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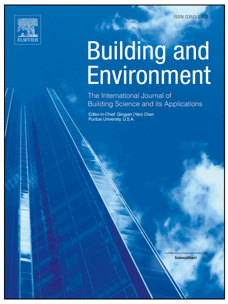

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Thermal comfort standards in the Middle East: current and future challenges

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Abstract

Cooling energy demand has increased three-fold in the Middle East (ME) over the last 30-years. This is driven by the need to maintain thermal comfort in an extremely hot climate, and supported by rising incomes, falling costs of air-conditioning and growth in the number of buildings. The definition of thermal comfort in these buildings is drawn from "international" standards, which, though empirically derived, have no basis data from this region. Hence, we ask, to what extent do indoor conditions in the ME fall within the standards recommended range of thermal comfort, and when they do, whether they are found to be comfortable by their occupants. We present the first large-scale study of thermal comfort in the ME, consisting of two approaches: (i) a meta-analysis of data from existing studies, (ii) independent field data covering four countries representing 27% of the region's population, 31 air-conditioned buildings of different types, including "green" buildings, and 1,101 subjects. The meta-analysis demonstrates that current thermal comfort standards fail to predict thermal sensation of 94% of occupants. Our own data show that, while indoor conditions are within standards-recommended ranges 58% of the time, only 40% of occupants find these conditions acceptable. We find evidence of overcooling in summers, with 39% occupants expressing cold discomfort. Computer models suggest that this is likely to have increased annual cooling energy demand between 13%-20%, compared to non-overcooled conditions. These results suggest the necessity of localised thermal comfort standards that mitigate excess cooling energy demand, without compromising occupant thermal comfort.

Nomenclature

T_a	Air Temperature	°C
T_r	Mean Radiant Temperature	°C
T_o	Operative Temperature	°C
T_g	Globe Temperature	°C
V_a	Air Movement Speed	ms^{-1}
RH	Relative Humidity	%
met	Metabolic Rate	met
clo	Clothes Thermal Insulation Value	clo
T_{out}	Outdoor Air Temperature	°C
RH_{out}	Outdoor Relative Humidity	%
T_n	Neutral Temperature	°C
$T_{n(TSV)}$	Neutral Temperature derived from TSV	°C
$T_{n(PMV)}$	Neutral Temperature derived from PMV	°C

1. Introduction

Heating, Ventilation, and Air-Conditioning (HVAC) systems currently consume around 50% of the global building energy demand [1,2]. In 2019, space cooling alone consumed 20% of the global electricity used in buildings [3,4]. In developing countries, many of which experience warm to hot climates, population growth combined with rising incomes has resulted in increasing the energy demand for space cooling 10% between 2018 and 2019 [4]. In low latitude countries (e.g., India, China, Africa, Northern Australia, South and Latin America, and Middle East (ME[1])), energy use for space

[1] There is no standard definition of the countries comprising the Middle East (ME). The most common definition classes fifteen countries namely Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Territories, Qatar, Saudi Arabia, Syria, United Arab Emirates, and Yemen [78], as the ME, and is the definition used here.

cooling is projected to rise from its present average of 32% of total building energy consumption to 72% by 2100 [5], driven largely by warmer outdoor temperatures as a result of climate change.

The ME is especially vulnerable to the impact of climate change projections due to its hot arid and semi-arid environment, with extreme climate conditions [6]. For example, the outdoor air temperature in summer frequently exceeds 50 °C in countries like Kuwait, Saudi Arabia, and Qatar, while in winter it drops down below 5 °C in Jordan, Syria, and Lebanon [6]. Currently, the building sector in the ME consumes 28% of the total energy consumption, with 70% attributed to space cooling [7–9]. The high space cooling demand is in response to the growing demand for better thermal comfort within the built environment, especially in non-domestic buildings (e.g., commercial, governmental, and health facilities) [1]. Indeed, cooling system penetration is around 65% across the ME [3,10]. Today, there are 1.1 billion air-conditioning units in the ME (i.e., three units per capita), and it is projected to increase to 3.1 billion units (five units per capita) by 2050 [11–13]. The need to drive this growth in a sustainable manner has resulted in the creation of several national-scale, and some regional-scale, voluntary Green Building Codes (GBCs). For example, the Pearl Building Rating System (PBRS) is localised to the United Arab Emirates (UAE) [14], whereas the Global Sustainability Assessment System (GSAS [15]), which was originally developed within Qatar (as QSAS), has now been adopted across the region. As many of these codes are often based on international codes such as the American LEED [16] or British BREEAM [17], a side effect has been the wholesale adoption of the underlying technical standards that these GBCs make reference to. In the case of thermal comfort, ASHRAE 55 [18] and ISO 7730 [19], have been adopted as these are seen as internationally applicable. There is a well-known trajectory for such codes to transition from voluntary to mandatory status, such as through incorporation within building regulations. It is therefore not surprising that eight countries out of fifteen in the ME have now adopted ASHRAE 55 and/or ISO 7730 as part of compliance procedures within national building regulations (see Section 1.1).

However, it has often been argued that thermal comfort could be affected by the complex interplay of several factors. These are usually grouped into three categories: behavioural (e.g., individual thermal adaptation), physiological (e.g., gender, race, age), and contextual (e.g., geographic location, climate, season) – none of which are factors within the international standards [20]. While some factors have been shown to not have a major influence (e.g., gender [21]), there is little in the literature to clearly demonstrate the effect of others, such as geography or culture [22,23]. More recently, however, there is some evidence to suggest that the adoption of these standards in warm climates can produce cooler than desired indoor conditions [24].

Hence, it is important to gather evidence on whether the international thermal comfort standards, if applied, produce comfortable indoor conditions in this region. If true, a straightforward pathway for their general adoption is opened, and indeed, may support their adoption in other parts of the world. However, if the application of these standards does not consistently deliver indoor thermal comfort, then more localised standards would be needed. This is the basic question investigated in this paper. We approach this problem for the ME by constructing two independent lines of evidence. First, we conduct a meta-analysis for all existing thermal comfort studies are done in the ME to collect related evidence (section 2). Second, we undertake new thermal comfort field surveys in four countries within the Middle East during cooling and heating season (section 3). Then, we combine our independent results (section 4) with the meta-analysis findings to create a large-scale thermal comfort dataset, which provides the opportunity to understand the thermal comfort patterns across the ME and show the potential saving in the building energy demand for space cooling and heating (section 5).

1.1 Current thermal comfort standards in the ME

GBCs are usually considered more inclusive and comprehensive because they include the national building regulations as a mandatory basic level that need to be met in advance of starting the assessment process. Given the trajectory of rules transitioning from voluntary to mandatory, as stated earlier, one can expect the set of building regulations making reference to thermal comfort standards to be a subset of GBCs making reference to the same standard. Further, GBCs will also frequently lay claim to higher quality indoor environments, and hence, any evaluation of the success or failure in the provision of thermal comfort must also include an assessment of the performance of GBC-certified buildings. We therefore commence with an analysis of thermal comfort standards as adopted within GBCs in the ME.

Of the fifteen countries in the ME, eight have developed a local GBC or equivalent. Hence, these eight codes are selected to investigate which thermal comfort standards are used in the ME. These GBCs are: ARZ Building Rating System in Lebanon [25], GSAS (formerly QSAS) in Qatar [15], Green Pyramid Rating System (GPRS) in Egypt [26], Israeli Green Building Standard (SI 5281) in Israel [27], Jordanian Green Building Guide (JGBG) in Jordan [28], Mostadam in Saudi Arabia [29], Palestinian Green Building Guide (PGBG) in the Palestinian Authority [30], and Pearl Building Rating System (PBRS) in UAE [14]. Table 1 shows that each of the investigated codes adopts either or both the ISO7730 and ASHRAE 55 standards. This is not surprising since they are based either on LEED and/or BREEAM, which use these standards. The thermal comfort standards and requirements are included in these codes either under the Indoor Environment Quality (IEQ) aspect (as in ARZ, GSAS, GPRS, PGBG, and JGBG) or under other aspects, i.e., health and wellbeing, liveable buildings, health and comfort.

There are minor differences in the implementation of the international standards within each of the eight codes, observable through the difference in treatment of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfaction (PPD) indices, that specify the acceptable range of thermal conditions for building users. Whereas PBRS and PGBG explicitly state the use of two classes of PMV/PPD for mechanically ventilated and mixed-mode buildings, broadly corresponding to the classes contained in ISO7730; SI 5281 and Mostadam only use the range for "normal" expectation, i.e., PMV [-0.5, +0.5] and PPD <10%. GSAS is unique within this group to separate design and operation stages, the latter being required to adhere to thermal conditions that would apply for "normal" levels of thermal expectation (i.e., the same as SI 5281 and Mostadam) but being pre-calculated assuming western office attire and standard levels of metabolic activity rates. This is odd, given that these conditions would be an automatic requirement within ISO 7730 for such levels of activity and attire, but precludes adjustment for other conditions.

Closer inspection of the thermal comfort requirements in Table 1 shows that among GSAS, PGBG, PBRS, Mostadam, and SI 5281, the thermal comfort credits are clustered around occupant control over indoor temperature, thermal zoning, the requirement for operable windows, and occupancy sensors. Thermal comfort modelling at the design stage is required explicitly in Mostadam, while it is implicitly mentioned in PBRS and not included within the total assigning credits. Only GSAS requires a thermal comfort survey after occupancy as a mandatory credit. The lack of any of the above details in ARZ, GPRS, and JGBG, is striking in comparison.

Overall, therefore, we find that there is a clear trend for GBCs in the region to adopt international thermal comfort standards. Although they prescribe some minor adjustments, one cannot conclude that this results in localisation since there is neither underpinning localised evidentiary basis for their use nor an implicit adjustment to the standards based on expert knowledge or experience. From this, we can inductively reason that buildings in the ME, in general, are likely to conform to an international thermal comfort standard when designed to be standards compliant.

Table 1 Summary of thermal comfort requirements specified in the Green Building Codes in the Middle East, • indicates that the element is explicitly mentioned in the tool, and it has weight of the total scale weight; ◊ indicates that the element is implicitly mentioned in the tool, n/a indicates not available.

