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Indoor thermal comfort predictions: Selected issues and trends

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ABSTRACT

Thermal comfort is a complex topic and the methods studied so far are only approximate. Many investigators are likely to face some of the issues addressed in this article. The focus of the review is on selected issues and trends relevant to thermal comfort. Meta-analysis was performed using the ASHRAE RPA-884 database. The aim is to address some of the methodological issues of preliminary data analysis and predictions of comfort temperatures. An examination of how to assess the age factor for thermal comfort consideration in the ASHRAE database was also conducted by using an explicit transparent methodology. A new procedure was developed for predicting and analysing comfort temperature. The suggested procedure goes beyond the obvious need for more research studies to underscore deficiencies in data collection, which will lead to better data analysis. Editors might use the results and recommendations from this investigation before publishing original research on thermal comfort.

1. Introduction

Energy demand is expected to increase in the near future due to global warming, the urban heat island effect, and other factors. Many studies have been carried out globally in the field of thermal comfort to optimize energy usage. Despite the worldwide energy crisis, a considerable amount of energy is consumed every year due to thermal comfort considerations. In parallel, an exponentially growing number of research studies on thermal comfort have been seen in the last few years [1]. Unfortunately, little is available about the effect of the adopted methodology on the prediction of comfort temperatures from field studies. A large-scale field study is most likely to be favoured by reviewers because of the sample size. However, the prediction of comfort temperature is not solely subject to the sample size. It is also essential to consider the patterns of data collection in the prediction of comfort temperatures and to take into account other factors. According to Wasserman [2],

> *Results from observational studies start to become believable when: (i) the results are replicated in many studies; (ii) each of the studies controlled for possible confounding variables, (iii) there is a plausible scientific explanation for the existence of a causal relationship.*

Field studies have little control over thermal comfort parameters and the characteristics of participants. Each of the parameters affecting subjects' thermal perceptions has the potential to unintentionally affect the results [3]. Consequently, meta-analyses that combine the findings of several studies have the ability to detect obvious patterns and produce interesting generalized results when possible. Once again, the results of a meta-analysis reflect the results obtained from individual studies. It is likely that if the individual studies are poorly designed, the results of a meta-analysis may not be useful [3]. The sample size, duration, time, location, and indoor and outdoor climates are some of the factors affecting thermal comfort results. Yet, comparisons of conclusions drawn by investigators are vital in observational research studies.

Currently, there is no specific data collection procedure for predicting neutral temperature. Thermal comfort studies are afflicted with uncertainty. If the dependent or independent variable turns out to be unreliable, further inference is distorted.

This article endeavours to address the associated thermal comfort methodological problems and their effect on the analysis and prediction of comfort temperature from various studies, thus filling part of the research methodology gap. The first objective is to identify quantitatively the effect of thermal comfort parameters on preliminary data analysis. This is done by exploring the effect of sampling design and descriptive statistics on prediction of comfort temperature. The second objective is to develop a clear methodology for predicting the optimum comfort temperature from a single study and combined studies. In the present study, the ASHRAE RP-884 database was selected [56]. This is the only openly available database for all researchers.

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2. Complexity of thermal comfort research studies

When designing a building for human thermal comfort, several factors require careful consideration, such as energy efficiency, the occupants' thermal requirements, climate variations, the occupants' heath, and many others [4]. Human behaviour is an important factor in thermal design of buildings. This is because unoccupied buildings do not require energy but humans do [5].

Unfortunately, it is very difficult to predict human behaviour toward the indoor thermal environment under varied conditions. Humans are continuously responding and adjusting to the indoor thermal environment. Such continuous adjustments enable humans not only to produce the optimum desired outcome under various indoor climates but also to survive under extreme climates. Other factors such as cultural, religious, social, and economic ones also affect humans' thermal perception and thermal comfort. In fact, it was reported that culture, religion, education, and experience tend to mediate our perception of the thermal environment [6]. This renders thermal comfort a complex topic.

The worldwide interest in minimizing energy consumption for thermal comfort and the complexity of the topic have led to the publication of more thermal comfort research studies. Thermal comfort surveys are costly and thus the methodology should be carefully designed and clearly reported.

3. Thermal comfort models

When a theory is developed, it is crucial that it is statistically tested in a research study. This is because humans exhibit variability in their thermal perceptions and behaviours. Thus by testing a theory statistically, we may obtain contradictory results. This may lead to a new discovery. Theories evolve and change over time [7]. Thanks to the works of Fanger and others, thermal comfort has become a discipline [8]. Currently, the predicted mean votes (PMV) and the adaptive models are widely used and recognized, at least in the ASHRAE standard [9].

Fanger initially developed the PMV model of a large number of subjects for use within temperate climate zones [10]. The model has been established as an international standard since the 1980s. It was developed based on the principles of thermal heat balance with the physiology of thermoregulation. An empirical fit of subjects' votes on the ASHRAE seven-point scale was used for the adjustment of the model [11]. The model requires six parameters: air temperature, mean radiant temperature, relative humidity, air movement, clothing insulation, and metabolic rate. The PMV model predicts the comfort temperatures well under a controlled environment, specifically under a cold climate [13]. Mishra et al. [4] stated that having more control over the surrounding environment might increase people's satisfaction toward their indoor thermal environment. This can be achieved, for instance, by providing personalized thermal environments.

In naturally ventilated buildings, behavioural, physiological, and psychological adaptive processes are important factors affecting comfort temperatures [12]. These factors are ignored in the PMV model. Occupants are not static but rather interact with their surroundings through adaptation [13]. The PMV model ignores the variation of subjects' state of mind over time. Subjects' long-term adaptation and changes are not taken into consideration in Fanger model. Occupants are subjected to different adaptation decisions in their daily lives. They may opt for the most awarding choices while considering all restrictions. An interesting quote may provide a better description of the situation [14]:

> *The perception of time involves an awareness of change, and there is no change. One can hardly speak of "behaviour" … it just sits there "doing nothing".*

This statement describes better the concept of the PMV model for predicting comfort temperature, even though the quoted statement is not about thermal comfort. Arens and Zhang conveyed that when the skin temperature is actively decreasing or increasing, the person perceives the thermal environment as much colder or warmer than when the temperature remains the same [15]. This shows, further, that the PMV model is only valid under steady-state conditions.

In 2004, the ASHRAE 55 standard replaced the PMV with the adaptive graph for naturally conditioned spaces only [16]. The adaptive model requires the examination of the data gathered during comfort surveys from field studies [17]. The ASHRAE model was developed based on a statistical analysis of about 21,000 records of indoor climatic observations and subjective assessment of thermal comfort [18]. The model was established mostly by the efforts of de Dear and Brager [19,20]. Upon the endorsement of the adaptive method in the ASHRAE 55-standard, the adaptive method was used pervasively in thermal comfort research studies. In recent years, many studies have developed adaptive thermal comfort models according to climate and location [21–24]. A recent adaptive model was developed in India. The investigators found that their adaptive model is also valid and robust within mixed mode buildings [25]. The adaptive model seems to be the preferred choice when considering energy savings under hot climatic conditions. The situation is probably the opposite under cold climates: the PMV model may help in minimizing energy consumption for heating purposes in cold to very cold climates.

The rapid spread of the adaptive model can probably be traced back to several factors. Firstly, the adaptive equation (not the elaborated theory) is a friendly and easy model compared to the PMV model. It requires outdoor air temperature values only; moreover, the historical monthly outdoor temperatures can be used for the prediction of the comfort range.

