposed by the World Health Organization: adults with BMI below 18.5 kg/m^2 are underweight, while above 25 kg/m^2 is overweight [41]. To calculate BMI, the height and weight of subjects need to be measured, which is challenging in field studies. Only 2326 data points record subjects' height and weight, among which, 18% are overweight, and 16% are underweight. Because of the relatively small sample size, the confidence interval of the regressed estimates is wider than other comparisons, leading to the observable translucent bands around the regression lines in Figure 6(b).

$$\mathrm{BMI} = \frac{\mathrm{weight}}{\mathrm{height} * \mathrm{height}} \qquad \text{Equation 2}$$



(a) Body build distribution (b) Regression result

Figure 6: Individual difference from body build, the translucent bands in the right figure refer to the confidence interval of the regressed estimates (sample size =2326)

Table 5: Individual difference from body build (Sample size: 2,326)

	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for *normal*	27.36	0.05	/	0.00	27.26	27.47
$\beta_{1\_underweight}$: Intercept difference between *normal* and *underweight*	0.00	0.12	0.00	1.00	-0.24	0.24
$\beta_{1\_overweight}$: Intercept difference between *normal* and *overweight*	-1.36	0.12	11.82	0.00	-1.59	-1.14
β_2: slope for *normal*	0.40	0.06	/	0.00	0.29	0.51
$\beta_{3\_underweight}$: slope difference between *normal* and *underweight*	0.01	0.13	0.11	0.92	-0.24	0.27
$\beta_{3\_overweight}$: slope difference between *normal* and *overweight*	0.24	0.12	2.00	0.05	0.00	0.48

The influence of BMI on thermal demands are shown in Figure 6(b) and Table 5. No statistically significant difference were found between normal and underweight subjects, no matter for the *neutral temperature* or *thermal sensitivity*. However, the difference between normal and overweight subjects are statistically significant. Overweight subjects have a 1.4 ºC lower neutral temperature and could accept a 60% wider temperature range. The finding that overweight subjects have a cooler neutral temperature has been presented in previous research [42]. However, overweight subjects are less sensitive to temperature variation has not been reported before, to the best of the authors' knowledge. From physiology point of the view, overweight subjects might be less sensitive to cool thermal environment due to the increased insulation of body fat, but more sensitive to warm environment due to increased body mass and metabolic rate. However, the smaller sample size in the database with body build information does not allow us to perform further detailed analysis by further sub-dividing the sample size to warm and cool sensation groups.

5. Building characteristics

A key inference from the adaptive comfort theory is that building characteristic would markedly influence occupants' adaptive behaviors and thermal expectations, leading to different thermal demands [43]. In this section, we will examine the influence of building type (commercial buildings and residential buildings) and HVAC operation mode (cooling, heating, and natural ventilation) on thermal demands.

5.1 Building type

There are five building types in the Database: office building, classroom, residential, senior center and others. Since the senior center and others only account for around 1% and 4% of the total data points, we only compared office building, classroom and residential buildings in this study. The sample size for this comparison is 51,164 (69% office, 25% classroom, and 6% residential).

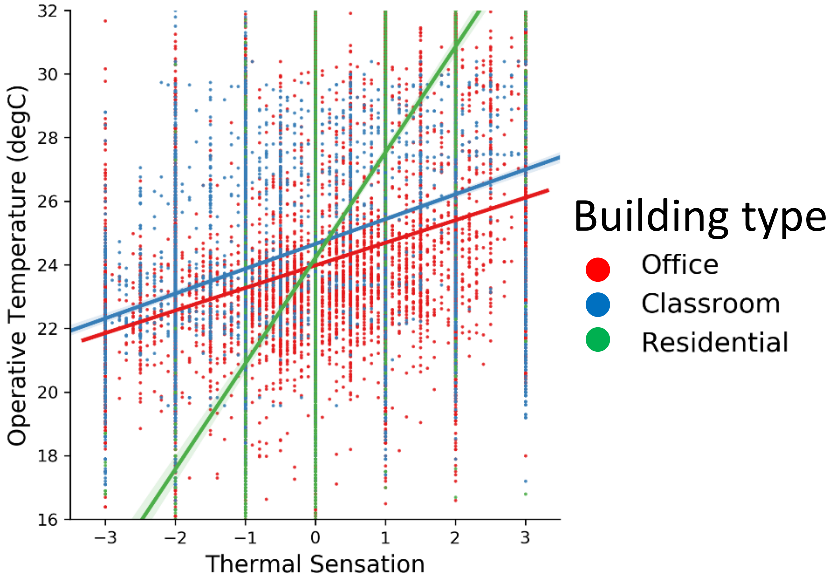


Figure 7: Individual difference from building type (sample size =51,164), the translucent bands in the figure refer to the confidence interval of the regressed estimates

Table 6: Individual difference from building type (Sample size: 51,164)