Tool	ARZ [25]	GSAS [15]	GPRS [26]	JGBG [28]	Mostadam [29]	PGBG [30]	PBRS [14]	SI 5281 [27]
Country	Lebanon	Qatar	Egypt	Jordan	Saudi Arabia	Palestinian Authority	UAE	Israel
Year	2008	2009	2011	2013	2019	2013	2007	2005
Thermal comfort standard	ASHRAE 55	ISO 7730 ASHRAE 55	ASHRAE 55	ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55
Assessment approach	n/a	Design stage: PMV for spaces with direct exposure to the solar heat and/or Air Diffusion Performance Index (ADPI) for other spaces Operation stage: Air temperature range of 22 – 25 °C, relative humidity range of 35% - 55%, air speed below 0.2 ms^{-1}	n/a	n/a	$-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$ $-0.7 \leq$ PMV ≤ 0.7 PPD $\leq 15\%$	Class I: $-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$ Class II: $-0.7 \leq$ PMV ≤ 0.7 PPD $\leq 15\%$	Mechanical class I: $-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$ Mechanical class II: $-0.7 \leq$ PMV ≤ 0.7 PPD $\leq 15\%$ Mixed-Mode ventilation (class B and C): 90% acceptability limits	$-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$
Thermal Comfort Requirement								
Thermal zoning							•	
Occupant control		◊			•	•	•	
Occupancy sensor linked to HVAC					•	•		
Operable windows		•				•	•	•
Thermal comfort modelling					•		◊	
Post-occupancy thermal comfort survey		•						

1.2 Research objectives

This study is designed to examine whether air-conditioned buildings in the ME fall within the recommended ranges of thermal comfort identified by the applied standards in this region, and when they do, to what extent they are found to be comfortable by their occupants. To address this, we start by a meta-analysis approach to aggregate the outcomes of multiple thermal comfort studies in the ME (Section 2) and then, we conduct new field surveys in four countries: Jordan, Qatar, Saudi Arabia, and the United Arab Emirates, representing 27% of the ME population, using the definition suggested earlier (Section 1). Our detailed objectives are:

1. To perform a meta-analysis of previous thermal comfort research in air-conditioned buildings in the ME.
2. To assess thermal conditions in GBC-certified and typical air-conditioned buildings in the ME against both the applied international thermal comfort standards and those proposed by localised GBCs.
3. To compare the predicted mean vote (PMV) and observed thermal sensation vote (TSV) in all building types and investigate any seasonal differences.
4. To calculate the difference between predicted and observed neutral (comfort) temperatures and estimate any potential reduction in the building energy use for space cooling and heating based on the obtained differences, if any.

2. Meta-analysis of evidence in the ME

There are two methods to perform the meta-analyses, either using individual participant data (i.e., raw data collected by multiple studies) or aggregate data (i.e., available evidence from literature) [31]. We rely on the latter approach, as the raw data were not publicly available. First, we systematically review the relevant literature [32], including the recently released ASHRAE Global Thermal Comfort Database II [33]. We determine the eligibility of studies for our meta-analysis based on two criteria: (i) the operation mode in the surveyed buildings (i.e., air-conditioned only), and (ii) the available thermal comfort data (Figure 1). Second, we extract the aggregate data from selected studies and compute summary statistics from each study [34].

Table 2 summarises the eight included studies in the meta-analysis. All studies investigated occupant thermal comfort in air-conditioned buildings in the ME and were done in the past ten years (2010 - 2020) during the cooling season. In the ME, the cooling season varies according to the climate zone, for example, coastal cities, such as Jeddah, Doha and Bahrain are humid and very hot throughout the year, thus air-conditioning is used for space cooling continuously. Whereas in cities at high elevations such as Amman, Beirut, and Damascus, the use of air conditioning for space cooling is limited to four months only between June and September; while in December, January and February, there is some space heating demand usually delivered via the air conditioning system or through supplementary heating. In these latter cities, therefore, there exists potential for natural ventilation during the remaining five months (i.e., March, April, May, October, and November).

Among the analysed studies, offices comprise the most studied group of buildings (80% of the total sample size [35,36]), some studies include homes [37,38], mosques [39,40], hospitals (covering patients only) [41], and educational buildings, i.e. university campuses [42]. The studies cover three countries namely Kuwait, Qatar, and Saudi Arabia and employ transverse sampling, except one which has a longitudinal design [50].

When all data are pooled, the resulting dataset covers 76 air-conditioned buildings and 2,825 subjects in the age range $\in$ [21, 34] years (mean = 31 years, s = 4.6 years), hence, this is a young sample. All studies (except one [38]), report aggregate data for five standard thermal comfort parameters: air temperature (T_a), relative humidity (RH), air speed (V_a), metabolic rate (met), and clothing thermal insulation (clo). Three studies report either the mean radiant temperature (T_r) [35,41] or the globe temperature (T_g), from which T_r can be derived [35,36]. All studies report the operative temperature (T_o), except two studies [37,39]. The summary statistics for these studies shown in Table 2 are based on a total of 7,077 records of environmental and subjective observations. We observe that mean clothing thermal insulation was 0.94 clo (s = 0.26 clo), with the lowest mean of 0.42 clo in homes. Estimated metabolic rates varied considerably between 2.3 met for employees in office buildings to 0.67 met in homes (dataset mean 1.24 met, s = 0.48 met).

RH ranged between 35% and 60% (mean 44%, s = 8.6%) with Kuwait at the lower end and Saudi Arabia at the higher end of the scale. V_a does not exceed 0.25 ms^{-1} (mean = 0.11 ms^{-1}, s = 0.09 ms^{-1}) in all studies. Means for T_a (23.2°C, s = 1.56 °C), T_r (23.1 °C, s = 0.63 °C), T_g (23.3 °C, s = 0.49 °C) and T_o (23.1 °C, s = 0.86 °C) were comparable through the dataset. Mean T_a ranged between 22– 24 °C, with the exception of data from homes in Saudi Arabia which reported a mean T_a of 27 °C.

An average of 43% of votes in the dataset can be classified as neutral (i.e., TSV$\in$ [-1, +1], Figure 2.a). Hence, none of these buildings achieve 80% acceptability as recommended by the ASHRAE 55 standard. A significant proportion of the votes (26% on average) demonstrate cold discomfort (i.e., TSV < -1), which is substantially higher than the average vote for warm discomfort (21%).

TSV is cooler on average than predicted by PMV in all types of buildings except in the hospital study (Figure 2. b and c). Hence, the observed neutral temperatures based on TSV ($T_{n(TSV)}$), in these buildings were higher compared to those predicted by PMV ($T_{n(PMV)}$), which underestimated neutrality by an average of 2.1 K (Figure 2. d). A possible cause for the hospital study resulting in PMV underestimating TSV, is that this study looks at thermal comfort in patients suffering from cardiovascular and respiratory diseases and are hence not directly comparable to healthy subjects in other studies. Here, we find that mean PMV = -0.5 compared to mean observed TSV = +0.3, corresponding to $T_{n(TSV)}$ = 22.7 °C and $T_{n(PMV)}$ = 25.6 °C, i.e. a difference of 2.9 K. While the authors of that study speculate that lowered met and clo may be the cause for this unusual result, this would seem counterintuitive and can hence be considered as not fully understood.

Overall, the meta-analysis suggests, with the exception of the hospital, as above, that the PMV model usually results in cooler conditions than those preferred by building occupants in the ME. However, given that the data cover only three countries and only typical buildings, there is clear potential for additional data from other locations including from more modern "green" buildings. That all the extant studies are from the cooling season (i.e., summer and autumn) also suggests the need to investigate the heating season, where appropriate. Finally, it would be useful to understand to what extent the results of the hospital study are due to the survey being confined to patients and not staff. Hence, the next part of this paper aims to increase the coverage of locations, seasons, building types and occupant types for thermal comfort data in the ME.

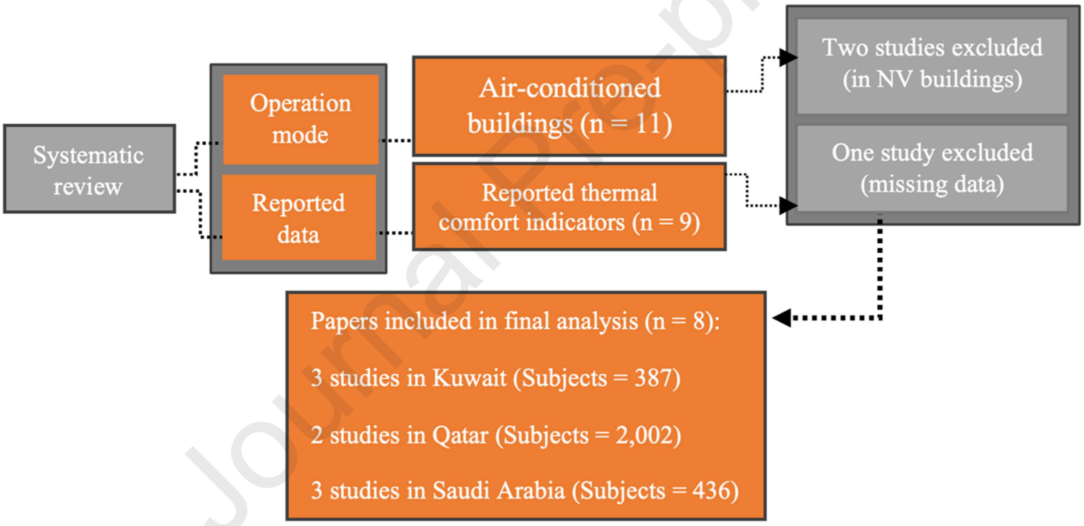

Figure 1 Schematic flow diagram of literature screening process, including the number of potentially relevant studies and the final number of included studies that met the two inclusion criteria.

Table 2 Descriptive summary statestic of the existing field thermal comfort studies in air-conditiond buildings in the ME during cooling season, the reported values for thermal comfort parameters in this table represent the mean for each study. Note: the mean value of age is not reported in two studies, as instead they report the percentage of multiple age group, ($n\_buildings = 76; n\_Subjects = 2{,}825$).

						Reported mean within each study													
Ref	Location	Bldg. Type	Bldg (*n*)	Subject (*n*)	Vote (*n*)	Age (y)	clo	met	T_a (°C)	T_g (°C)	T_r (°C)	V_a (ms^{-1})	RH (%)	T_o (°C)	PMV	TSV	$T_{n(PMV)}$ (°C)	$T_{n(TSV)}$ (°C)	Diff (°C)
[37]	Kuwait	Homes	25	111	111	32.1	0.90	1.20	22.7	-	-	0.13	34.5	23.7	0.13	-0.28	23.3	25.2	1.90
[39]	Kuwait	Mosques	6	140	140	32.6	0.93	1.30	23.0	-	-	0.23	44.1	23.9	0.19	-0.26	23.3	26.1	2.80
[40]	Saudi Arabia	Mosques	1	281	422	-	1.13	1.30	21.7	-	-	0.25	31.9	21.5	0.01	-0.19	21.5	22.3	0.80
[41]	Saudi Arabia	Hospital	1	120	120	-	1.30	0.80	23.1	-	23.4	0.04	48.3	23.3	-0.5	0.32	25.6	22.7	-2.90
[35]	Qatar	Offices	9	828	1,926	32.7	1.00	1.10	23.1	22.7	22.5	0.02	44.9	22.8	0.04	-0.23	23.7	24.1	0.40
[36]	Qatar	Offices	10	1,174	3,742	32.9	0.80	2.30	23.8	23.4	-	0.04	45.7	-	-	-0.54	-	24.8	-
[42]	Kuwait	Campuses	7	136	136	21.6	1.01	1.30	22.8	-	-	0.09	46.0	23.3	0.50	0.11	18.9	22.9	4.0
[38]	Saudi Arabia	Homes	17	35	480	34.0	0.42	0.67	27.0	-	-	-	60.0	-	-	1.30	-	-	-
Mean (SD)						31 (4.6)	0.94 (0.3)	1.2 (0.4)	23.2 (1.5)	23.3 (0.4)	23.1 (0.6)	0.11 (0.1)	44.2 (8.6)	23.1 (0.8)	0.06 (0.3)	0.03 (0.6)	23.3 (2.3)	24.3 (1.4)	
Total			76	2,825	7,077														