Although several investigators supported the adaptive approach concept, it has been reported that the adaptive approach has a tendency to produce varying outcomes from different field studies [10]. In fact, the accuracy of the prediction of comfort temperatures for the adaptive model is tied to the accuracy of the predicted indoor comfort temperatures from various studies. The accuracy of the predicted indoor comfort temperature of a single study relies on the quality of the data recorded during the survey. It is also linked to the approach used for the prediction.

The present study does not intend to argue about the PMV model or the adaptive model, which is beyond the scope of the study. It rather provides insight into the ASHRAE database by analysing and interpreting the data using visualization and other techniques. Data visualization as an observational tool has been recently established as a definite discipline [26]. Visualization techniques have been developed to discover patterns, trends, or sub-problems in several datasets.

4. Methodology

In this investigation, the ASHRAE RP-884 database was selected. A few assumptions and requirements were considered prior to data analysis. The data of responses to longitudinal surveys were assumed independent. This assumption is widely accepted in thermal comfort studies. For instance, in the European Smart Controls and Thermal Comfort (SCATs) project, the investigators assumed that the data were independent even though each respondent reported his or her thermal perception of the indoor environment monthly [27]. The SCATs project forms the basis of the adaptive model for European offices [27]. It has been reported that, in an early study by McIntyre [28], the variability among subjects' thermal comfort votes was found to be close to the variability of votes from one subject [27].

In this investigation, the preliminary requirements for a study to be considered for further analysis in this article are that all the environmental, personal thermal comfort, and subject age parameters should be reported.

The operative temperature is a widely accepted index for prediction

Table 1
Field database characteristics used in the present review.

D	Location	Country	HVAC/NV	Building Type	Climate According to ASHRAE Report	Principal Author	Sample size used	Season	Ref
1	Bangkok	Thailand	HVAC	Office	Hot humid climate	Busch	761	Summer	[57–60]
2	Bangkok	Thailand	NV	Office	Hot humid climate	Busch	390	Summer	
3	Montreal	Canada	HVAC	Office	Continental Subarctic	Donnini	441	Summer	[61]
4	Montreal	Canada	HVAC	Office	Continental Subarctic	Donnini	426	Winter	
5	Brisbane	Australia	HVAC	Office	Humid Subtropical	de Dear	561	Summer	[62–65]
6	Brisbane	Australia	NV	Office	Humid Subtropical	de Dear	608	Summer	
7	Darwin	Australia	HVAC	Office	Tropical Savanna (Wet)	de Dear	491	Summer	
8	Darwin	Australia	HVAC	Office	Tropical Savanna (Dry)	de Dear	555	Summer	
9	Melbourne	Australia	HVAC	Office	Temperate (Marine)	de Dear	509	Summer	
10	Melbourne	Australia	NV	Office	Temperate (Marine)	de Dear	552	Summer	
11	Karachi	Pakistan	NV	Residential houses & offices	Desert (Hot Arid)	Nicol	190	Summer	[66]
12	Karachi	Pakistan	NV	Residential houses & offices	Desert (Hot Arid)	Nicol	470	Winter	
13	Multan	Pakistan	NV	Residential houses & offices	Desert (hot arid)	Nicol	437	Summer	
14	Peshawar	Pakistan	NV	Residential houses & offices	Semi-arid Midlatitude	Nicol	556	Summer	
15	Peshawar	Pakistan	NV	Residential houses & offices	semi-arid Midlatitude	Nicol	513	Winter	
16	Quetta	Pakistan	NV	Residential houses & offices	Desert (Hot Arid)	Nicol	492	Summer	
17	Quetta	Pakistan	NV	Residential houses & offices	Desert (Hot Arid)	Nicol	425	Winter	
18	Saidu Sharif	Pakistan	NV	Residential houses & offices	Semi-Arid (High Altitude)	Nicol	568	Summer	
19	Saidu Sharif	Pakistan	NV	Residential houses & offices	Semi-Arid (High Altitude)	Nicol	568	Winter	
20	Oxford	Britain	NV	Office	West Coast Marine	Raja	875	Summer	[67]
21	Townsville	Australia	HVAC	Office	Tropical Savanna	de Dear	624	Summer warm-dry	[68–70]
22	Townsville	Australia	HVAC	Office	Tropical Savanna	de Dear	598	summer hot-wet	
23	Kalgoorlie-Boulder	Australia	HVAC	Office	Hot Arid	Cena	638	Winter	[71,72]
24	Kalgoorlie-Boulder	Australia	HVAC	Office	Hot Arid	Cena	589	Summer	

Note: The listed sample size is different from the ASHRAE database. It was reduced due to the requirements set in this research.

of comfort temperature and evaluation. The operative temperature and air temperature were found to produce almost the same results in most indoor conditions [29]. The operative temperature is also recognized by the ASHRAE 55 and ISO 7730 standards [16,30]. The operative temperature was the independent variable selected for predicting and analysing comfort temperatures. In this study, no requirement was set for the indoor operative temperatures, except for checking any anomaly or possible error in the database.

The minimum relative humidity set in this study is 5%. Any value below 5% was excluded. This is because there is always water vapour in the air, including in the driest conditions. To the best of our knowledge, zero relative humidity has never been recorded in the world.

Air movement affects human thermal comfort [31]. The selected air velocity range from the database is between 0 and 1 m/s. When the air velocity is above 1 m/s, it may cause papers to blow about. Most of the selected studies recorded very low air movements [20]. In fact, there were very limited records above 1 m/s when considering other requirements set for this study.

The clothing insulation records were also investigated. In the ASHRAE RP-884 database, the clothing insulation data were modified by de Dear and Brager according to ASHRAE 55-1995. The approximate insulation values of the chairs, which were omitted by the original investigators, were added by de Dear and Brager [23]. In the present study, no further corrections were made. The selected clothing insulation range was from 0.02 to 2 Clo. Values below 0.02 represent an almost naked person. There were limited records of clothing insulation below 0.2 except for the research investigation carried out by de Dear et al. [32] in Singapore. However, this study was excluded because of the preliminary requirements set for the age.

Metabolic rate is among the least well-known factors affecting human thermal comfort [33]. It is a very difficult parameter to estimate or to predict accurately except in a climate chamber [34]. In this study, the selected range for the prediction of neutral temperatures was from 0.8 to 1.3 MET. The selected range represents the metabolic rate generated by occupants engaged in near sedentary activities [16].

Many factors affect people's thermal perception of indoor environments, such as individual physiology, age, and gender [1]. Therefore, new ways of looking at thermal comfort were recommended [1]. In this investigation, the age of the subjects was carefully analysed for possible exploration of the effect of age on people's thermal comfort in the near future. The selected age range was from 18 to 75. There were limited values of age above 75. Those were excluded.

After preliminary screening, each indoor thermal comfort parameter was analysed and discussed. The indoor operative temperature and relative humidity were categorized according to the indoor climate classification set in this study. The classification was then compared with the outdoor climate descriptions. In addition to that, the age distribution of the subjects was analysed using a visualization technique.

Descriptive statistics were also used for a preliminary data analysis. Finally, the comfort temperatures were analysed using an exploratory visualization technique. The results were compared using least squares linear regression and discussed. The least squares linear regression is a traditional model that is widely applied in studies in the field of thermal comfort to fit operative temperature to subjects' votes on the ASHRAE seven-point scale. The method is also widely used in developing adaptive regression models.

The present planned methodology helps in gaining familiarity with the ASHRAE RP-884 database. It also minimizes time consumption and error in analysing thermal comfort data. This seems to be vital prior to the selection of any rigorous and advanced statistical methods. Finally, a systematic methodology for preliminary data analysis of thermal comfort field studies is recommended.

5. Results and discussion

After data screenings and filtration against the criteria set for this research, a total of 8757 observations met the inclusion criteria. Finally, 24 study groups were reviewed. The selected Excel files from the ASHRAE database [56] are files 3, 4, 9–16,18–26, 28, 36, 37, 47, and 48.