	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for *office*	23.98	0.02	/	0.00	23.95	24.01
$\beta_{1\_residential}$: Intercept difference between *office* and *residential*	0.23	0.06	3.71	0.00	0.11	0.34
$\beta_{1\_classroom}$: Intercept difference between *office* and *classroom*	0.67	0.03	21.67	0.00	0.61	0.73
β_2: slope for *office*	0.71	0.01	/	0.00	0.69	0.74
$\beta_{3\_residential}$: slope difference between *office* and *residential*	2.61	0.05	48.74	0.00	2.51	2.72
$\beta_{3\_classroom}$: slope difference between *office* and *classroom*	0.07	0.02	3.02	0.00	0.03	0.12

The most obvious difference we could observe from Figure 7 and Table 6 is that subjects from residential buildings could accept a much larger temperature variation than those in office buildings or classrooms. If we define thermal sensation between -0.5 and +0.5 as the acceptable thermal range[4], then subjects from residential buildings could accept 3.3 ºC ($\beta_2 = 0.71,\ \beta_{3\_office} = 2.61$) temperature variation, while subjects from offices and classrooms could only accept 0.7 ($\beta_2 = 0.71$) and 0.8 ºC ($\beta_2 = 0.71,\ \beta_{3\_classroom} = 0.07$) respectively. This finding could be explained from the following three aspects. First, people at home have much more freedom to take adaptive measures to achieve thermal neutrality, for example adjusting their clothing without considering any dress codes required in office settings. Second, occupants in residential buildings have

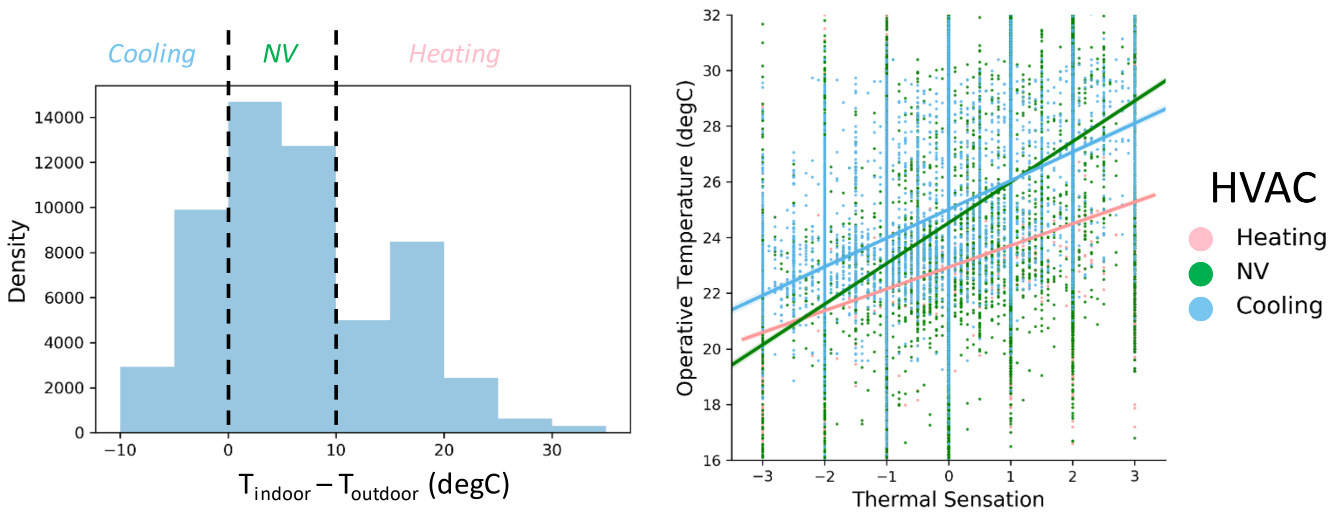
[4] According to ASHRAE Standard 55-2017 [18], the comfort zone is defined as the combination of conditions for which the PMV is between -0.5 and +0.5. Considering the Thermal Sensation Vote (TSV) has similar implication and high correlation with PMV, we set thermal sensation vote between -0.5 to +0.5 as acceptable range in this study.

greater control over the room environment, without sharing the thermostat with their colleagues or classmates [44]. The remarkably high perceived control over the thermal environment in residential buildings results in a wider acceptable temperature range [45]. Third, occupants in residential buildings need to pay for cooling and heating, economically incentivizing themselves [46] to adapt to a wider temperature range, rather than solely relying on HVAC to control the thermal environment within the comfort range without considering the energy bill as in office settings.

Unlike the markedly different thermal demands between residential and commercial buildings, the size of difference between subjects from office buildings and classrooms is marginal even though this difference is statistically significant: the neutral temperature difference is 0.67 °C and the thermal sensitivity difference is 0.07K/TS. Occupants from classroom has a higher *neutral temperature* than those from office buildings, which is consistent to the previous finding that the *neutral temperature* of teenagers is higher than that of adults, as more data from classrooms are from teenagers in the database. Another possible explanation is that the classrooms are less controlled by HVAC systems comparing to office buildings, so people in classrooms are more adaptive. It is difficult to distinguish whether the building type or the factor of age is the cause for this difference. As we know, a shortcoming of statistical analysis is that it could only reveal correlation but not causality.