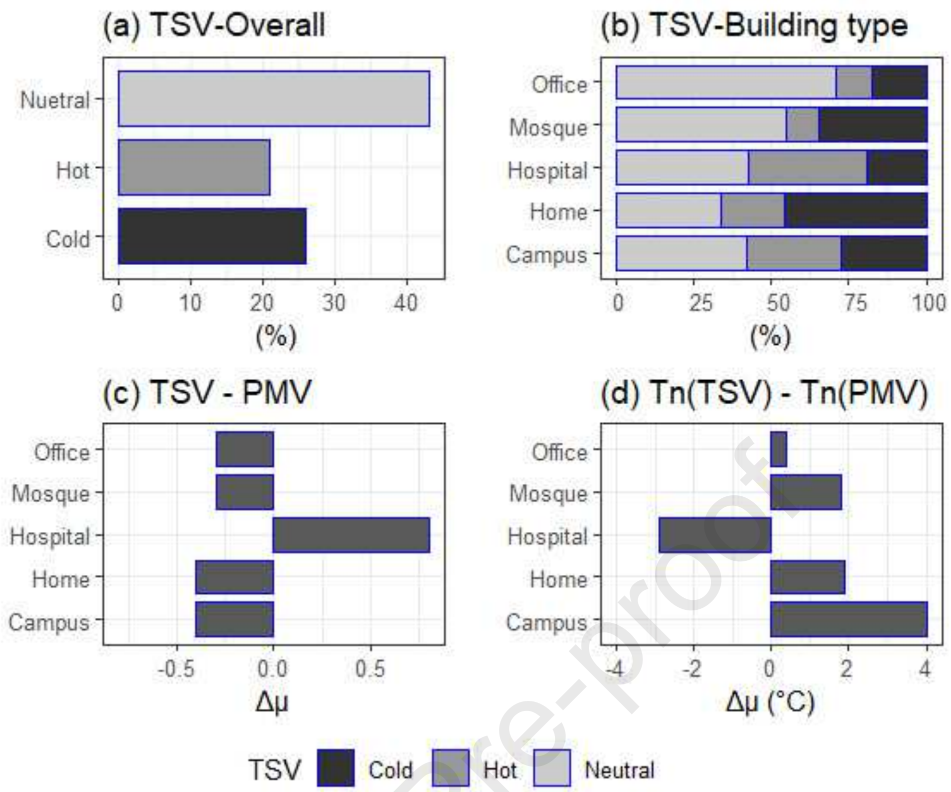

Figure 2 Summary results of the meta-analysis with $n_{buildings} = 76; n_{occupants} = 2{,}825$, (a) raw TSV distribution for the dataset, (b) TSV distributions split by building type, (c) the difference between mean scores (i.e., Δμ = TSV-PMV) based on the building type, i.e. (Δμ > 0) indicates TSV is greater than PMV, (d) the difference between mean neutral temperatures derived from TSV ($T_{n(TSV)}$) and PMV ($T_{n(PMV)}$).

3. New thermal comfort dataset in the ME: methods

To achieve the aim outlined at the end of Section 2, we undertook seven standardised thermal comfort field surveys over three years between May 2017 and Sept 2019 (Figure 3), using methods described in the following sections.

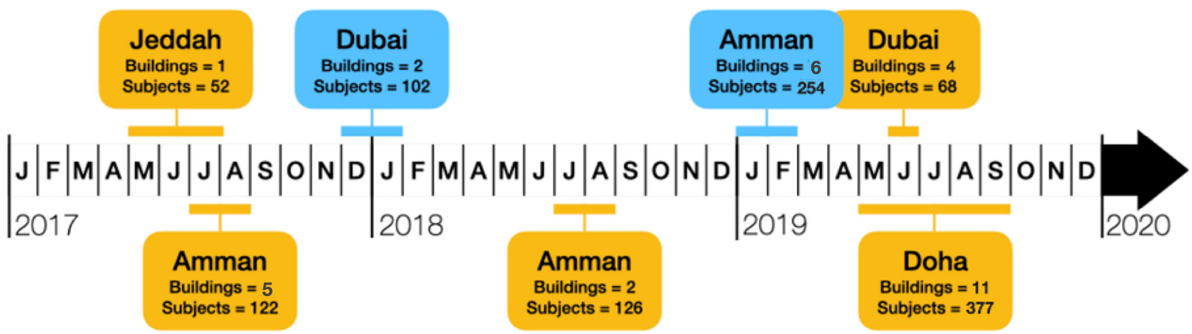

Figure 3 Timeline of data collection in the present study. Data were collected between May 2017 and Sept 2019 in four countries in the ME, Yellow represents studies undertaken in the summer, and blue, winter. The length of bars adjacent to each label indicates the months over which data were collected. $n\_buildings = 31; n\_subjects = 1{,}101$.

3.1 Outdoor conditions in the survey areas

According to the widely used Köppen climate classification [6], the climate for Doha, Dubai and Jeddah are classified as hot desert (BWh), with extremely hot summers and warm dry winters. Amman, on the other hand, is classified as a composite climate, i.e., one with hot semi-arid conditions (BSh) but bordering on cold semi-arid (BSk), with a long hot summer and short cold winter [43]. However, this is a broad classification, and we hence use the annual heating degree days (HDDs) and cooling degree days (CDDs) for each city to illustrate how winters and summers are distributed (Table 3). We find that, while Doha and Jeddah do not experience wintry conditions (4 and 0 HDDs respectively), there may be some merit in investigating winter comfort in Dubai (21 HDDs) and definitely for Amman (873 HDDs). CDDs, on the other hand, are uniformly large. Thus, our field surveys were conducted in peak summer for all cities and peak winter in Amman and Dubai only.

Table 3 also presents the mean daily outdoor air temperature (T_{out}) and relative humidity (RH_{out}) in the surveyed cities during the time of the surveys, using data obtained from local weather stations. It is noteworthy that observed temperatures during the studies in Amman and Doha are likely to be higher than shown due to the well-known urban heat island effect, given that the data were obtained from the nearby airport [44].

Outdoor summer mean temperatures are comparable in Amman, Dubai, and Jeddah with a range of 32.6 °C and 34.1 °C, while Doha had higher mean T_{out} of 40.5 °C. In Amman, where we have data from two consecutive summers, mean T_{out} in summer 2017 was slightly lower compared to the same time period in the following year 2018, with a difference of 1.1 °C. In winter, the mean T_{out} in Amman (10.4 °C) was lower than in Dubai (20.1 °C). The relative humidity ranges in Amman and Dubai during winter were higher than in summer. The RH_{out} range in Jeddah varied between 31.9% - 91% and was comparatively higher than the RH_{out} in Doha.

Table 3 The daily mean outdoor temperature (T_{out}) and relative humidity (RH_{out}) recorded during the study periods in Amman, Doha, Jeddah and Dubai. Annual heating degree days (HDD) and annual cooling degree days (CDD) are calculated using a base temperature [> 18 °C and < 18 °C], respectively.

City	Amman[1]			Doha[2]	Jeddah[3]	Dubai[4]	
Climate	BSh + BSK			BWh	BWh	BWh	
HDDs	873			4	0	21	
CDDs	3,814			5,006	6,587	5,392	
Time of survey	Jul – Aug 2017	Jul – Aug 2018	Jan – Feb 2019	May - Sep 2019	May – Jul 2017	Dec – Jan 2017 - 18	Jun 2019
T_{out} (°C)							
Mean	33.2	34.1	10.4	40.5	32.6	20.1	33.4
Max.	40.1	41.2	22.0	45.5	42.6	31.3	36.7
Min.	25.3	26.1	5.0	38.0	23.8	12.9	25.3
Range	[25.3, 40.1]	[26.1, 41.2]	[5.0, 22.0]	[38.0, 45.5]	[23.8, 42.6]	[12.9, 31.3]	[25.3, 36.7]
RH_{out} (%)							
Mean	42.3	47.4	70.3	46.6	49.9	66.4	62.3
Max.	52.1	56.6	75.1	58.0	91.0	80.1	78.7
Min.	13.4	15.1	69.1	37.0	31.9	50.5	41.1
Range	[13.4, 52.1]	[15.1, 56.6]	[69.1, 70.3]	[37, 58]	[31.9, 91.0]	[50.5, 80.1]	[41.1, 78.7]

Data sources:
[1]Jordan meteorological department, Amman civil Airport
[2]Department of meteorology, Civil Aviation Authority, Doha
[3]Department of meteorology, King Abdul-Aziz University, Jeddah
[4]National center of meteorology, UAE

3.2 Sampling

In the literature, there are two common methods for undertaking thermal comfort surveys: (i)longitudinal with repeated measures, usually with a small sample size [45] and (ii) transverse with a large number of responses collected once [46]. Our interest is in investigating indoor conditions and comfort across a large number of buildings and hence the latter method is used. Surveys were conducted in the four locations discussed earlier and thermal comfort data were collected using a standardised questionnaire ([18], Appendix A), as well as the necessary objective data (see Section 3.3). Data were obtained from 1,101 subjects from 31 different buildings, with each subject providing one response. A range of non-domestic occupancy types were covered, including twenty-five office buildings (n = 849), three schools (n = 98), two mosques (n = 102), and one hospital (nursing staff only, n = 52).

Surveyed buildings were constructed in the last twenty years, twenty-six buildings are mechanically air-conditioned, and five buildings have mixed-mode ventilation (Figure 4). Seven of the office buildings are green-certified, under either local GBCs (e.g., JGBG, GSAS) or the international LEED. In addition, the surveyed buildings in Dubai and Jeddah were recipients of regional design awards and can therefore be considered as high-quality (see Appendix B for the specific details of the investigated buildings). All subjects have voluntarily participated in the survey, prior informed consent being obtained. A comprehensive profile of the participating subjects is presented in Table 4.

Figure 4 Examples of the surveyed buildings in this study, (a) mosque in Dubai, (b – e) office buildings in Amman, (f) hospital in Jeddah (source: IMC Research Centre, Saudi Arabia, reproduced with permission), (g) example of mixed-mode ventilation office, (h) example of fully HVAC office, and (i) interior shot of prayer hall in the mosque, $n_{Buildings} = 31$.

Table 4 Comprehensive profile of subjects in each surveyed city. Height, age, and weight data for Dubai are unavailable, $n\_subjects =$ 1,101.