In the present review, sample sizes of the selected studies ranged from 190 to 875. The average number of observations was 543.88 ± 26.684 (mean ± standard error of mean). The median of the sample size was 553.5. A summary of the field database characteristics is listed in Table 1.

5.1. Operative temperatures

The operative temperature is a combination of air and radiant temperature [29]. The average indoor operative temperature distributions of the selected data are shown in Fig. 1.

A preliminary look at the available ASHRAE database showed that the indoor climate did not necessarily reflect the outdoor climate. This most probably occurred due to the usage of heating, ventilation, and air conditioning (HVAC) systems in some buildings. In addition to that, the time factor, building characteristics, and microclimate surrounding the buildings might affect the indoor climate. For a better description of the indoor temperatures at the surveyed locations, the indoor temperature classification listed in Table 2 was used.

A close observation of the database revealed that most of the investigations were conducted in summer. This observation was later confirmed from the ASHRAE final report [20]. When analysing the indoor climates of the selected studies, the results in Table 3 showed that the indoor air temperature in HVAC buildings did not reflect the outdoor climatic patterns. Additionally, the indoor climates in the HVAC buildings were all categorized as temperate indoor climates. Extreme temperatures records were observed in two case studies in Kalgoorlie-Boulder in Australia and Darwin (Study IDs 23 and 8). The outdoor climates of those two locations are classified as hot arid (winter) and Tropical Savanna (Dry summer). When considering all studies, the coefficient of variation of the operative temperatures in HVAC buildings was very narrow. It was within the range 3.5–6.9% with an average variation of 5.3%. The coefficient of variation is the standard deviation of a parameter under investigation in a study over the mean of the parameter. The coefficient of variation provides a normalized measure of the spread. It is widely recommended for comparison among studies instead of using the standard deviation. It is usually multiplied by 100, which is the case in the present study.

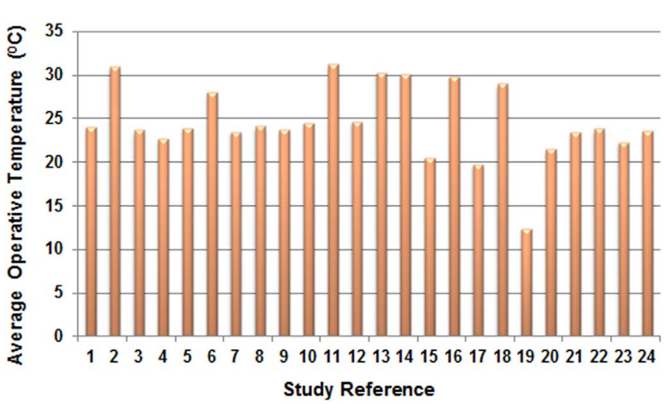

Fig. 1. Average indoor temperature distribution.

Table 2
Indoor temperature classification.

Range	Description	Notation
< =5	Extremely Cold	EC
5–10	Very Cold	VC
10–15	Cold	CD
15–20	Cool	CL
20–25	Temperate	TE
25–30	Warm	WM
30–35	Hot	HT
35–40	Very Hot	VHT
> 40	Extremely Hot	EHT

On average, the indoor operative temperatures climates in the HVAC buildings were within a narrow range of 22.2–24.1 °C. Response to stimuli is an important characteristic of humans for staying in balance. It has been reported that maintaining a narrow temperature band has negatively affected human health. This is because the body's natural ability to respond to environmental challenges is lessened [35]. Further, a reasonable amount of temperature variability in the indoor environment is usually appreciated. This is because human beings are naturally exposed to unexpected variation of air temperature. This certainly affects the human response to the thermal environment [36].

For naturally ventilated buildings, the average indoor temperature was categorized as cold to warm. The lowest recorded value was 12.4 °C (Study ID 19), and in this case the outdoor climate was categorized as semi-arid high altitude. This was in Saidu Sharif, Pakistan, during the winter season. It was the only study subject to a cold indoor temperature. At the other end of the scale, the highest average indoor temperature was 31.2 °C (Study ID 11) and was recorded in Karachi, Pakistan, during the summer season. The outdoor climate was categorized as desert (hot arid) climate.

In naturally ventilated buildings, there were also a few discrepancies between the climate descriptions of a few locations and the average indoor operative temperatures. For instance, the overall outdoor climates of Karachi and Quetta, which are both located in Pakistan, were classified under the category desert – hot arid; both studies were conducted in the winter season. However, when applying the indoor temperature classification, they were classified as temperate and cool, respectively. The operative mean temperatures were 19.8 and 24.6 °C. Initially, the discrepancy was attributed to the time of the survey. However, Fergus and Susan [37] provided further insight into the field study conducted in Pakistan. The survey was carried out in July 1993 and January 1994. The investigators mentioned that in winter, the subjects in Quetta all lived in heated homes. They also clearly reported that this was not the case in Karachi. However, they did not clearly report the kinds of heating systems to which the subjects were exposed. They also mentioned that most subjects in the survey were in naturally ventilated buildings.

Finally, the coefficient of variation of the operative temperature when considering all studies was within the range of 2.4–20.9%. Both values were recorded in Pakistan. The average coefficient of variation obtained from this analysis was 10.1%. This is almost twice the estimated value in HVAC buildings. It is apparent from the present analysis and the results listed in Table 3 that the description of the indoor thermal environment is important for understanding the indoor climate.

5.2. Relative humidity

Humidity is the amount of water vapour in the air. Relative humidity is a good indicator of the likelihood of dew and rain. In hot outdoor weather, the elevation of outdoor relative humidity may increase the apparent temperature for humans. This may take place

Table 3
Characterization of indoor operative temperature.

ID	Mean TOP	CV Top	Climate According to ASHRAE Report	Indoor Climate Description	Conditioning Type	Season
3	23.7	5.2	Continental subarctic	Temperate	HVAC	Summer
4	22.6	3.5	Continental subarctic	Temperate	HVAC	Winter
24	23.54	5.8	Hot arid	Temperate	HVAC	Summer
23	22.2	5.3	Hot arid	Temperate	HVAC	Winter
1	23.9	5.5	Hot humid climate	Temperate	HVAC	Summer
5	23.9	5.3	Humid subtropical	Temperate	HVAC	Summer
9	23.7	6.5	Temperate marine	Temperate	HVAC	Summer
21	23.4	3.9	Tropical savanna	Temperate	HVAC	summer warm-dry
22	23.8	4.2	Tropical savanna	Temperate	HVAC	summer hot-wet
8	24.1	6.9	Tropical savanna (Dry)	Temperate	HVAC	Summer
7	23.5	6.6	Tropical savanna (Wet)	Temperate	HVAC	Summer
16	29.8	8.8	Desert (hot arid	Warm	NV	Summer
17	19.8	19.2	Desert (hot arid	Cool	NV	Winter
11	31.2	2.4	Desert (hot arid)	Hot	NV	Summer
13	30.3	8.2	Desert (hot arid)	Hot	NV	Summer
12	24.6	7.0	Desert (hot arid)	Temperate	NV	Winter
2	30.9	5.2	Hot humid climate	Hot	NV	Summer
6	28.0	4.3	Humid subtropical	Warm	NV	Summer
18	29.0	14.1	Semi-arid high altitude	Warm	NV	Summer
19	12.4	20.9	Semi-arid high altitude	cold	NV	Winter
14	30.1	9.9	Semi-arid midlatitude	Hot	NV	Summer
15	20.5	10.8	Semi-arid midlatitude	Cool	NV	Winter
10	24.5	12.3	temperat marine	Temperate	NV	Summer
20	21.5	8.1	West coast marine	Temperate	NV	Summer

by preventing the evaporation of perspiration from the skin. Evaporation of body moisture is considered a highly efficient heat-removal process [15]. In ASHRAE 55, there is no lower limit for humidity. The upper limit is set at 0.012 kg/kg dry air (at one atm) [4]. Unlike insects, humans do not possess skin humidity receptors, but psychophysical studies have identified in humans many potential sensory cues that could contribute to sensing wetness like pressure or vibration [38]. There are a substantial number of sweat glands in the bodies of newborn babies, but it has been reported that these glands could become irretrievably inactive. This may occur if the person is not exposed to a hot climate in infancy [15]. For the adaptive model, no requirements for relative humidity or other thermal comfort factors are recommended. The situation is likely to be different with the PMV.