5.2 HVAC operation mode

In ASHRAE Database, whether the space is heated or cooled was not explicitly recorded. However, the HVAC operation mode could be inferred by comparing the room temperature and outdoor temperature. In a conditioned building, there is often a large temperature difference between indoor and outdoor air [47], while in naturally ventilated building, the indoor thermal environment is closer to the outdoor. This difference might result in occupants' different thermal behaviors and demands. Considering the fact that there are internal heat gains from occupants, appliances and lighting, the indoor temperature should be slightly higher than outdoor temperature if there is no mechanical heating or cooling system running. We assume the indoor space is in cooling mode if the indoor temperature is lower than outdoor temperature, and indoor space is in heating mode if the indoor temperature is 10 °C higher than the outdoor temperature. The 10 °C criteria corresponds to the scenario that when the outdoor temperature is 10 °C or less, the indoor temperature should be at least 20 °C in heating mode. Additionally, we included NV building as the comparison baseline. Based on this criterion, 22% of data points analyzed are in cooling mode and 30% are in heating mode.



(a) HVAC mode distribution (b) Regression result

Figure 8: Individual difference from HVAC mode (sample size =57,821), the translucent bands in the right figure refer to the confidence interval of the regressed estimates

Table 7: Individual difference from HVAC mode (Sample size: 57,821)

	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for *NV*	24.53	0.02	/	0.00	24.49	24.56
$\beta_{1\_cooling}$: Intercept difference between *NV* and *cooling*	0.49	0.04	13.92	0.00	0.42	0.55
$\beta_{1\_heating}$: Intercept difference between *NV* and *heating*	-1.59	0.03	50.14	0.00	-1.66	-1.53
β_2: slope for *NV*	1.46	0.02	/	0.00	1.43	1.49
$\beta_{3\_cooling}$: slope difference between *NV* and *cooling*	-0.43	0.03	15.46	0.00	-0.48	-0.38
$\beta_{3\_heating}$: slope difference between *NV* and *heating*	-0.68	0.02	28.32	0.00	-0.73	-0.63

Two major conclusions could be drawn from Figure 8(b) and Table 7. First, the *neutral temperature* of subjects in cooling mode is the highest (25.02 ^oC) (give a value), followed by the NV building (24.53 ^oC) , and is the lowest in heating mode (22.94 ^oC). Second, occupants in NV buildings could accept a larger temperature variation than those in cooling and heating modes (1.46 K/TS scale for NV vs. 1.03 K/TS scale for cooling and 0.78 K/TS scale for heating). Both of these two findings are consistent with the predictions from the adaptive comfort theory. The adaptive comfort theory predicts a higher *neutral temperature* in summer when the cooling is needed and a lower *neutral temperature* in winter when the heating is required. Additionally, adaptive comfort theory argued that occupants in NV buildings are more likely to take adaptive measures so that they could accept a wider temperature range.

6. Geographical factors

There are a few field studies which evaluated the effect of climate or culture background on thermal comfort [48], [49], [50], [51], [52], however, because the sizes of these data is small, normally within double digit, therefore, the analysis is limited and not conclusive. As an international collaborative effort, the ASHRAE Global Thermal Comfort Database provides a good chance to compare thermal demands of subjects from different countries and climate zones with a large and unified data set. The data collected in the ASHRAE Global Thermal Comfort Database include subjects from 28 countries. As shown in Figure 9, the top three dataset collected are from United Kingdom, United States and India, followed by China, Australia and Brazil. Only a marginal proportion of data are from African continent.

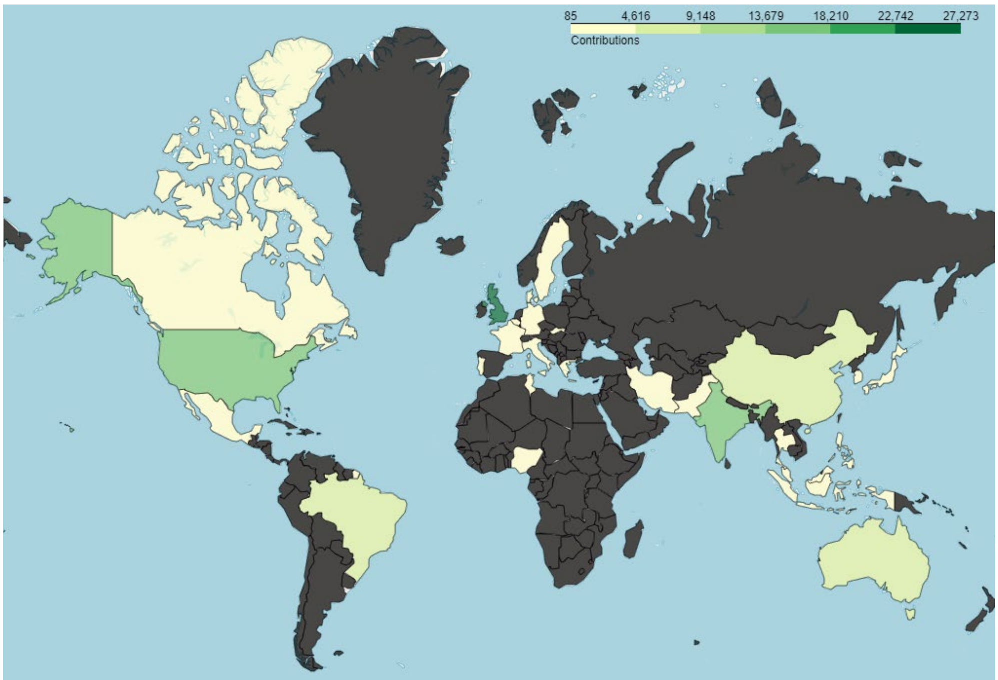


Figure 9: Geographical distribution of data points in ASHRAE Global Thermal Comfort Database