City	Sample (n)	Gender		Height (cm)		Weight (Kg)		Age (y)	
		Female	Male	Mean	SD	Mean	SD	Mean	SD
Amman	502	223	279	172.2	11.2	76.8	13.3	29.3	5.3
Doha	377	70	307	169.6	10.9	77.6	16.3	38.2	9.3
Dubai	170	23	79	-	-	-	-	-	-
Jeddah	52	39	14	160.9	7.6	65.2	12.2	34.6	7.2

3.3 Thermal comfort parameters measurements

We measure all four physical parameters affecting thermal sensation (i.e., T_a, T_r, RH, and V_a) in all surveyed buildings, except for the two buildings in Dubai during summer, where only measurements for T_a and RH were possible. Thus, data from Dubai (summer) survey are used to gain an idea of the indoor thermal conditions, while the PMV calculation for these two buildings was not possible, due to the absence of other thermal comfort indices. The measurements of the four physical parameters in all buildings were coincident with the time of each individual survey. In Amman, Doha, and Jeddah two instruments were used to monitor all parameters, SWEMA [47] and HD 32.3 [48], both compliant with ISO 7726 [49] and ISO 7730 [19] standards. In Dubai (winter) study, an Extech HT200 heat stress wet bulb globe thermometer was used to monitor T_a, T_r, and RH, and ATP unidirectional hot wire thermo-anemometer was used to simultaneously measure V_a. The latter set while not being ISO compliant, produces data of sufficient accuracy for use in fieldwork (e.g., [50]). Technical specifications of all instruments are in Appendix C.

The sample period of T_a, T_r, RH, and V_a was five minutes including two minutes for sensors to stabilise and additional three minutes to provide a stable PMV reading. Measurements in the office buildings, schools (staff room), and hospital (nursing stations and corridors) were taken at height 60 – 110 cm from the ground level, and the instrument was located on the subject's desk (Figure 5. a and b) [51], during working hours between 09:00 – 17:00. In the mosques, measurements were taken at height 60 cm above the floor level for seated subjects as specified in ISO 7726 and ASHRAE 55, the instruments were located in the main prayer hall during Friday's congregational prayer, i.e., at maximum occupancy. The clothing thermal insulation level was calculated based on ASHRAE 55 and ISO 9920 [52] (Figure 5. c - e). Similarly, the metabolic rate of subjects was calculated based on the standard tables provided by ASHRAE 55 and ISO 8996 [53].

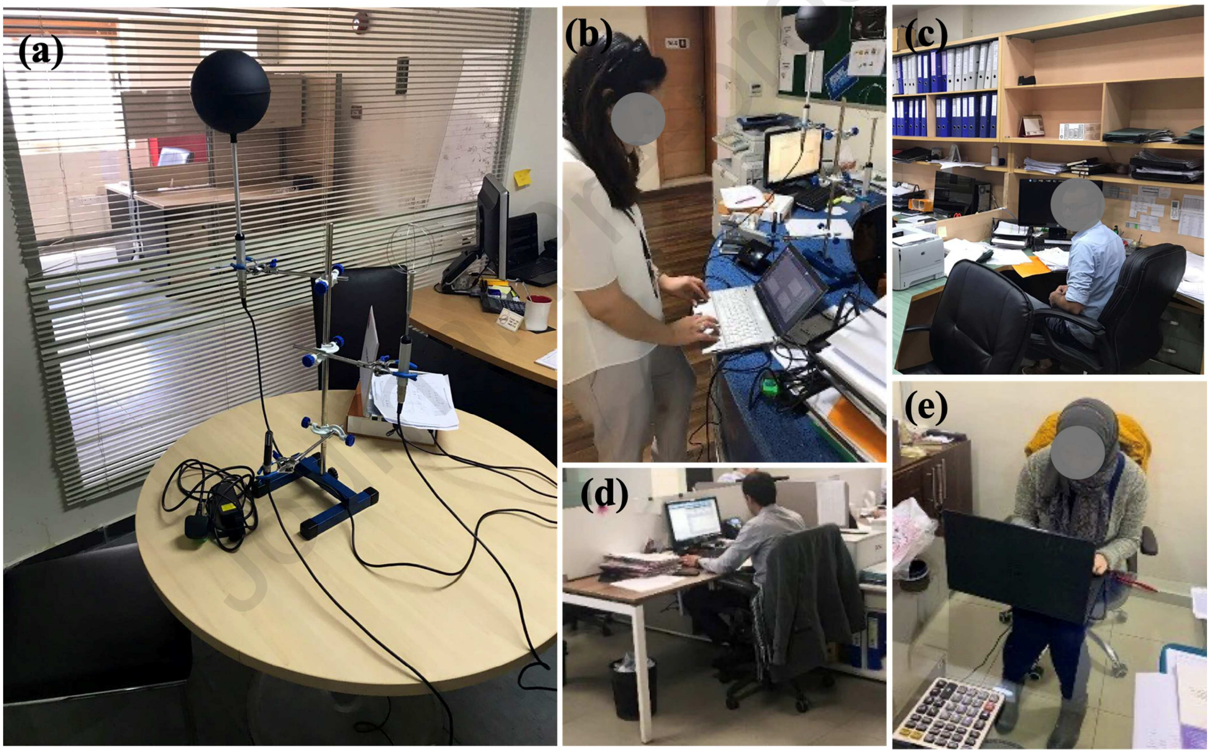

Figure 5 The instrument setup in surveyed buildings (a and b), examples of indoor subjects' summer clothing (c), winter clothing (d), and female subject with headwear (e).

3.4 Subjective measurements

The questionnaire consists of two sections. The first pertains to socio-demographic data on age, gender, height, weight, job role, and nationality. The second section covers the standardised thermal comfort survey based on ASHRAE 55. The survey was designed and written in English and translated to Arabic as most respondents speak Arabic as a first language. In Doha, Dubai and Jeddah, classical Arabic was used as it is the common dialect, however, for respondents in Amman, the Levantine-Arabic dialect was used (see Appendix A). This resulted in subtle but important differences in the coding of the questionnaire, particularly for TSV [54]. The Arabic and English versions were combined with a consent form and distributed randomly within the surveyed buildings. The questionnaire was paper based instead of online to promote the response rate, as some subjects, i.e., those at prayer and nurses did not have access to a computer or internet connection during the survey time. The survey completion time ranged between 40 - 60 seconds, with ten multiple-choice questions, all completed concurrently with the sensor measurement, per Section 3.3. All the buildings' managers/owners were interviewed to introduce the research idea and their written consent was obtained. While extraneous factors such as family circumstances, driving to work etc. may affect perceptions, these are not explicitly explored here due to the need to keep survey times low and thus maximise response rates, whilst being consistent with other studies. This is somewhat mitigated by the cross-sectional nature of the survey that will reduce the effect of aleatory uncertainties, though not systematic bias.

3.5 Analysis methods

A total of 1,101 data points was aggregated, analysed, and presented based on three levels namely location, building type, and season. Operative temperatures (T_o) were calculated per ISO 7726 [49]. As our data are numerical, differences in means are analysed using standard statistical inference, i.e., *t*-test, 95% confidence intervals and Cohen's well-known d metric for effect size. The mixed-effects model was used to test the differences between data and deal with non-independence. PMV was classified into three categories: cold discomfort ∈ [-3, -0.5), neutral ∈ [-0.5, +0.5] and hot discomfort ∈ (+0.5, +3], since PMV ±0.5 is considered neutral for typical buildings, Category II in ASHRAE 55 [18]. Although hospitals and schools could be classified as Category I buildings, where PMV ±0.2 would be considered neutral, we do not use this definition for consistency with the other data; and the fact that we are surveying only staff in the hospitals and schools.

Observed TSV were classified into cold ∈ [-3, -1), neutral or comfort ∈ [-1, +1] and hot ∈ (+1, +3]. This choice of neutrality is consistent with other studies in the literature [36] and relates to the likelihood of the TSV scale being interpreted as ordinal, rather than interval, during subject self-completion. Note that this is likely to suggest a wider neutral band in the observed TSV than would be the case with a band consistent with PMV, and hence lead to an *underestimate* of the cold and hot discomfort classification on either side of neutral.

3.5.1 Calculating neutral (comfort) temperature

Simple linear regression is used to calculate the neutral temperature (T_n) from PMV and TSV for each surveyed city. We plot observed TSV and PMV against T_o and identify the neutral temperature as the temperature when the mean of PMV or TSV equals zero. We thus use the following equations:

$$\text{TSV} = \alpha \text{T}_\text{o} + b \quad (1)$$

$$\text{PMV} = \alpha \text{T}_\text{o} + b \quad (2)$$

$$\text{T}_\text{n} = -b/\alpha \quad (3)$$

where (α) indicates the regression coefficient (gradient), and (b) refers to the intercept on the y-axis, i.e., TSV or PMV. For data with a small disparity in operative temperatures (e.g., Amman), we instead use the well-known Griffith's method to compute the neutral temperature derived from TSV using following equation:

$$\text{T}_\text{n} = \text{T}_\text{o} + (0 - \text{TSV})\ /G \quad (4)$$

where G indicates the Griffith's constant. There are several commonly used values for G in the literature ranging ∈ [0.25/K, 0.5/K]. We use G = 0.5/K in line with similar studies in the ME, such as [36,55]. T_n is difficult to calculate with a small dataset [56], and hence was not computed for schools and mosques in Doha and Dubai respectively. All analysis is conducted using R [57], due to the convenient availability of the 'comf' package [58] for thermal comfort plus data management and plotting packages such as the 'tidyverse' family [59] and 'cowplot' [60].

3.5.2 Simulation of building energy consumption

We carried out energy model simulations for the calculated $T_{n(PMV)}$ and observed $T_{n(TSV)}$ to illustrate the variation in building energy demand for the two indices. The well-known EnergyPlus building energy simulator [61], is used with ANSI (American National Standards Institute)/ASHRAE/IES (Illuminating Engineering Society) Standard 90.1 prototype building models for our analysis [62].

The simulation is done for two occupancy types: office buildings in Amman and Doha (medium office prototype building) and hospital in Jeddah (hospital prototype building) (see Appendix D). The schools and mosques were excluded due to small sample sizes and hence no predicted T_n, as mentioned earlier. The selected models resemble the real size and function of the buildings where the data were originally collected to maintain suitability with the building energy simulation results. Considering the default commercial prototype building model operational mode for both cooling and heating and the calculated $T_{n(PMV)}$ and $T_{n(TSV)}$, the cooling and heating setpoints for occupancy hours were adjusted to reflect the recommended upper and lower neutral temperature conditions. Amman, Doha and Jeddah models are simulated with the three calculated neutral temperatures using TSV and PMV as building setpoint temperatures in each city's climate respectively.

4. Results

This section presents results of the data obtained from our field study covering 31 air-conditioned buildings, four occupancy types, and 1,101 subjects, during summer and winter.

4.1 TSV and ASHRAE 55 comfort zones

Table 5 illustrates the mean scores of measured thermal comfort parameters based on season, city and building type. The mean T_a over summer and winter is within a relatively narrow range [21.7 °C, 24.0 °C], or 2.3 K, for all the buildings. RH was slightly higher in summer (pooled mean 46%) than in winter (pooled mean 43%) but over a wide range [36%, 58%]. V_a ranged between [0.05 ms^{-1}, 0.17 ms^{-1}] which is below the maximum acceptable air speed of 0.20 ms^{-1} given in the ASHRAE 55 standard.