Little agreement on the effect of relative humidity on indoor thermal comfort was found [39]. Humphreys et al. [27] stated that it is the temperature part of the relative humidity, and not the water vapour, that affects the thermal perception. In fact it is well known that the amount of water vapour in the air depends on the air temperature. The body becomes cooler through the evaporation of sweat when the air is dry. However, when the air is still and saturated and the person is not exposed to solar radiation, evaporation of sweat may not occur. Interestingly, it has been reported that rapid fluctuations of relative humidity with periodicities of less than an hour may not be noticed, in contrast to slower variations [4].

The average indoor relative humidity distribution of the selected studies is shown in Fig. 2. On average, relative humidity values were 47.5% and 49.6% in HVAC buildings and naturally ventilated buildings, respectively. The lowest average value of relative humidity of 21.3% was recorded in HVAC offices in Montreal, Canada, during winter (Study ID 4). The reason for the very low average relative humidity in this case study is not clear. Relative humidity levels below 25% are associated with increased discomfort [40].

In naturally ventilated buildings, the highest average relative humidity was 73% and was recorded in naturally ventilated offices in Bangkok. Cities near to the equator and closer to coastal regions are widely known for their high relative humidity, such as in the cases of Malaysia and Singapore. Overall, when considering all studies, the average relative humidity was 48.7%.

The coefficients of variation of relative humidity in HVAC buildings and in naturally ventilated buildings were 15.7% and 25.5% respectively, reflecting the wide fluctuation of relative humidity compared to indoor operative temperature. A plot of relative humidity versus coefficient of variation of the same variable was generated. Fig. 3 depicts the wide variation of the coefficient of variation for studies with lower average relative humidity records. On the other hand, the coefficient of variation becomes small with the elevation of the average relative humidity. This means that the indoor relative humidity did not differ much at the extremes of higher average records.

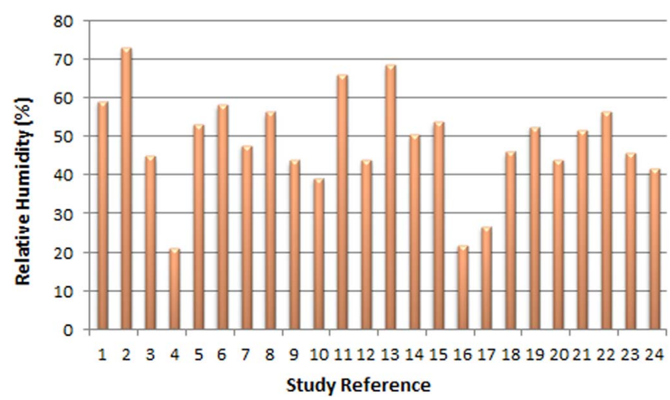

Fig. 2. Average relative humidity distribution.

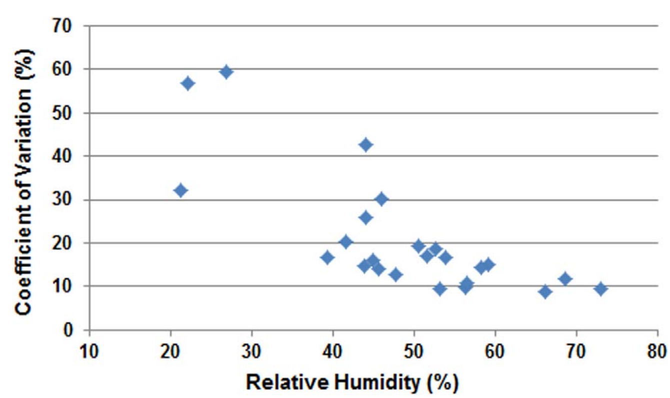

Fig. 3. Coefficient of variation of mean relative humidity.

Table 4
Indoor relative humidity classification.

Range	Description	Notation
< =20	Very Dry	VD
21–40	Dry	DR
41–60	Nether Dry nor Humid	NDH
61–80	Humid	HD
> 81	Very Humid	VH

For an accurate description of the indoor relative humidity, a relative humidity scale was used to characterize the data according to the location. The developed scale is shown in Table 4. This scale helps in quantifying the dryness or wetness of the indoor climate. It can be compared to the outdoor climate of the location. For instance, a city located in a humid country may be subject to a different indoor relative humidity because of air-conditioning. Another case that may occur is when the time of the survey does not reflect the overall climate of the location. The climate is dynamic and therefore subject to variation in time and space. The variation might occur at micro- and macro-scale level. Table 5 provides a general characterization of indoor relative humidity according to conditioning type.

Overall, the average indoor relative humidity values in HVAC buildings were categorized as neither dry nor humid, regardless of the outdoor climate. Such a situation was expected in artificially conditioned buildings. However, one unusual observation was made for the case study in Montreal, Canada. In naturally ventilated buildings, there were also few discrepancies between climate description and humidity records. For instance, the overall outdoor climates of Karachi and Multan located in Pakistan were classified under the category of desert – hot arid. When using the indoor relative humidity classification, they were classified as humid in summer.

Returning to the overall outdoor climate, the Koppen Kurger classification is the most widely used method of characterizing the outdoor climate of any location [41]. This classification is based on two parameters: air temperature and precipitation. These two parameters are widely used due to the limited accessibility of other climate data [42]. The climate characterization used in the ASHRAE report is quite similar to the Koppen Kurger classification.

Little has been reported on the usefulness of such a climate classification for thermal comfort. This study provides further insight into the limitations of such a classification. The Koppen procedure was first developed to categorize the climate based on variability of plants. The reason behind the selection of plants for climate classification is well justified by Koppen [43]. He attributed his classification to the difficulty or impossibility of finding suitable organic food due to the absence of plants. Koppen observed that it was not the unfavourable weather but rather the availability of food that was the major issue in human settlements. Koppen distinguished between plants of the equatorial zone (A), arid zone (B), warm temperate zone (C), snow zone (D), and polar zone. This classification, according to the same author, is most suitable for plants and cold-blooded animals. It is not about humans.

Koppen's procedure for climate classification certainly was not developed to suit human thermal comfort. The reader may refer to Table 1 in the reported publication [41] to understand the categorization of the main and sub climate types. Koppen used plants instead of humans because of the fast response of the plants to climate change, in contrast to humans [42]. Humans may survive at extremes of climate variation, which is not necessary in the case of plants. A recent publication showed the limitation of the Koppen Kurger classification in evaluating the impact of climate variation on thermal comfort in a Melbourne case study. The selected case study was from the ASHRAE database [44].