6.1 Country

Considering that there are 28 countries recorded in the ASHRAE Database and the sample size for each country is unbalanced (ranging from 85 from Belgium to 27273 from the UK), it is impractical and inappropriate to do a one-on-one comparison on the thermal demands of different countries. Therefore, we classified the 28 countries into two groups based on income: high-income countries and non-high-income countries, because we hypothesis that people in high income countries are more likely to rely on air-conditioning than people from non-high-income countries. Relying on air-conditioning might cause people less adaptive to ambient environment. We adopted the definition of high-income proposed by the World Bank. The countries with Gross National Income per capita higher than 12,056 US Dollars are high-income economies [53] [5]. Among the 57,908 data points analyzed, 67% are from high-income economies and the remaining 33% are from non-high-income economies.

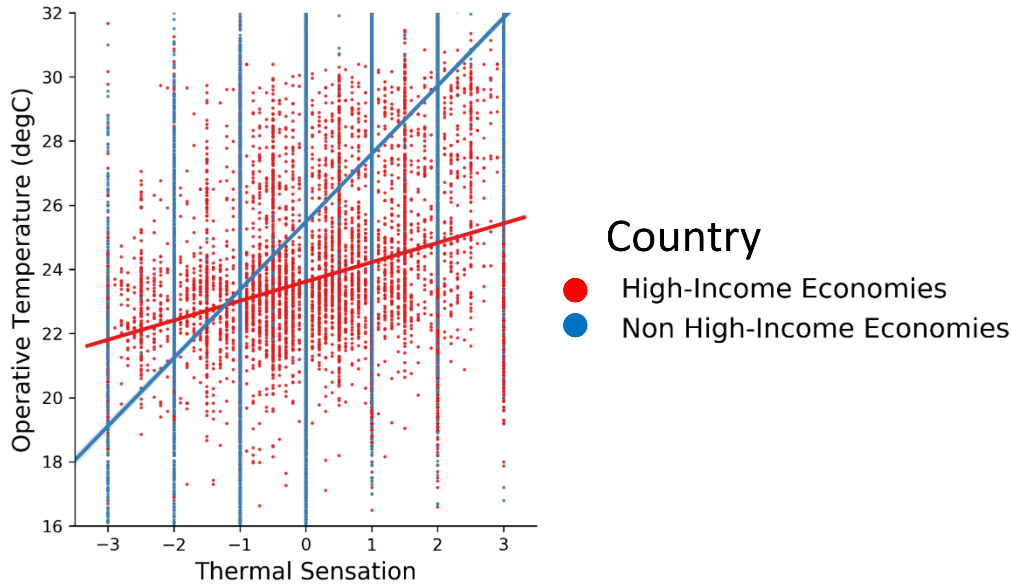


Figure 10: Individual difference from country (sample size =57,908), the translucent bands in the figure refer to the confidence interval of the regressed estimates

Table 8: Individual difference from country (Sample size: 57,908)

	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for *high-income economies*	23.62	0.02	/	0.00	23.59	23.65
β_1: Intercept difference	1.86	0.03	67.41	0.00	1.81	1.92
β_2: slope for *high-income economies*	0.60	0.01	/	0.00	0.58	0.63
β_3: slope difference	1.52	0.02	72.08	0.00	1.48	1.56

As shown in Figure 10 and Table 8, subjects from high-income economies have a 1.86 °C lower neutral temperature and 60% narrower acceptable temperature range than people from non-high-income countries, both of which might be ascribed to the wider application of air conditioning. In developing countries where HVAC equipment is less affordable, and people are more likely to accept a higher *neutral temperature* and a wider temperature variation.

6.2 Climate zone

According to the prediction of adaptive comfort theory, local climate also plays a significant role to determine occupants' thermal demand and preference. ASHRAE Database categorized climate based on the Köppen Climate Classification (KCC).

[5] Among the 28 countries included in the database, high-income countries include: Australia, Belgium, Canada, Denmark, France, Germany, Greece, Italy, Japan, Portugal, Singapore, Slovak, South Korea, Sweden, UK, USA; non-high-income countries include: Brazil, China, India, Indonesia, Iran, Malaysia, Mexico, Nigeria, Pakistan, Philippines, Thailand, Tunisia

KCC divides the climates into five major groups: tropical, dry, temperate, continental, and polar. Except for polar, the remaining four climate regions are all included in the database: 22% from tropical, 14% from dry, 54% from temperate, and 10% from continental.