For the subjects in the survey, the mean values of metabolic rate ranged between 1.08 met for sitting with passive work in office buildings and 2.49 met for praying in the mosques. In all surveyed cities, most (92%) male subjects were wearing western clothing, with the remaining wearing non-western clothing with clo value varied between 1.10 - 1.57 clo. A small proportion (22%) of female respondents wore headwear (Figure 5. e), which resulted in an increased insulation value of 0.03 clo [63], with the rest wearing western clothing, with no headwear at 1.08 clo. Surprisingly, the clo value of subjects in summer was higher than in winter, with difference +0.03 clo in Amman, and +0.20 clo in Dubai. The lowest clo value was observed in the hospital in Jeddah, as nursing staff wear very light uniform (mean = 0.59 clo).

Figure 6 compares the observed thermal comfort zones in all surveyed buildings among the four cities to the recommended comfort zone by ASHRAE 55 standard [18]. We observe that all surveyed buildings in Amman and Doha were within the recommended comfort zone during summer and winter, whereas the thermal comfort zone in mosques in Dubai was shifted to the left side and this refers to the high metabolic rate in mosques (mean = 2.5). The hospital in Jeddah was also completely outside the standard-recommended comfort zone. Hence, we can conclude that the buildings in Amman and Doha were thermal comfort standards compliant whereas those in Dubai and Jeddah were not.

Table 5 Summary of the monitored thermal comfort parameters in the surveyed buildings in the four cities during summer and winter, T_a and V_a were not available for Dubai (summer) survey, $n\_buildings = 31, n\_subjects = 1{,}101$.

Season	City	Bldg. Type	clo		met		T_a (°C)		T_r (°C)		RH (%)		V_a (ms^{-1})	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Summer	Amman	Offices	1.3	0.05	1.2	0.18	21.7	1.76	22.0	1.82	37.4	3.29	0.1	0.15
	Doha	Offices	1.1	0.26	1.2	0.00	23.8	1.39	23.8	1.44	47.8	8.86	0.2	0.19
	Doha	Schools	1.1	0.19	1.2	0.00	23.7	0.96	23.9	1.28	42.2	3.53	0.2	0.18
	Dubai	Schools	1.2	0.12	1.2	0.10	24.0	1.23	-	-	57.7	3.59	-	-
	Jeddah	Hospital	0.6	0.05	1.1	0.12	21.8	1.36	22.1	1.32	45.1	2.11	0.1	0.11
Winter	Amman	Offices	1.3	0.13	1.2	0.20	22.1	0.84	22.1	0.87	35.6	2.74	0.2	0.09
	Dubai	Mosques	1.0	0.31	2.5	0.23	23.3	1.73	23.2	1.62	51.2	4.00	0.1	0.07

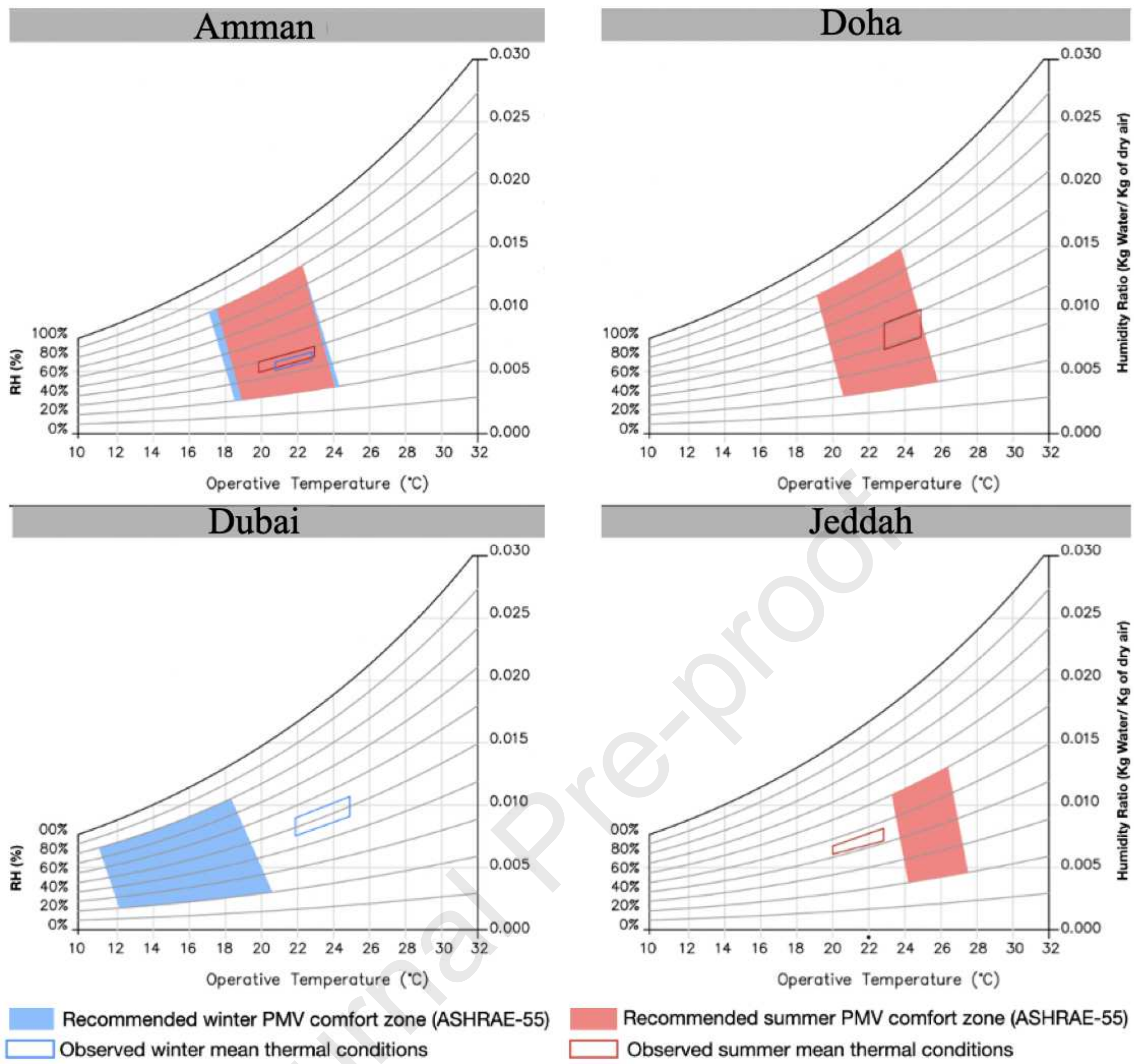

Figure 6 The observed thermal conditions for all surveyed buildings (outlined boxes) in Amman, Doha, Dubai, and Jeddah on psychrometric charts compared to the recommended thermal comfort zones (shaded boxes) provided by ASHRAE 55 standards [18], plots generated using the CBE tool [64].

4.2 Distribution of TSV and PMV

Table 6 illustrates the overall distribution of PMV and TSV during summer and winter, the votes being classified into three categories, i.e., hot, cold, and neutral (see section 3.5). In summer, while PMV predicted that 53% of votes would be in the neutral category, substantially below the 80% acceptability criterion specified by the ASHRAE 55 standard [18], TSV was even lower at only 41% votes falling into neutrality. Surprisingly, while PMV predicts 40% of votes would fall in hot discomfort, TSV shows an almost exact proportion (39%) falling into *cold discomfort*. In winter, while PMV predicted 78% votes to fall into neutral (i.e., almost meeting the acceptability criterion), only 35% TSV are actually comfortable, 48% subjects suggesting a sensation of warm discomfort. Amman and Doha perform differently to Dubai and Jeddah, due to the former group falling within the recommended standards (Figure 6).

Figure 7 shows the distribution of PMV and TSV based on the occupancy types. The average of PMV-hot was higher in office buildings and schools (average 35%), while it was negligible in mosques and hospital buildings. PMV-hot was higher in Doha offices compared to Amman offices, due to the variation in the operation mode, as five buildings out of thirteen in Amman have mixed-mode ventilation, contrary to Doha offices, that have no operable windows (see Appendix B). In mosques during winter, though PMV predicts neutrality for 97% of subjects, the majority of TSVs were on the warm side (Figure 7), this could be due to the high metabolic rate for prayers. In the hospital building, the PMV shows a cold state for 87% of subjects, and this was supported with 50% of observed TSV.

Table 6 The distribution of predicted PMV and observed TSV in all surveyed buildings in the four cities during summer and winter, the votes are classified into three categories (i.e., cold, neutral, and hot).

		PMV			TSV		
Season	Subjects (n)	Cold	Neutral	Hot	Cold	Neutral	Hot
Summer	677	7%	53%	40%	39%	41%	20%
Winter	356	5%	78%	17%	18%	35%	48%
Overall	1033	7%	58%	35%	33%	40%	28%

Figure 7 The distribution of observed TSV and PMV based on occupancy type and city during summer and winter, $n\_subjects = 1{,}033$, the subject votes are classified into three categories (i.e., cold, neutral, and hot).

4.3 Difference between TSV and PMV

Figure 8 shows the recorded indoor air temperature in each building in all surveyed cities across summer and winter. In summer, the indoor temperature ranged between 17.2 °C and 26.1 °C. In winter, we observe that the reported minimum indoor air temperature (20.2 °C, s = 0.9 °C) was higher than the reported temperature in summer. Further, to examine the differences in mean scores between the PMV and observed TSV in all surveyed buildings, we use the mixed-effects model to deal with the non-independence, as our sample has yielded 1,033 valid individual thermal comfort responses (i.e., TSV and PMV)[2], from four occupancy types, and from four cities. The dependent variable was identified to be the difference between TSV and PMV (i.e., Δμ = TSV - PMV). The city, season, and building type were identified as predictors. In addition, building identity (ID) were included as a random effect, as there were multiple measurements from each building and analysis has to consider this clustering.

Results from mixed-effects model show that the only significant predictor found to be city [Δμ = -0.56, 95% CI = -0.93 to -0.19] thanks to mean temperatures being 0.56 °C lower in Doha than Amman. While season [Δμ

[2] Dubai-summer data (n = 68) were omitted from the total number of dataset (n = 1,101) due to unavailable PMV, this resulted to reduce dataset to n = 1,033 (see section 3.3).

= 0.19, 95% CI = -0.22 to 0.59] and building type [Δμ = 0.54, 95% CI = -0.12 to 1.20] were not significant predictors. Further, our analysis of the random effect shows that not all buildings were the same in each city, slight differences between all the individual buildings were observed. There were only three office buildings in Doha namely QO1 [Δμ = 0.01, 95% CI = 0.20 to 0.94]; QO8 [Δμ = -1.8, 95% CI = -0.96 to -0.15]; and QO9 [Δμ = -1.41, 95% CI = -0.78 to -0.05], where the difference between TSV and PMV appears to be significantly different from zero (Figure 9). Therefore, the cities differ significantly from one another, Doha has a lower mean score for (Δμ) compared to the other three cities. while no overall significant difference between summer and winter was reported.