Another issue relevant to climate and thermal comfort worth clarifying is related to La Niña or El Niño. When considering the ASHRAE database, few studies have taken place in the El Niño period. This means that the survey might not be representative of typical conditions for a few cases. For instance, a very strong El Niño was observed in 1982–1983 [45]. This coincides with only a few thermal comfort studies, which were conducted in the years 1982–1987. A very strong El Niño must equal or exceed the threshold for at least three consecutive overlapping three-month periods. The effect of such phenomena on thermal comfort is beyond the scope of this study. However, this shows that the indoor and the outdoor climates also need to be carefully and thoroughly described using different classifications such as the method used for the categorization for air temperature and relative humidity in this study.

Lastly, when investigating the impact of outdoor climate on indoor thermal comfort and adaptability, an important question emerges:

Table 5
Characterization of relative humidity scale.

ID	Average Relative Humidity	Standard Deviation	Description	Climate According to ASHRAE Report	Conditioning Type
4	21.3	6.8	Dry	Continental subarctic	HVAC
1	59.2	9.0	Neither Dry nor Humid	Hot humid climate	HVAC
3	45.0	7.3	Neither Dry nor Humid	Continental subarctic	HVAC
5	53.2	5.0	Neither Dry nor Humid	Humid subtropical	HVAC
7	47.8	6.2	Neither Dry nor Humid	Tropical savanna (Wet)	HVAC
8	56.4	5.6	Neither Dry nor Humid	Tropical savanna (Dry)	HVAC
9	43.9	6.5	Neither Dry nor Humid	Temperate marine	HVAC
21	51.6	8.7	Neither Dry nor Humid	Tropical savanna	HVAC
22	56.5	6.1	Neither Dry nor Humid	Tropical savanna	HVAC
23	45.7	6.4	Neither Dry nor Humid	Hot arid	HVAC
24	41.6	8.5	Neither Dry nor Humid	Hot arid	HVAC
10	39.2	6.6	Dry	temperate marine	NV
16	22.0	12.5	Dry	Desert (hot arid)	NV
17	26.8	16.0	Dry	Desert (hot arid)	NV
2	73.0	7.0	Humid	Hot humid climate	NV
11	66.2	5.9	Humid	Desert (hot arid)	NV
13	68.6	8.1	Humid	Desert (hot arid)	NV
6	58.3	8.5	Neither Dry nor Humid	Humid subtropical	NV
12	44.0	18.8	Neither Dry nor Humid	Desert (hot arid)	NV
14	50.5	9.7	Neither Dry nor Humid	Semi-arid midlatitude	NV
15	53.9	9.0	Neither Dry nor Humid	Semi-arid midlatitude	NV
18	46.1	13.9	Neither Dry nor Humid	Semi-arid high altitude	NV
19	52.6	9.8	Neither Dry nor Humid	Semi-arid high altitude	NV
20	44.0	11.4	Neither Dry nor Humid	West coast marine	NV

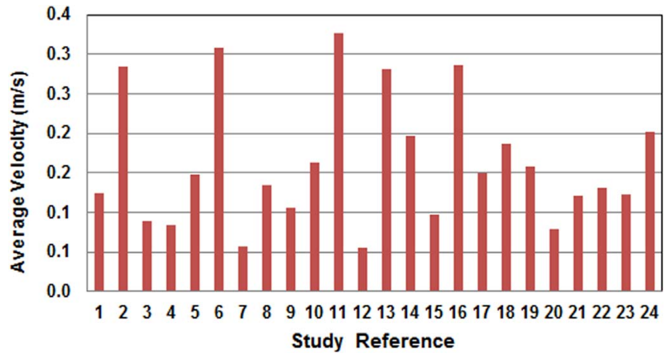

Fig. 4. Average velocity distribution.

What are the boundaries of adaptability at thermal comfort level? This is because at the survival level, we are no longer addressing thermal comfort. Admittedly, the author does not have a short answer and thus this paper will not deal with this issue.

5.3. Air velocity

The influence of natural and artificial air movement on thermal comfort has attracted increasing interest. Heat loss by convection increases when air movement increases. This situation is certainly preferred in the humid tropics at low altitude when the temperature is warm to hot all year round. However, in cool or cold environments, a gentle breeze will probably be perceived as a draught [31,46]. Skin-temperature changes can accurately describe the mixed sensation of human thermal experiences [31].

The average indoor velocity distribution of the selected data is shown in Fig. 4. The lowest value of 0.06 m/s was recorded in Darwin, Australia in HVAC offices (Study ID 7). The highest value of 0.33 m/s was recorded in Karachi, Pakistan (Study ID 11) in naturally ventilated buildings. Nicol and Roaf reported that in the Pakistani case study, nearly all subjects used fans in summer and only a few used evaporative coolers [37].

According to De Vecchi et al. [47], people have a tendency to prefer similar cooling strategies if they are exposed to an air-conditioned environment for a longer time. The authors stated that whether or not such a tendency toward an air-conditioned environment is reversible is not known. This will certainly depend on many factors, such as age, the duration of air-conditioning usage, and probably others. The situation is probably different when using fans for cooling purposes.

5.4. Clothing insulation

Thermal insulation and the evaporative resistance of clothing control the transfer of heat and water vapour between the environment and human body [48]. Clothing insulation measurements are very costly. The insulation values provided in standards are usually determined from a stationary thermal manikin subject to indoor air movement in the range of 0.15–0.2 m/s [33]. The reliability and usability of the insulation values and their effects on the accuracy of thermal comfort studies have been raised by several authors [20,49].

Clothing insulation is often measured in clo units. A clo unit typically corresponds to a person wearing a business suit, and zero clo corresponds to a naked person. The distribution of clothing insulation over the selected operative temperature range is shown in Fig. 5.

From the figure, it is apparent that the clothing insulation pattern followed the indoor temperature variation in the approximate range from 16 to 24 °C. On average, below 16 °C, the clothing insulation did not have clear trend, but above 24 °C, it tended to be constant, with an average value of about 0.6 clo. Such observations may vary according to the location under investigation. However, the explanation of the trend

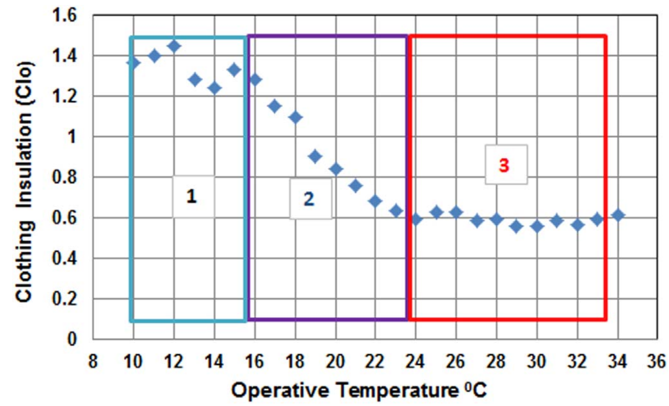

Fig. 5. Average clothing insulation distribution.

is well documented in Ref. [50]. When the operative temperature increased to a specific value, the clothing insulation reached its minimum. When the temperature dropped to an optimum value, it was observed that a further increase of the clothing insulation level did not occur. Concisely, the clothing insulation level of the population under investigation was bounded between two values. The clothing insulation variation is also subject to religious, social, cultural, and other factors. When taking the indoor operative range from 16 to 24 °C, it was observed that the average clothing insulation (I_{avg}) (Clo) increased exponentially with the elevation of the indoor operative temperature (t_o) according to Eq. (1):

$$I_{avg}=6.7229 \quad Exp(-0.103t_o) \quad (R^2=0.99) \tag{1}$$

This equation certainly should not be generalized. Clothing insulation is one of the most difficult parameters to estimate with a good approximation. Clothing is an important aspect of occupant behaviour. It cannot be controlled or predicted [35]. Thus, for the prediction of the neutral temperature from field studies, it seems appropriate that the investigator check whether or not the level of clothing insulation worn by the subject is considered acceptable. This is a prerequisite for thermal comfort.