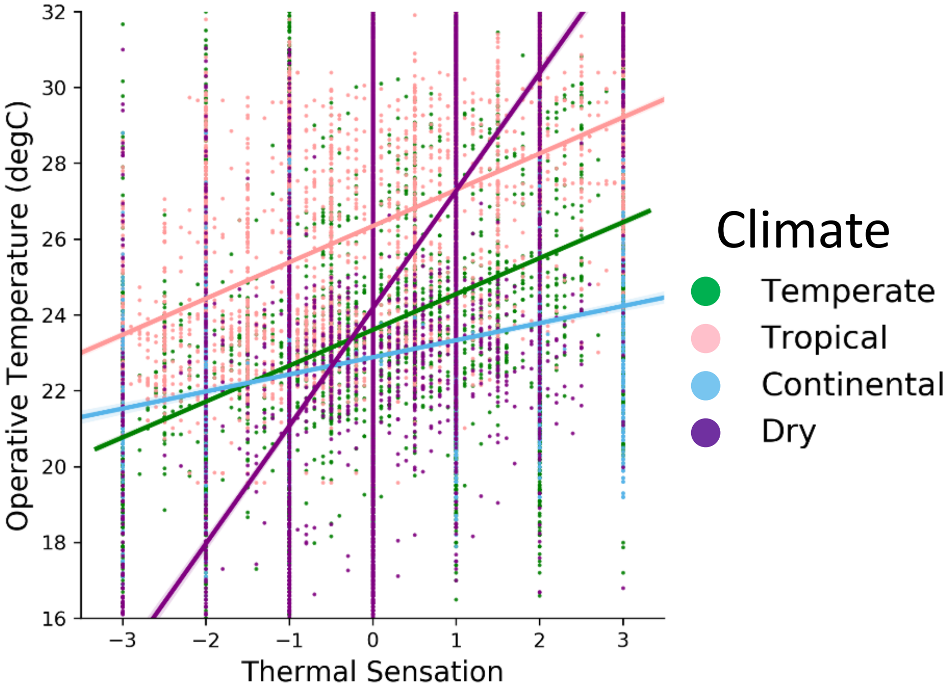


Figure 11: Individual difference from climate zone (sample size =56,292), the translucent bands in the figure refer to the confidence interval of the regressed estimates

Table 9: Individual difference from climate zone (Sample size: 56,292)

	Coefficient	Std. Err.	t-statistic	P>|t|	[0.025	0.975]
β_0: Intercept for *Continental*	22.88	0.04	/	0.00	22.81	22.95
$\beta_{1\_temperate}$: Intercept difference between *Continental* and *Temperate*	0.72	0.04	18.61	0.00	0.65	0.80
$\beta_{1\_tropical}$: Intercept difference between *Continental* and *Tropical*	3.46	0.04	80.75	0.00	3.38	3.55
β_{1_dry}: Intercept difference between *Continental* and *Dry*	1.29	0.05	24.37	0.00	1.18	1.39
β_2: slope for *office*	0.45	0.03	/	0.00	0.40	0.50
$\beta_{3\_temperate}$: slope difference between *Continental* and *Temperate*	0.50	0.03	17.51	0.00	0.44	0.55
$\beta_{3\_tropical}$: slope difference between *Continental* and *Tropical*	0.51	0.03	16.00	0.00	0.44	0.57
β_{3_dry}: slope difference between *Continental* and *Dry*	2.65	0.04	67.18	0.00	2.57	2.73

As shown in Figure 11 and Table 9, subjects coming from tropical area have the highest *neutral temperature*, which is at least 2 ºC higher than the other three climate regions. People from continental region has the lowest neutral temperature. The adaptive comfort theory predict that people would adapt themselves to local climates gradually through behavioral, physiological and psychological adjustments. Therefore, people coming from tropical area would get used to hot climates and people coming from cold region would get used to cold climates. It could also be found that subjects from dry area could accept a much wider temperature range than subjects from the remaining three climate regions. One possible explanation is that, because more data for dry area in the database is from less developed economies, for example Africa and India, where people rely less on air-conditioning and are more adaptive. Another possible explanation is that dry climate might have larger ambient temperature ranges (like in the desert), therefore people from the dry climate gradually adapt to and be able to accept a larger temperature difference.

7. Discussion

7.1 Findings and contributions

A key support of this method is the recently released ASHRAE database. It is the largest thermal comfort database so far. The large sample size is critical for data-driven models such as the one presented in this paper. Additionally, the ASHRAE Global Thermal Comfort Database provide a unique opportunity to compare the different influential factors with a single unified data set. This comparison has not been done in existing studies. In existing literature, each study focus on a subset of potential factors. It is difficult to compare which factor is more statistically important for thermal comfort, as the results are from different datasets. The recently released ASHRAE database open the door to compare different factors with a single uniform dataset, which allows us to study and compare individual, building, and geographic factors, as listed in Figure 1.

The thermal comfort index of special interest in this study is *neutral temperature* and *thermal sensitivity*. We selected these two index because they are important in determining the HVAC temperature set-point ($T_{neutral}$) as well as the comfort range ($T_{neutral} \pm k * thermalSensitivity$)[6]. It is worthy to point out that the *thermal sensitivity* defined in this study is the reciprocal of the Griffiths Constant. The large variability of *thermal sensitivity* for different group of people confirms other researchers' finding that the Griffiths Constant should not be considered as a constant, as it varies in different occasions [37].