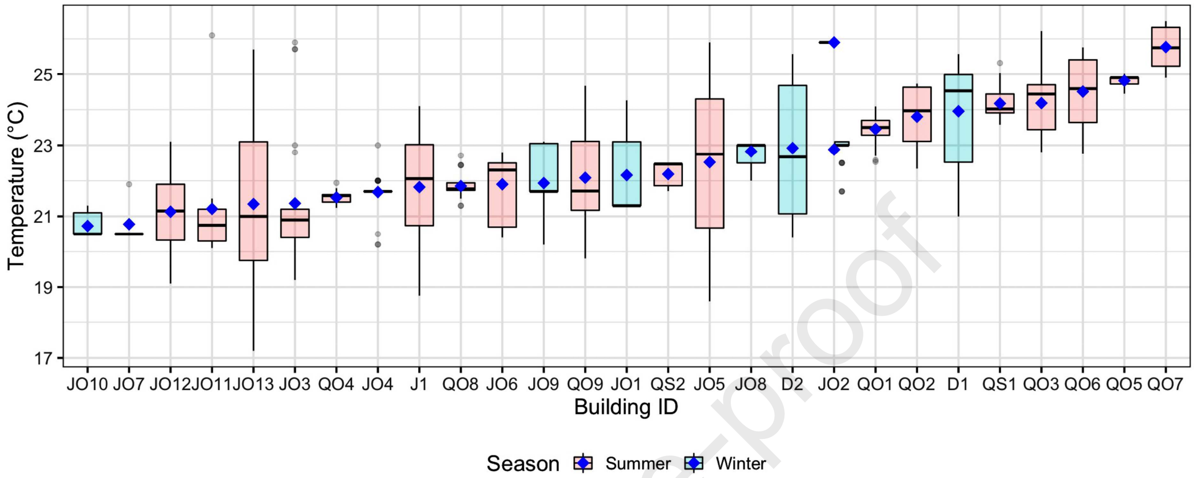

Figure 8 Ranked boxplots for mean indoor air temperatures for each building in the four surveyed cities in winter (blue) and summer (red), (each building has a unique ID, see Appendix B), whiskers indicate the minimum and maximum scores, black dots indicate outliers, blue square indicates mean score for each building.

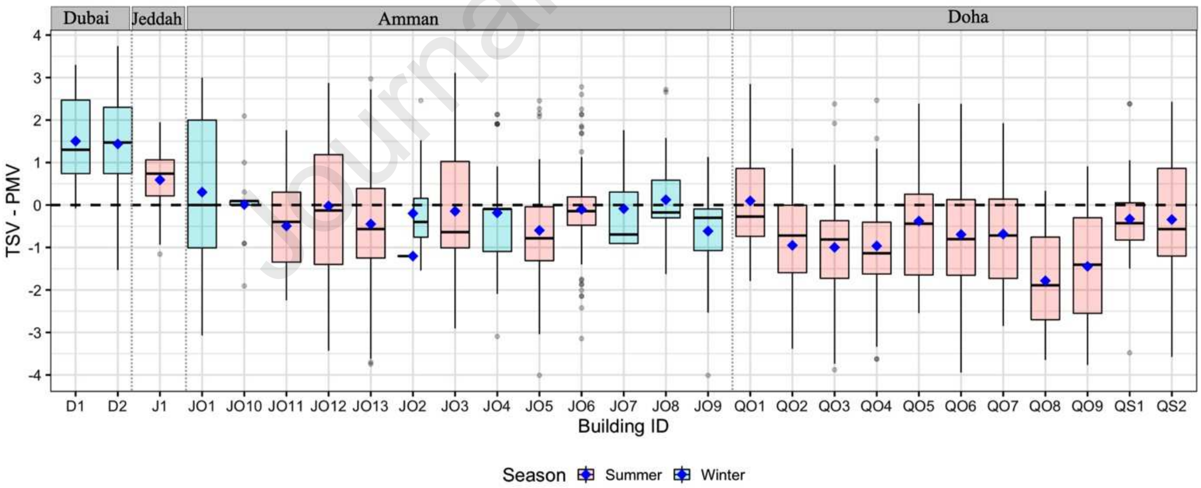

Figure 9 Boxplots for winter (blue) and summer (red) show the difference values between the observed TSV and predicted PMV (TSV - PMV) over all surveyed cities in each individual building during summer and winter, (each building has a unique ID, see Appendix B), whiskers indicate the minimum and maximum scores, black dots indicate outliers, blue square indicates mean score for each building, $n\_subjects = 1{,}033$.

4.4 Compare TSV to other thermal comfort models

The analysis in Section (4.2) has demonstrated that the PMV model results in indoor conditions that do not result in 80% acceptability. It is therefore pertinent to ask whether other thermal comfort models would fare better. Hence, here we present a systematic comparison between TSV and three extant thermal comfort models to investigate their applicability in predicting occupant's thermal sensation in the ME. The selected models are: (i) the predicted thermal sensation (T_{sens}) by Gagge [65], (ii) PMV_g that is Gagge's version of PMV [65], and

(iii) PMV* which is similar to PMV except that is calculated using SET* (Standard Effective Temperature) rather than operative temperature. SET* is calculated using the surface temperature and skin wettedness [66]. These models are acknowledged in the literature and used only in air-conditioned buildings.

Figure 10 shows the mean scores of all tested thermal comfort models and the TSV, with the latter has the lowest mean value (-0.12). To examine the difference between mean scores of all tested variables, a one-way ANOVA test was used. Result shows statistically significant differences between all means ($F(4) = 337.5$, $p < 0.00$), except the difference between means of T_{sens} and PMV_g , was not statistically significant (Table 7), as suggested by the Post-hoc test. As we see from Table 7, the difference between mean of TSV and means of all thermal comfort models were statistically significant, with adjusted *p*-value < 0.001. This finding shows discrepancies between observed TSV and all tested thermal comfort models' predictions, though this is least between PMV and TSV.

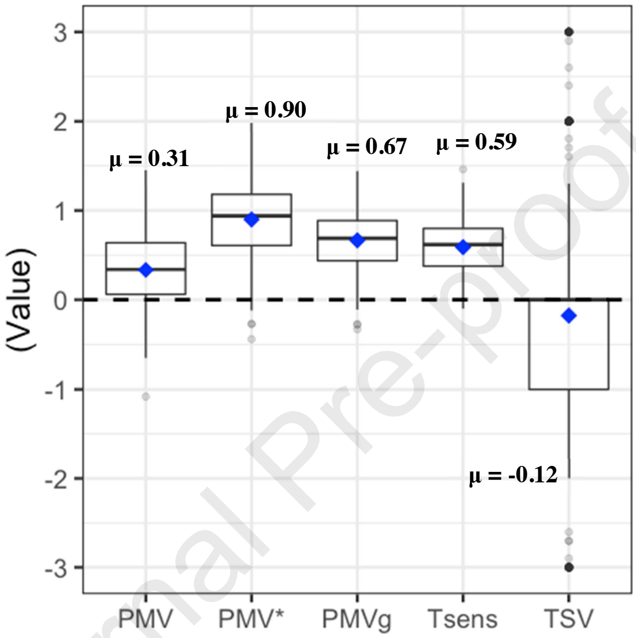

Figure 10 Boxplots show the differences in mean scores between the observed TSV and four thermal comfort models used in air-conditioned buildings, whiskers indicate the minimum and maximum scores, black dots indicate outliers, blue square indicates mean score for each variable.

Table 7 The reported results of Post-hoc test, *** indicates $p < 0.00$, n.s. indicates not statistically significant.

Difference of Levels	Difference of means	95% CI		Adjusted *p*-value
PMV* - PMV	0.57	0.48	0.65	0.00***
PMVg - PMV	0.33	0.25	0.42	0.00***
Tsens - PMV	0.26	0.17	0.34	0.00***
TSV - PMV	-0.51	-0.60	-0.42	0.00***
PMVg - PMV*	-0.23	-0.32	-0.15	0.00***
Tsens - PMV*	-0.31	-0.40	-0.22	0.00***
TSV - PMV*	-1.08	-1.16	-0.99	0.00***
Tsens - PMVg	-0.08	-0.16	0.01	0.11 n.s.
TSV - PMVg	-0.84	-0.93	-0.76	0.00***
TSV - Tsens	-0.77	-0.85	-0.68	0.00***

4.5 Thermal comfort in green buildings

To investigate whether green buildings in the ME improve subjects' thermal comfort compared to the occupant in non-green buildings, we compare the observed TSV to the predicted PMV in seven green buildings and 17 non-green buildings in Amman and Doha (Figure 11). Note that Figure 6 has already shown that all buildings in our sample in Amman and Doha are standards compliant, so the goal here to examine whether there is a difference in acceptability. The green buildings in Amman are both LEED and JGBG-certified, which rely on ASHRAE 55 standard recommended range for thermal comfort, while green buildings in Doha are designed to the localised GSAS, that defines particular thermal conditions for operation stage as illustrated in section 1.1. The t-test suggests statistically significant differences between mean scores of TSV and PMV in both building types in Amman and Doha (p-value < 0.05).

In non-green buildings, we observed that mean PMV was significantly higher than mean TSV, with differences of -0.33 and -0.75 in Amman and Doha, respectively. In green buildings, the differences between mean scores of PMV and TSV were also statistically significant and ranged between [-0.18, -1.32]. The difference was higher in green buildings in Doha compared to those in Amman. The majority of observed TSVs in buildings (i.e., green and non-green) in Doha were on the cold side. This result shows that green buildings that expected to provide better thermal environment for their occupants compared to non-green buildings have failed to do this. Further, result from green buildings in Doha questions the capability of the localised thermal comfort codes in improving occupant thermal comfort in the region.

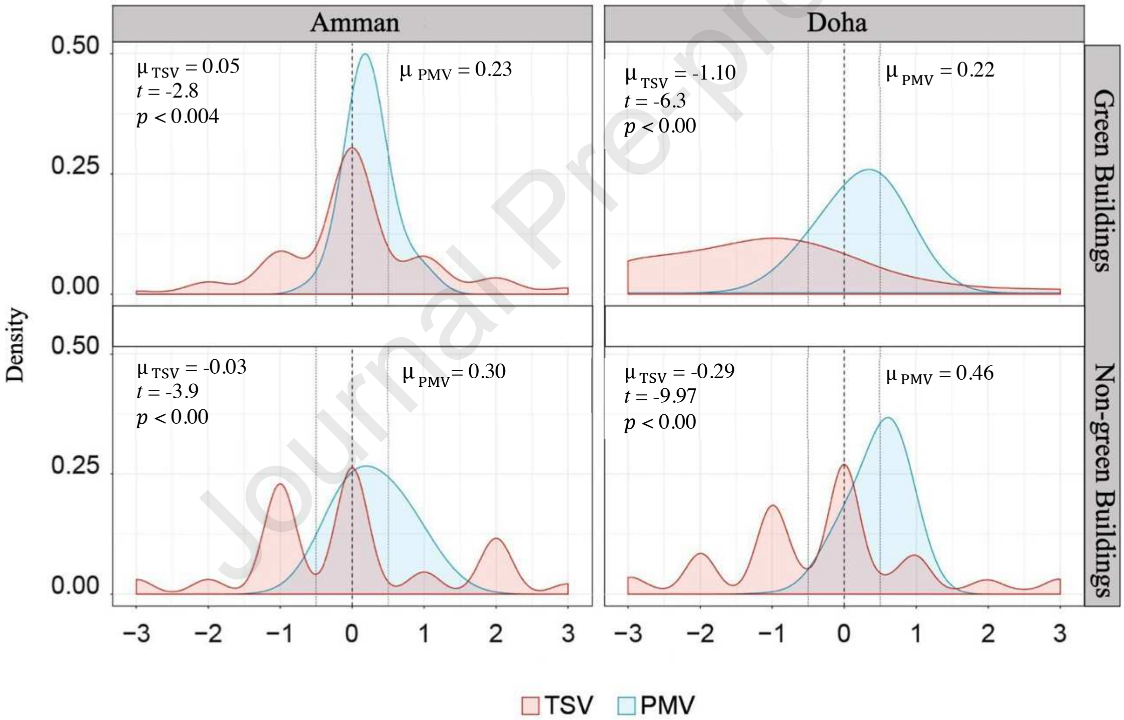

Figure 11 Comparison between the observed TSV and PMV in the certified-green buildings and non-green buildings in Amman and Doha. Green buildings in Doha are GSAS-certified and those in Amman are LEED + JGBG-certified, $n\_Amman = 502$, $n\_Doha = 377$, $n\_GB = 7, n_{non} - GB = 17$.