5.5. Metabolic rate

Metabolic rate is the energy produced by the human body, and it varies with activity level. It is expressed in MET units, where 1 MET is equivalent to about 58 W/m^2 [49]. This is equal to the energy produced per unit of surface area of a seated person at rest. It is necessary to mention that body surface area and weight are important factors in the estimation of metabolic rate. However, an increase in body weight among the American and European populations has been observed during the past 45 years. Additionally, body surface area differs between males and females. Regional differences in body surface area are also widely documented [35]. Fig. 6 portrays the average metabolic distribution of the selected studies. Little variation in the metabolic rate has been observed due to this narrow range. It appears to be a constant rather than a variable. Overall, the minimum average metabolic rate when considering each case study was 1 MET and the maximum average value recorded was about 1.2.

5.6. Subjects' votes on ASHRAE scale

The ASHRAE seven-point scale was selected for predicting and analysing comfort temperatures. This scale varies from −3 (cold) to −2 (cool), −1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), and finally 3 (hot). It is not clear why the ASHRAE seven-point scale has a constant unit for the various thermal perceptions. Human physiological responses to the thermal environment are not symmetrical above and below the neutral temperature [35]. So, why is the ASHRAE seven-

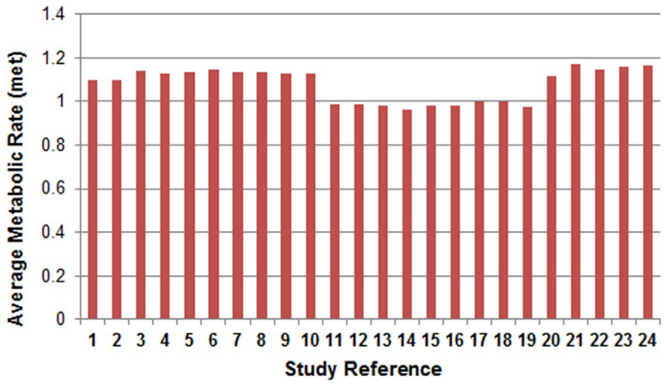

Fig. 6. Average metabolic rate distribution.

point scale not a logarithmic scale, for instance? Schweiker *et al.* concluded from their research study that common assumptions concerning the equidistance of thermal sensation scales appear to be wrong [51]. Varshney and Sun [52] put forward an interesting hypothesis about why humans perceive logarithmically. Their hypothesis was not directly associated with thermal comfort; rather, they hypothesized that humans notice mostly relative changes in stimuli and not absolute changes. They recommended that experimental tests be conducted to check this hypothesis. This is because certain specialized sensory modes in humans, such as night vision, do not have logarithmic psychophysical scales.

Turning to our research study from the current database, the subjects' votes on the ASHRAE scale can be broadly divided into three categories. In the first category, some investigators allowed the subjects to vote between the seven points of the ASHRAE scale (continuous scale). In the second category, the subjects voted on the major seven points of the ASHRAE scale. In addition, some voted at the mid-points between the main points. In the third category, the votes were made strictly according to the seven-point ASHRAE scale (discrete scale). A question that may arise is: Which of the three methods will predict a neutral temperature better?

According to Aguinis [53], polychotomization has been used to enable researchers to conduct an ANOVA using the artificially created groups, but with the availability of multiple regressions, they stated that researchers should avoid dichotomizing or polychotomizing truly continuous variables. This procedure has the effect of reducing the variance of the variables involved, leading, in many cases, to a decrease in power.

The main issue in using a continuous ASHRAE scale concerns subjects' behaviour toward the scale. In a previous study, Harimi et al. [54] observed that most subjects' preferred voting at the seven points of the ASHRAE scale. Some also voted at the mid-points, but only a few voted at any point on a continuous ASHRAE scale. Further, the variation of human thermal perception of various indoor temperatures may not be linearly scaled. It has been already reported that cold environments seem to be perceived more strongly and rapidly than hot environments [19]. This was attributed to the fact that the number of sensitive cold points was greater than the number of hot points on the skin. Apparently, this is not reflected on the ASHRAE thermal sensation scale. Other issues relevant to the ASHRAE scale were addressed in our previous investigation [54].

5.7. Age of the subjects

Another criterion for study acceptance was the age range of the subjects. Fig. 7 provides a general characterization of subjects' ages. It was observed that transversal studies have more variety in the recorded ages compared to longitudinal surveys. This would be expected due to the repeated measurements with a limited number of subjects.

There were six transversal surveys (Study IDs 5–10) in Brisbane and Melbourne worth further discussion. These surveys were conducted in naturally ventlilated and HVAC buildings in Australia. The age distributions in these studies look similar to longitudinal surveys. At first glance, it was thought that such cases should not be categorized under transversal surveys. So, why were they categorized as transversal ones? The main distinction that separates longitudinal surveys (i.e. Study IDs 11–20) from transversal surveys (Study IDs 5–10) is the pseudo-randomness of the age distribution. Fig. 7 revealed that the age of subjects in those studies was most likely categorized by range. Therefore, no pseudo-randomness was observed in these cases. In another study carried out by de Dear et al. in Singapore [32], the age of the subjects was apparently categorized by group. However, the Singapore case study was excluded because the ages of the subjects were assigned values from one to five.

This procedure of investigating the thermal comfort database is recommended in meta-analysis. Without such careful analysis, one may assume that there were erroneous records of subjects' ages. They would probably be ignored in other cases. This certainly helps in investigating the effect of age on thermal comfort. The available literature showed that generally, younger people have a higher activity level than older people. Therefore, their thermal requirements may not be the same [55]. The body's response to temperature changes tends to be reduced with age.

5.8. Prediction of comfort temperatures

Prior to predicting comfort temperatures, the records of subjects' responses to the indoor temperatures were counted at various indoor temperatures. The results are shown in Fig. 8. Highlighted in grey are the cases in which the number of records was below 25. The first row represents the operative temperatures of the selected studies. The first column represents the study ID. When looking at the indoor temperature distributions, it is apparent that the indoor temperature range varied considerably among studies. Wide operative temperature ranges were observed in the case studies in Pakistan (IDs 16–18). Study ID 17 was carried out in Quettar, Pakistan, in winter. The temperature in this study varied from nearly 10–28 °C. The recorded range was as large as 18 °C. In this case study and in another few locations, there were less than 25 records at certain temperatures. The limited data collection at various indoor temperatures may further lead to erroneous conclusions.

Overall, a large sample size does not necessarily lead to better prediction of comfort temperature. For instance, a study may collect 500 records at a single indoor temperature but only a few records at various indoor temperatures. In such cases, the reliability of the prediction is questionable. On the other hand, having a small sample size does not necessarily lead to better prediction. It is obvious that the wider the indoor operative temperature range, the bigger should be the sample size, such as in case study IDs 16–18. Additionally, there should be sufficient records at various indoor operative temperatures for better prediction. Further, the survey should capture the full indoor operative range. This does not seem to be possible in thermal comfort field studies when the range of outdoor temperatures of the location is wide. Further discussion of how to resolve this dilemma is addressed in the next sections.