Among all the comparisons we've done in this study, only the difference between normal weight subjects and underweight subjects is not statistical significant, the remaining are all significant from the statistical point of view. However, in this study, we care about not only the statistical significance, but also the size effect, because a small size effect would not make any practical differences in the building industry. These findings indicate that the neutral temperature and thermal sensitivity vary a lot for different group of occupants, different building characteristics and in different regions of the world. There should be no single thermal comfort standards universally valid for all scenarios.

Figure 12 and Table 10 summarizes the magnitude of differences (size effect) in *neutral temperature* and *thermal sensitivity* resulted from all the seven factors explored in this study. Each dot in Figure 12 stands for the difference between two sub-groups with different features. For instance, the single dot in the column sex stands for the difference between male and female; similarly, the six dots in column climate stand for the difference between six comparison pairs from the four climate groups[7]. From Table 10, it is clear that climate zone and country are most influential factors for *neutral temperature* while climate zone and building type markedly influenced occupants' *thermal sensitivity*.

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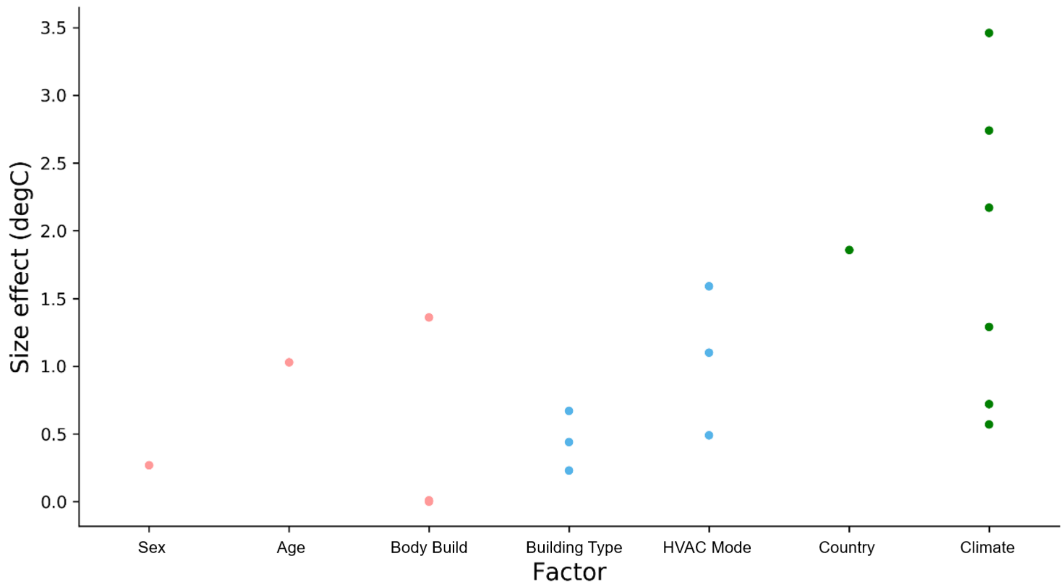
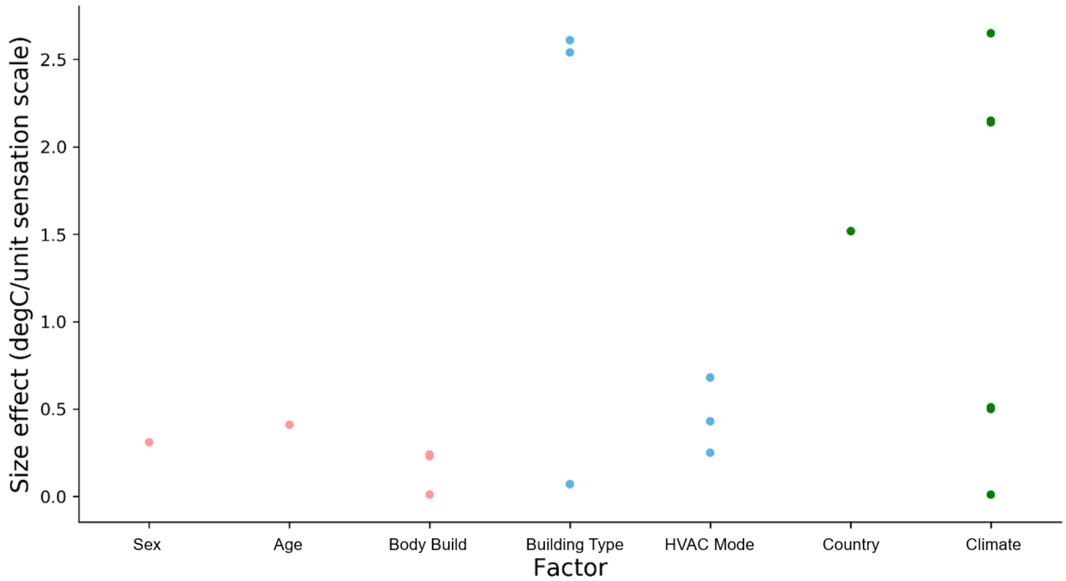
[6] The selection of k might depend on how tight you want the controlled temperature range would be