4.6 Neutral (comfort) temperature for the ME

We use linear regression to calculate the neutral temperature (T_n), based on TSV and PMV (see equation (1), (2) and (3)), T_n was calculated for each city separately. At the outset, the TSV and PMV were regressed with the indoor operative temperature (T_o) to predict the T_n. The observed TSV were binned in 1°C intervals [54,67,68]. The gradient of the linear regression (α) represents the temperature perturbation required for a one-unit change on the TSV scale, thus we can measure the subjects' sensitivity to changes in the indoor thermal environment [54,69,70]. Table 8 illustrates the gradient (α) and intercept (b) of the fitted linear models together with the p-value for the gradient and the coefficient of determination (R^2). Looking at Table 8, the $T_{n(PMV)}$ showed a varied range of temperatures; cooler comfort temperature of 19.62 °C in office buildings in Amman, moderate conditions of 20.66 °C in office buildings in Doha, and warmer perceptions of 25.42 °C in the hospital in Jeddah.

Likewise, $T_{n(TSV)}$ was calculated based on the observed TSV. In Doha and Jeddah, the R^2 generated from TSV were high (0.85 and 0.76 respectively), and T_o can hence be used as a good predictor to estimate T_n in these two cities (Table 8). In contrast, in Amman R^2 was low at 0.18 and hence too small to predict T_n. Therefore, T_n in Amman was instead predicted using Griffith's method (see equation (4)), which gives T_n = 21.96 °C. Results from mosque buildings in Dubai were not significant for both PMV and TSV (p-value > 0.05), thus T_n could not be predicted.

Figure 12 shows the plotted regression lines of TSV and PMV against the T_o in the three cities, the mean neutral temperature is the point where the regression lines corresponding to mean PMV/TSV of zero. The gradient of the regression line for Doha and Jeddah (both α = 0.34 K) is steeper than those seen for other studies in the ME; 0.23 K in domestic buildings in Kuwait [37], 0.21 K in offices in Qatar [35] but the smooth gradient was found in air-conditioned mosques of 0.13 K [39]. The PMV predictions underestimated the observed neutrality in offices in Amman and Doha by about 2.34 °C and 4.08 °C respectively, while in hospital building in Jeddah, the PMV overestimated the observed neutrality by 2.78 °C. This may indicate that air-conditioning systems in hospital are operated in a way that does not consider the nature of nurses' job, that requires to move around between patient rooms (higher activity levels). In contrast, employees in workplaces preferred warmer temperature due to their sedentary levels.

Table 8 Linear regressions of TSV and PMV versus operative temperature, T_o was binned into 1 °C interval, (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s. indicates not significant). The results from Dubai study were not significant for both PMV and TSV, thus not presented in the table, $n\_Amman = 502, n\_Doha = 377, n\_Jeddah = 52$.

Index	Location	α(/°C)	b	R^2	p-value	T_n ± SE (°C)
PMV	Amman	0.165	-3.24	0.97	0.001***	19.62 ± 0.20
	Doha	0.125	-2.48	0.96	0.001***	20.66 ± 0.26
	Jeddah	0.304	-7.73	0.97	0.001***	25.42 ± 0.42
TSV	Amman[a]	-	-	0.18	0.20 n.s.	21.96
	Doha	0.341	-8.44	0.85	0.01**	24.74 ± 1.41
	Jeddah	0.342	-7.74	0.76	0.01**	22.64 ± 1.79

[a] $T_{n(TSV)}$ for Amman is calculated using Griffith's method, that has no gradient and intercept, the reported value for Amman represents the mean value of observed neutral temperature.

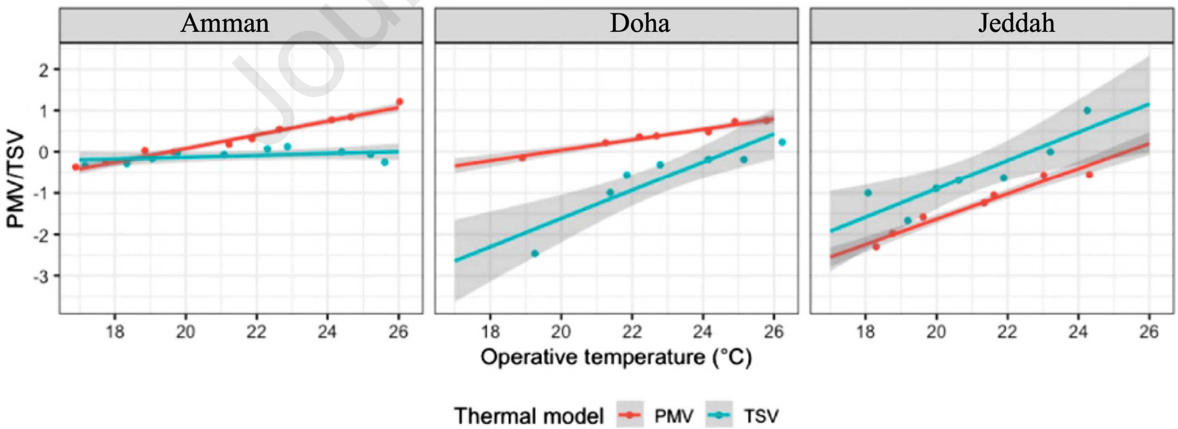

Figure 12 The relation between TSV and PMV with indoor operative temperature (T_o) in Amman, Doha, and Jeddah, each dot is a binned into 1 °C interval, so each dot represents several data points, $n\_Amman = 502, n\_Doha = 377, n\_Jeddah = 52$, (statistical analysis in Table 8).

4.6.1 Energy saving scenario

Table 9 shows the results from the Energy Plus models for the calculated $T_{n(PMV)}$ and observed $T_{n(TSV)}$ and the potential reduction in the annual building energy demand. In the office building models in Amman and

Doha, the annual building energy demand was reduced by 20% and 13%, respectively, while the reduction was smaller (1.5%) in the hospital building model in Jeddah. Most of the reduction in the office building models has resulted from the higher indoor temperature for cooling set point based on the observed $T_{n(TSV)}$ compared to the predicted $T_{n(PMV)}$. The estimated overall building energy demand for space cooling was reduced from 27.04 kWh/m^2 to 16.39 kWh/m^2 in office models in Amman, and from 60.71 kWh/m^2 to 49.87 kWh/m^2 in Doha (Table 9). While, in the hospital model, the reduction in cooling energy demand was very small (6.00 kWh/m^2). In all building models, the heating energy demand reduction was negligible, less than 1.0% of the total building energy demand reduction.

Table 9 Annual building energy demand for simulated models based on the proposed $T_{n(PMV)}$ and observed $T_{n(TSV)}$ in office buildings in Amman and Doha and hospital in Jeddah. Note: other end uses for each model (e.g., lighting, equipment operation, water systems, humidification, heat recovery, fans, and refrigeration) are excluded from the table due to their small values (< 2.0 kWh/m^2).

Location	Amman			Doha			Jeddah		
Bldg. Type	Office building			Office building			Hospital		
End Use (kWh/m^2)	$T_{n(PMV)}$	$T_{n(TSV)}$	Diff	$T_{n(PMV)}$	$T_{n(TSV)}$	Diff	$T_{n(PMV)}$	$T_{n(TSV)}$	Diff
Heating	4.99	0.91	4.08	0.24	0.11	0.13	0.01	0.01	0.01
Cooling	27.04	16.39	10.66	60.71	49.87	10.84	77.81	71.81	6.00

5. Discussion

Since this study has two lines of evidence, we first discuss our independent results that are obtained from the new thermal comfort field surveys, then we pool them with results from the meta-analysis of the existing thermal comfort studies in the ME.

5.1 New field evidence

The energy demand for space cooling is the fastest-growing end-use in building sector, as it has tripled over the past twenty years between 1990 and 2020. In countries with extreme hot climate, such as the ME, it is expected that the energy demand for space cooling would triple by 2050 [4]. This growth rate in cooling energy demand needs to be alleviated, starting by a large-scale investigation to question the applicability of current codes that used to design the indoor thermal environment in air-conditioned buildings in the ME. There is a need to ensure that such codes promote occupant thermal comfort and simultaneously contribute to achieve the energy efficiency development scenario is targeted by this region. Thus, the present study was designed to collect evidence of whether the air-conditioned buildings in the ME comply with standards recommended ranges, and if so, whether they are found to be comfortable by their occupants.

Our findings showed that the monitored thermal conditions in the surveyed buildings in Amman and Doha (i.e., offices and schools) were within the ASHRAE 55 recommended comfort zone. While the recorded thermal conditions in buildings of Dubai and Jeddah (i.e., mosques and hospital) failed to be within the recommended limits. Overall, the PMV predicted that 58% of votes would be in the neutral category, and only 40% of subjects voted neutral, this is significantly below the ASHRAE 55 recommended value of 80% [18]. Interestingly, during the cooling season, 39% of subjects through all surveyed cities expressed cold sensation, contrary to the PMV prediction that suggested 40% of subjects would feel hot, this was clearly observed in office buildings and schools.

In the hospital, the PMV prediction of cold discomfort for 87% of votes, was supported by 50% of the observed nurses' votes, which show cold state. This can be explained by three reasons: (i) nurses had a variety of metabolic rates with low clo (mean = 0.6) and this may affect their thermal sensation, especially during sitting with light work, (ii) the different requirements of thermal zones within hospital buildings, as nurses were surveyed at several locations at the inpatient wards nursing stations, and corridors (in front of patient rooms), these locations have no strict requirements within ASHRAE 170 standard for ventilation in health care facilities [71] in terms of design temperature and relative humidity compared to other spaces, (i.e., patient rooms, intensive care units), and (iii) the HVAC system is optimised to provide cooler temperatures in the nursing stations, due to prior expectation considering the nature of nurses' job that required high metabolic rate. In the mosques, during heating season, PMV expected that 97% of votes would be in the neutral category, while 93% of subjects felt hot. This is possibly due to excessive heating in the praying halls designed to heat the entire volume during the winter. Taking into consideration that those attending prayers spend a maximum of 15 minutes in the mosque and had high metabolic rate (mean = 2.5), which could affect their thermal sensitivity.