Returning to this research investigation, we used a different approach to predict the comfort temperatures. Fig. 9 depicts the average votes on the ASHRAE scale cast at various indoor operative temperatures. In cases where the number of votes was below 25, the average thermal perception of the votes is highlighted in grey. The inconsistency of the votes due to the limited number of votes is obvious in many studies. It is very important to mention that the average values (last row and last column) of Fig. 9 represent the average estimate of the entire data. This cannot be estimated directly from Fig. 9. In order to overcome the reported issue, the average votes where the number of subjects was below 25 were removed. The remaining results are shown

Age	Study Reference																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
18	2				49	121	73	40	15	51						8		70	77		5	3	2	2
19	5		1																		5	5		2
20	7	1	1															158	93	1	7	14	7	5
21	12	3																			11	8	7	6
22	28	6		1									124								14	16	11	4
23	32	10												66						82	18	13	16	8
24	36	10	3		161	161	187	134	176	205											13	13	12	16
25	55	19	3	3							27	191									18	20	15	12
26	64	16	4	1								54				68	67			35	13	10	11	9
27	51	12	5	3																40	13	13	13	11
28	46	26	4	4																79	10	11	11	12
29	52	32	5	7									38								11	8	11	13
30	42	29	5	7										79	69					14	11	12	6	5
31	44	13	9	5	125	105	86	122	101	140										42	10	10	12	9
32	34	11	13	14							11					75	81			31	14	14	11	10
33	24	16	10	7																	12	9	10	7
34	18	14	9	9																	10	9	8	9
35	25	21	21	8									63								13	8	19	16
36	22	14	15	15													30				11	5	11	8
37	26	13	15	19							29			23	71						10	4	9	4
38	16	16	19	15	93	52	43	96	80			58									9	4	6	7
39	13	7	15	14						43											9	17	11	7
40	12	11	17	25																	11	8	6	10
41	6	9	10	12																	5	3	9	7
42	6	5	13	21																50	5	5	9	10
43	4	4	17	8																70	8	11	6	7
44	3	7	12	13																21	3	1	3	3
45	7	3	17	18	18	24	5	27	25	25						43	72				8	6	15	12
46	5	6	14	15																	7	4	9	8
47	5	4	14	19							34									98	4	6	7	9
48	4	10	6	6																	10	3	7	10
49	5	2	13	10																	3	4	5	7
50	4	4	10	12												47					4	4	5	5
51	2	5	5	4																	3	2	1	1
52	5	3	6	8	5	14		36	40	16											3	2	5	3
53	3	1	11	8														83	98		1	1	3	7
54	3	1	4	4																	1	1	3	2
55	2	1	5	5									12								4	1	3	3
56	2	1	2	1																	1	1	1	1
57	1	1	2	2										90	73						3	3	2	4
58		2	3	3												93	94				2	1	1	
59	1	5	4	6																	3	2		1
60	1		4	1	9	6		29	12	5										21	3	3		
61	1	1		1																		1		
62																					1			
63			1																					
64				1																				
65	1					2																		
66																								1
67																							1	
75	1																							

Fig. 7. Total age distribution.

in Fig. 10. Finally, when feasible, the neutral temperature was identified. It is highlighted in grey in Fig. 10. It represents the transition of subjects' votes on thermal sensation from a negative value (slightly cool) to a positive value (slightly warm). The lowest value of absolute average thermal sensation represents a neutral temperature. For instance, the neutral temperature in the first study is between 24 and 25 °C. At 24 °C, the average thermal sensation vote is −0.1. At 25 °C the average thermal sensation vote on the ASHRAE scale is 0.3. Therefore, the neutral temperature is close to the average thermal sensation (−0.1), which is 24 °C.

It is obvious from Fig. 10 that the neutral temperature cannot be determined from all studies. This is because few studies were either above or below the neutral temperature at various indoor temperatures (i.e. Study IDs 6, 15, 19, and 23). However, the results of most of the studies were very close to neutrality.

When looking closely at the results, a striking pattern emerges: many studies agreed that 24–25 °C is the optimum neutral temperature. Surprisingly, this was observed for naturally ventilated and air conditioned buildings. On average, 24 °C appears to be the optimum value. Should it be considered a universal comfort temperature or did this happen by chance?

In thermal comfort investigations, the acceptance range is also

ID	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	41	Total
1													2	15	95	181	187	154	85	19														738
2																		1	3	8	7	46	79	85	91	29	26							375
3														3	47	129	82	43	37	6														347
4													4	22	92	176	40	1																335
5												3	10	3	34	87	174	120	27	2														460
6																			46	156	99	119	61	4										485
7											1	3	9	20	62	97	106	67	19	7	1		1	1										394
8														13	72	112	114	67	55	40	7	3	1											484
9												1	2	20	76	115	106	63	52	8	5			1										449
10												3	17	46	71	99	56	44	29	34	13	20	38	10	3	2								485
11																							13	55	27	6								101
12												1	6	7	18	32	61	98	50	15	7	7	1											303
13																1	1	5	7	15	20	42	38	33	27	21	22	3			2			237
14																	5	7	23	22	20	30	40	34	18	30	11	6	3	7	2			258
15									1	6	36	45	37	31	9	15	17	15		1														213
16													1	1		2	3	13	15	16	26	60	64	67	30	17	11	1	3		1	1	2	334
17			1	2	3	9	19	12	34	32	28	18	33	31	39	16	21	22	15	8	1													344
18													4	5	7	12	17	36	23	7	18	36	18	31	32	27	11	10	13	2	2			311
19	13	14	24	60	59	30	13	13	17	7	14	3	1																					268
20								1		5	20	61	73	124	126	105	47	19	2	1														584
21														10	48	110	139	28	5															340
22														1	20	94	116	48	18	1	1													299
23										1	4	4	8	52	107	99	45																	320
24													5	8	45	95	77	49	7	4	2				1									293
Avg	13	14	25	62	62	39	32	26	52	51	103	142	212	412	968	1577	1414	900	518	370	227	363	354	321	229	132	81	20	19	9	7	1	2	8757

Fig. 8. Number of votes on ASHRAE scale at various indoor temperatures.

required. This study followed the ASHRAE 55 standard. According to ASHRAE 55, thermal comfort is a state of mind that describes the satisfaction with the indoor thermal environment. According to the same reference, people voting +2, +3, −2, or −3 on the thermal sensation scale are dissatisfied. When looking at Fig. 8, it is apparent that most of the participants in the studies voted above −2 and below +2 or between −1 and 1. There were few exceptions, such the case study carried out in Saidu Sharif, Pakistan (Study ID 19). In that particular study, it was reported that most of the subjects in the survey occupied naturally ventilated buildings. Further, all used fans but a few used evaporative cooling in summer [37].

Close observation of Fig. 10 showed that extension of the investigated temperature range is required to estimate the acceptable comfort range, such as in Bangkok (Study ID 1) and other studies. It would also be of interest to replicate some studies under different conditions such as offices versus residential houses. Beyond doubt, the suggested simplified method of estimating comfort range is useful for understanding subjects' votes.

In this investigation, we also applied least squares linear regression analysis to predict the neutral temperature for the selected cases. The application of regression analysis to thermal comfort may be traced back to Bedford. Currently, it is widely used by many investigators for predicting neutral temperature in unconditioned buildings. Table 6 provides a summary of the obtained results. Interestingly, the method developed in Fig. 10 provided comfort temperatures similar to those found by the linear regression method. However, the suggested procedure provided more help in understanding the database and subjects' votes. The insignificance of a study was reflected by the inconsistency of the votes. The present designed procedure allows the investigator to select the neutral temperature and temperature range. This is highly recommended when the optimum value cannot be identified, such as when all subjects' votes are above or below neutrality. Further, it is also recommended for investigating whether or not the limits of acceptability (+/−1 on the ASHRAE scale) are reached.