[7] The number of possible combinations of 2 objects (climate zone) from a set of 4 objects is $C(4,2) = 6$, therefore we have 6 dots



(a) Neutral temperature



(b) Thermal sensitivity

Figure 12: Effect size of different influential factors

Table 10: Effect size of different influential factors

		Neutral temperature (°C)	Thermal sensitivity (°C/unit TSV)
Individual factors	Sex	0.3	0.4
	Age	0.1	0.5
	Body build	1.4	0.3
Building characteristics	Building Type	0.7	2.7
	HVAC mode	1.7	0.8
Geographic factors	Country	2.0	1.7
	Climate	3.5	2.7

The geographic factors have the most marked impact on the *neutral temperature*. The *neutral temperature* of people from

Tropical climate region might be 3.5 °C higher than the *neutral temperature* of subjects from Continental climate region. The *neutral temperature* is also influenced by individual factors and building characteristics, among which the body build of subjects and HVAC operating mode has a stronger influence than the factor of sex, age and building type.

In terms of *thermal sensitivity*, climate zones and building characteristics are found to play the most important roles. Subjects from the Dry climate zone or in residential buildings could accept 2.7°C wider temperature range compared with the other three climate regions analyzed. Occupants in residential buildings could accept 2.7°C wider temperature range than those in office buildings. Additionally, people from non-high-income countries have a 1.7°C wider acceptable temperature range than those from high-income economies. Individual factors, including sex, age and body build, are found to play a marginal role in determining subjects' *thermal sensitivity*.

It is worthy to point out that the factor of sex, which has been explored most frequently in thermal comfort studies, actually does not have a strong effect on either the *neutral temperature* or *thermal sensitivity*. This finding is consistent with previous literature reviews [29], [26], indicating that we might need to shift our research focus from the factor of sex to other more important factors.

The major contribution of this study are twofold. First, we explored the influence of individual factors, building characteristics and geographical factors on *neutral temperature* and *thermal sensitivity* with the largest database in thermal comfort field. Second, we compared the statistical significance and size effect of multiple influential factors with a unified data set, which has not been done in previous studies. As the robustness and reliability of statistical analysis heavily depends on the sample size, the authors believe the findings from this analysis are capable to answer the questions of great interest in thermal comfort field regarding which factors would result in different thermal demands and what is the magnitude of those influences. Additionally, the findings from this study could be used to select features for the development of personal comfort models [56]. For instance, the findings of this research suggest that where the subjects originally come from and whether he is overweight or not might be more important features than sex in determining his/her thermal demand. Contrarily, previous thermal comfort studies focus a lot on the difference between male and female. Almost every study collected the information of gender, but overlooked other important features such as where the subjects come from and their BMI.

7.2 Limitation

A major limitation of this research is that we only explored the correlations among the studied factors, but not the causality of these correlations, because we applied statistical analysis that could only prove correlation. Although possible explanations have been discussed in the manuscript, we failed to reveal the root cause behind those individual differences. To answer this question, purely data-driven approach is not enough. It might be helpful if we could collect physiological data [54]. Another limitation is due to the constraint of relatively high missing rate, we utilized univariate regression, which is not as powerful as multivariate regression to study the influence from compounding multiple factors.

To mitigate the limitations resulting from using univariate regression rather than multivariate regression, we plotted the Correlation Matrix of all the factors studied in this research in Figure 13. A closer-to-zero correlation is preferred, as it indicates decoupled effects between the two studied factors, such as the factor pairs of building type/sex, HVAC mode/BMI, and etc. It could also be observed from Figure 13 that some factor pairs are highly correlated, for instance age and climate zone. In this study, lots of teenager samples are coming from tropical climate area, which means the factor of age and climate zone are correlating with each other. Even though the regression results showed that teenagers have a higher neutral temperature than adults, it is more likely that this higher neutral temperature is the result of climate zone rather than solely of the age. To properly decouple these compounding effects, multivariate regression is necessary. Contrarily, if the univariate regression is used, the results might be biased. Other factor pairs that are highly correlated (with correlation coefficient higher than 0.3, or lower than -0.3) include BMI/age, country/HVAC mode, climate zone/HVAC mode, and country/climate zone.