It is important to emphasize that the insignificance of the studies

ID	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	41	Avg.	
1													-0.5	-0.9	-0.8	-0.4	-0.1	0.3	0.5	0.8														-0.1	**AC**
2																		0.0	0.0	0.4	0.5	0.8	1.0	1.3	1.5	1.9	2.0							1.3	NV
3														-2.0	-1.1	-0.8	-0.2	0.7	1.2	1.7														-0.3	**AC**
4													-1.5	-1.3	-0.6	-0.2	0.5	0.0																-0.3	AC
5												-1.8	-1.2	-1.2	-0.9	-0.4	0.0	0.5	0.9	0.0														0.0	AC
6																			0.1	0.4	0.9	1.2	1.6	1.8										0.9	NV
7											-3.0	-2.0	-1.6	-1.6	-1.0	-1.0	-0.3	0.3	0.5	1.0	2.0		2.5	1.5										-0.5	AC
8														-1.1	-0.9	-0.7	-0.3	0.2	0.7	1.0	1.9	1.7	0.0											-0.2	AC
9												-2.2	-1.3	-0.3	-0.3	0.0	0.3	0.7	0.8	1.5	1.8			1.0										0.2	AC
10												-0.3	-0.3	-0.3	0.0	0.2	0.5	0.8	1.2	1.5	2.1	2.2	2.1	2.2	2.8	1.8								0.7	NV
11																							0.3	0.7	0.6	0.0								0.6	NV
12												-1.0	-0.5	-1.4	-0.6	-0.4	-0.2	0.0	0.1	0.0	0.0	0.0	0.0											-0.2	NV
13																-1.0	-1.0	-0.4	0.0	0.2	0.2	0.2	0.3	0.6	1.1	1.1	1.6	1.3			2.0			0.6	NV
14																	0.2	-1.0	-0.6	-0.1	-0.5	0.1	0.2	##	0.7	1.7	1.7	2.3	2.3	2.1	1.5			0.4	NV
15									0.0	0.0	-0.5	-0.4	-0.1	-0.1	0.2	-0.1	0.2	0.3		-1.0														-0.2	NV
16													0.0	1.0		0.5	-0.3	-0.2	0.5	0.6	0.9	0.6	0.8	0.8	1.4	1.8	2.3	1.0	1.7		0.0	3.0	2.0	0.9	NV
17			0.0	-1.0	-0.7	-0.9	-0.3	-0.3	-0.6	-0.3	-0.3	-0.6	-0.2	-0.4	-0.2	0.1	0.0	0.0	0.2	0.5	-1.0													-0.3	NV
18													-1.5	-1.2	-0.6	-0.3	-0.3	0.4	0.7	0.6	0.8	0.5	0.7	0.9	1.5	1.6	1.3	1.5	2.1	2.0	1.5			0.8	NV
19	-2.2	-2.0	-2.0	-2.2	-2.2	-1.9	-2.2	-2.7	-2.9	-2.9	-1.9	-1.3	-1.0																					-2.2	NV
20								-1.0		-1.2	-0.6	-0.7	-0.5	-0.2	-0.1	0.0	0.3	0.1	0.0	0.0														-0.2	NV
21														-1.4	-1.2	-0.6	-0.2	0.4	1.0															-0.4	AC
22														-1.0	-1.2	-0.7	-0.2	0.4	0.7	2.0	3.0													-0.3	AC
23										-0.7	-0.9	-1.3	-0.3	0.3	0.3	0.5	0.9																	0.4	AC
24													-1.0	-0.6	-0.7	-0.2	0.0	0.5	1.2	0.7	0.2				2.0									-0.1	AC
Avg	-2.2	-2.0	-1.9	-2.2	-2.1	-1.7	-1.1	-1.5	-1.3	-0.7	-0.7	-0.7	-0.5	-0.4	-0.5	-0.3	0.0	0.3	0.5	0.6	0.8	0.8	1.0	0.9	1.3	1.6	1.8	1.7	2.1	2.1	1.4	3.0	2.0	0.1	

Fig. 9. Subjects Votes on ASHRAE scale at various indoor temperatures.

ID	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	41
1															-0.8	-0.4	-0.1	0.3	0.5														
2																						0.8	1.0	1.3	1.5	1.9	2.0						
3															-1.1	-0.8	-0.2	0.7	1.2														
4															-0.6	-0.2	0.5																
5															-0.9	-0.4	0.0	0.5	0.9														
6																			0.1	0.4	0.9	1.2	1.6										
7															-1.0	-1.0	-0.3	0.3	0.5														
8															-0.9	-0.7	-0.3	0.2	0.7	1.0													
9															-0.3	0.0	0.3	0.7	0.8														
10														-0.3	0.0	0.2	0.5	0.8	1.2	1.5			2.1										
11																								0.7	0.6								
12																-0.4	-0.2	0.0	0.1														
13																						0.2	0.3	0.6	1.1								
14																						0.1	0.2	-0.1	0.7	1.7							
15											-0.5	-0.4	-0.1	-0.1																			
16																					0.9	0.6	0.8	0.8	1.4								
17									-0.6	-0.3	-0.3		-0.2	-0.4	-0.2																		
18																		0.4				0.5		0.9	1.5	1.6							
19				-2.2	-2.2	-1.9																											
20												-0.7	-0.5	-0.2	-0.1	0.0	0.3																
21														-1.4	-1.2	-0.6	-0.2																
22																-0.7	-0.2	0.4															
23														0.3	0.3	0.5	0.9																
24															-0.7	-0.2	0.0	0.5															
Grand Total				-2.2	-2.1	-1.7	-1.1	-1.5	-1.3	-0.7	-0.7	-0.7	-0.5	-0.4	-0.5	-0.3	0.0	0.3	0.5	0.6	0.8	0.8	1.0	0.9	1.3	1.6	1.8						

Fig. 10. Updated Subjects votes on ASHRAE Scale at various indoor temperatures.

Table 6
Neutral temperatures from the least square linear regression and the present designed method.

ID	Conditioning Type	Neutral Temperature (present method)	Neutral Temperature (Least Square)	Sig
1	HVAC	24	24	S
2	NV	ND	26	S
3	HVAC	24	24	S
4	HVAC	23	23	S
5	HVAC	24	24	S
6	NV	ND	26	S
7	HVAC	25	25	S
8	HVAC	25	25	S
9	HVAC	23	23	S
10	NV	22	22	S
11	NV	/	39	NS
12	NV	25	25	S
13	NV	ND	28	S
14	NV	ND	29	S
15	NV	ND	22	S
16	NV	ND	24	S
17	NV	ND	24	S
18	NV	ND	24	S
19	NV	/	−74	NS
20	NV	23	23	S
21	HVAC	ND	24	S
22	HVAC	ND	24	S
23	HVAC	ND	21	S
24	HVAC	24	24	S

ND: Not Determined, NS: P*value* less than 0.05.

(*P*-value) did not necessarily occur because of the sample size. For instance, the *P*-value was not significant in case study ID 18, even though the number of votes was more than 500. The limited number of votes at each temperature affected the results.

5.9. Conclusions

This study analysed the ASHRAE RP-884 database using different criteria and methods. Several requirements were set for each parameter. A preliminary data analysis was carried out prior to predicting the comfort temperature of the selected locations. This study described the indoor temperature and relative humidity using new classifications. The results were then compared with the outdoor climate. Discrepancies between results showed the importance of using the suggested new indoor climatic classification for the best description of the indoor climate. In addition, a new procedure was developed to detect any anomalies and to obtain further insight into the data (i.e. the age of the subjects).

This study also suggested a new method for predicting comfort temperatures. The results showed the efficiency of the developed method in predicting comfort temperatures. The method will be useful for detecting anomalies in the votes and for understanding the limitations of the collected data. The results showed that the number of votes at various indoor temperatures should be sufficient to give an acceptable estimation of the average of subjects' votes on the ASHRAE scale. The results of this investigation showed that a large sample size does not necessarily reflect the quality of the predicted neutral temperature.

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