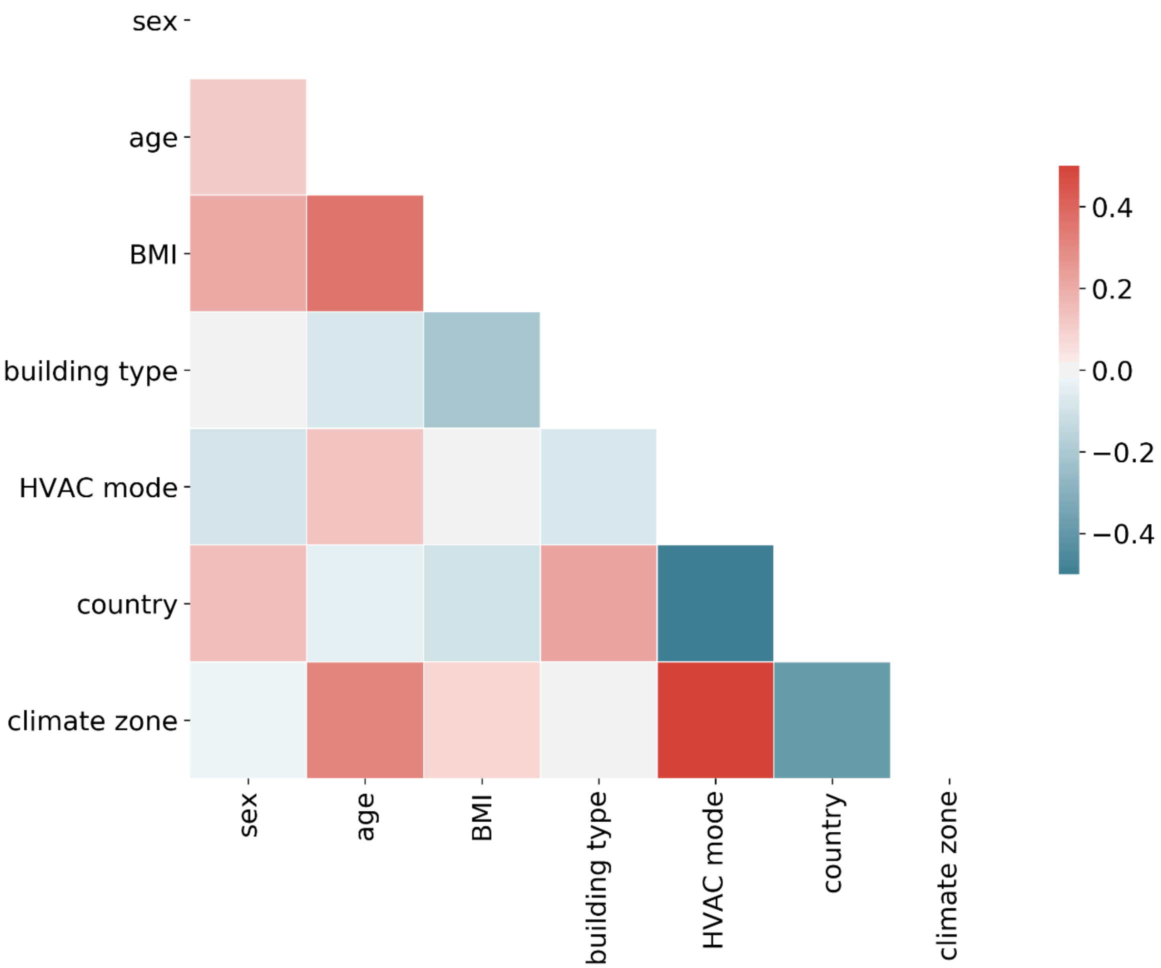


Figure 13: Correlation Matrix among factors

In this study, three types of factors which might lead to different thermal demands have been studied, i.e. individual factors (sex, age and BMI), building characteristics (building type and HVAC operation mode) and geographical factors (country and climate zone). It is worthwhile to point out that there are other factors might also affect personal thermal comfort, for instance the personal control [45], [55], . However, those factors have not been analyzed as they were not recorded in the ASHRAE Database, which constitutes another limitation of this study.

8. Conclusion

Individual difference in thermal comfort leads to a low occupant satisfaction rate, despite the high energy consumption by HVAC system. This research analyzed the ASHRAE Global Thermal Comfort Database with statistical method to answer the key research questions: which factors would lead to individual difference, and what the magnitude of this difference is. Individual factors (sex, age, body build), building characteristics (building type, HVAC operation mode), and geographical factors (country, climate zone) have been identified and quantitatively analyzed in this study.

Neutral temperature: we found that the local climate has the most marked impact on the *neutral temperature*, the size effect of which might be as large as 3.5 °C. The factors of country, HVAC operation mode, body build and age also result in a difference of more than 1 °C. The building type and sex has a relatively marginal influence on the *neutral temperature*.

Thermal sensitivity: building type and local climate are the most influential factors for *thermal sensitivity*. Subjects in residential buildings or coming from *Dry* climate zone could accept 2.5 °C wider temperature range than those in office, education buildings or from *Continental* climate zone. The thermal sensitivity differs for more than 1.5 °C per thermal sensation scale unit between subjects from high-income economies and non-high-income economies. The impact of sex, age and body build on *thermal sensitivity* is less than 0.5 °C per scale unit.

This is the first study that examines and compares major influential factors of individual difference in thermal comfort with one unified data set which has a large sample size. The findings of this research confirmed that there should be no single thermal comfort standards universally valid for all scenarios. For instance, the comfort standard for different climate zone and building type should be different. Additionally, the findings could help thermal comfort researchers to identify influential factors that might lead to significant individual difference. This study also sheds light on the feature selection for the development of personal thermal comfort models and personalized comfort systems.

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