The discrepancy between PMV and TSV was seen also between the recommended and observed neutral temperature. As our calculations for $T_{n(TSV)}$ in air-conditioned office buildings in Amman and Doha were found to be 21.96 °C and 24.74 °C, which were comparatively higher than the predicted $T_{n(PMV)}$ of 19.62 °C and 20.66 °C, respectively. In contrast, the $T_{n(TSV)}$ in the hospital in Jeddah was 22.64 °C, lower than the $T_{n(PMV)}$ of 25.42 °C, with difference of 2.87 °C. These findings encourage us to compute the potential reduction in the building energy demand for space cooling, assuming $T_{n(TSV)}$ is used instead of the recommended temperatures by PMV. We find that a reduction in the annual building energy consumption of between 13% and 20% is possible in office buildings, whereas it is significantly lower in the hospital (1.5%). These reductions correspond to raising the indoor temperatures in office buildings by 4.08 °C in Doha and 2.34 °C in Amman.

From an economical perspective, raising the indoor temperature in office building in Amman by 2.3 °C may save 10.66 kWh/m^2 /year of space cooling energy demand, and since the Jordanian government priced the electricity at 0.18 JD/kWh (0.25 USD/kWh) for commercial sector [72], this resulted in annual energy saving of 5,756 JD (8,118 USD) for the single unit that has an average floor area of 3000 m^2 .Likewise, adjustment the indoor temperature of 4.1 °C in the office building in Doha could cut the annual energy demand for space cooling by 10.84 kWh/maintain. This resulted in dropping the annual cost for space cooling from 30,500 QR (8,377 USD) to 25,000 QR (6866 USD), with annual saving of 5,500 QR (1,479 USD) per the single office building, considering the electricity in Qatar is priced at 0.20 QR/kWh (0.05 USD/kWh) [73] and the building typical floor area is around 2,500 m^2, similar to buildings surveyed in this study.

In Qatar, the total annual energy demand for space cooling is around 14.7 TWh, with total annual cost around 5.5 billion QR (1.5 billion USD) [74], the total number of the commercial buildings over the last ten years is found to be around 9,518 units [75]. Hence the expected energy cost saving in commercial buildings based on our estimation is around 0.05 billion per year. This value constitutes 1.1% of the total annual electricity cost for space cooling in Qatar. It is worth mentioning that the cost of electricity tariffs in most of the ME countries, specifically in the Gulf Cooperation Council countries, i.e. Qatar are among the lowest in the world [75], with substantial price subsidised by governments, this could be one of the reason behind the continuous energy demand growth in air-conditioned buildings in this region.

5.2 Pattern of thermal comfort across the ME

To gain an aerial perspective of the occupant thermal comfort trend across the ME, we aggregate the meta-analysis results from section 2 with our obtained results from the present study (section 4), thus we have a large scale dataset covering five countries, six different occupancy types, with a total of 2,649 subjects (see Appendix E). Figure 13 (a) shows a forest plot for the calculated values of differences in mean scores between TSV and PMV (i.e., Δμ) through the whole dataset. Most thermal comfort studies in the ME reported similar results regardless the building type or the location of the study, with the majority of difference values were on the negative side and ranged between [-0.18 and -0.81], i.e., mean scores of TSV were generally lower than mean scores of PMV. Indeed, the latter fail to predict the thermal sensation for 94% of subjects in this dataset.

However, two studies reported contrary results, i.e., the hospital and mosque buildings. These differences could be a result of several factors including the building design, the low thermal insulation level for patients and staff in hospitals and the high metabolic rate for prayers in mosques. Overall, this suggests that there is likely to be no “one size fits all” solution to resolving the differences between predicted and observed thermal comfort, with some building categories such as hospitals and mosques potentially needing further study.

Further, the tendency to over predict hot discomfort by the PMV model is likely resulting in an oversizing of cooling systems, this was reflected on the predicted $T_{n(PMV)}$, which was generally lower than the observed $T_{n(TSV)}$ with difference ranged between [0.4 °C, 4.1 °C] through all dataset (Figure 13. b). However, only in the hospital study, the difference was on negative side, which means subjects preferred lower indoor temperature than the delivered.

Overall, this robust evidence shows the gap between the current thermal comfort codes used in the ME and the actual occupant thermal sensation, also it offers evidence on the potential energy reduction in the air-conditioned buildings if more localised thermal comfort codes are enforced. Although there are emerging attempts by Middle Eastern countries, i.e., Qatar to develop local thermal comfort codes, it seems that these codes lack supporting evidence from any field survey as shown in section 4.5, despite the fact that GSAS requires a thermal comfort survey after occupancy as a compulsory credit (see section 1.1).

Similarly, other international thermal comfort models, i.e., T_{sens}, PMV_g, and PMV^* have failed in predicting occupant’s thermal sensation, while they provided similar results to those yielded by the PMV model.

Therefore, a thermal comfort paradigm shift that can effectively and assuredly offset the exponential increase in the space cooling energy demand, without compromising the occupant thermal comfort is timely and necessary in the ME. This would not only reduce energy consumption and hence carbon emissions [76], but also improve overall health, well-being, and work performance [77] by obviating the need to wear warm clothing indoors or the need to resort to secondary heating, which has been anecdotally observed in some buildings in our study.

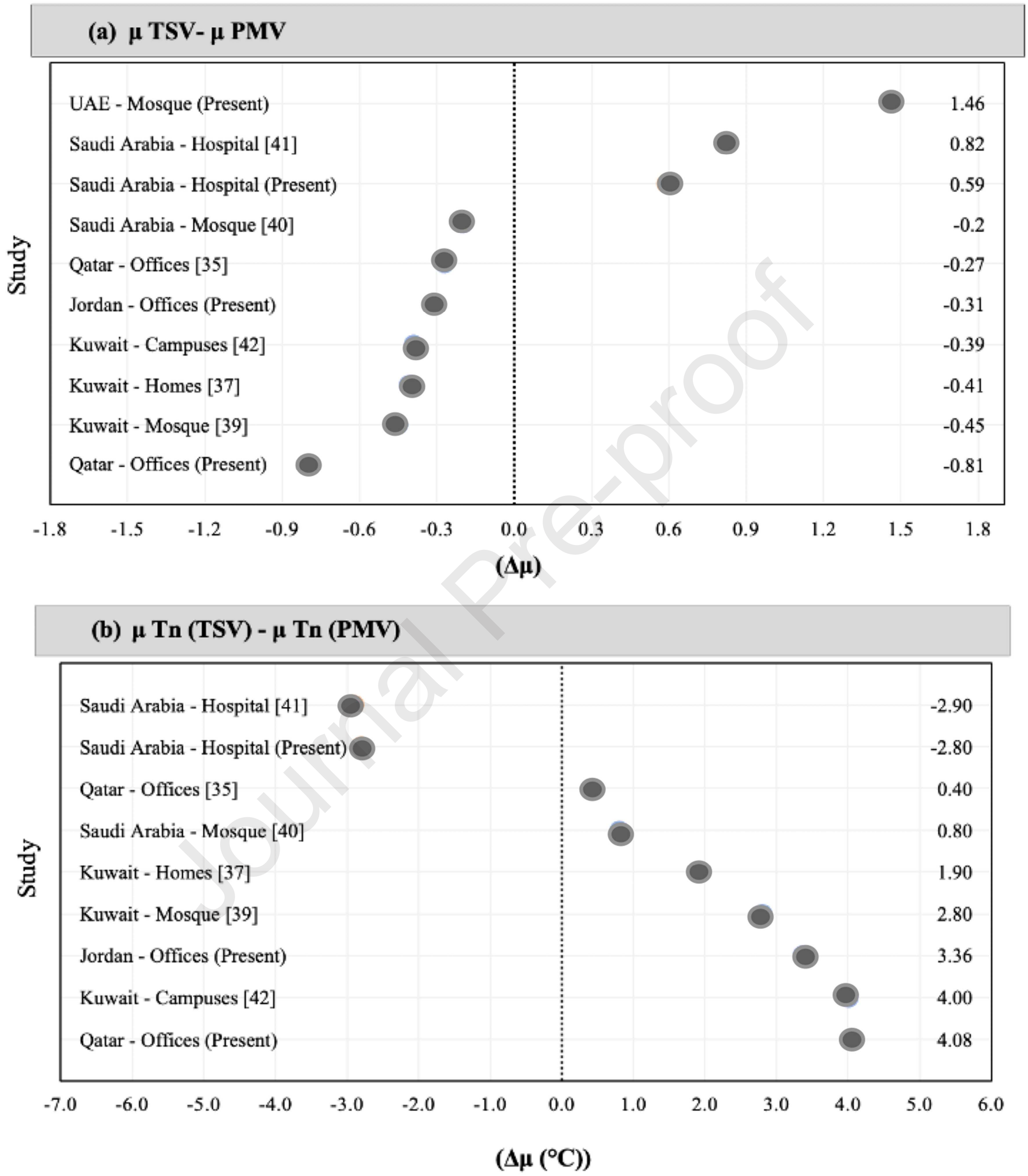

Figure 13 Forest plots from pooled analysis including the present study, (a) the difference between mean scores (i.e., Δμ = μ TSV- μ PMV) for each study, i.e. (Δμ > 0) indicates TSV is greater than PMV, (b) the difference between the observed neutral temperature $T_{n(TSV)}$, and predicted neutral temperature $T_{n(PMV)}$, through all datasets, $n = 2{,}649$, x-axis represents the standardised mean difference and vertical dotted line represents the value of no difference, studies are identified by country, building type, and reference.

6. Conclusion

In the Middle East, the international standards ASHRAE 55 and/or ISO 7730 are the de-facto industry tools used to design the indoor thermal environment in air-conditioned buildings. However, occupants' thermal comfort in these buildings is still questionable. This study set out to investigate whether the air-conditioned buildings in the ME comply with standard recommended ranges for thermal comfort, and when they do, whether they are found to be comfortable by their occupants. From a meta-analysis using summary statistics of thermal comfort evidence in the ME, we demonstrate, for the first time, that the PMV model failed in predicting the occupant thermal sensation for 94% of occupants in five occupancy types (i.e., offices, homes, university campuses, hospitals, and mosques). We produce a second, independent, line of evidence using large-scale thermal comfort field surveys of 1,101 subjects in 31 air-conditioned buildings within four countries in the ME that strongly supports the initial obtained findings. We show that the monitored indoor conditions in surveyed buildings were within the standard recommended range for 58% of the time, and only 40% of subjects found these conditions acceptable. We observe a gap between the expected thermal comfort and the observed subjects' thermal sensation during the cooling season. We find that 39% of subjects felt cold, contrary to the PMV prediction, which suggested 40% of subjects would feel hot. This is the reason for the large variation between the predicted $T_{n(PMV)}$ and the observed $T_{n(TSV)}$. In office buildings in Amman and Doha, the $T_{n(TSV)}$ were found to be 21.96 °C and 24.74 °C, which were higher than those expected by PMV, at 19.62 °C and 20.66 °C respectively. Finally, we use the yielded data to estimate the potential reduction in the annual building energy demand for space cooling. We demonstrate that raising the indoor temperature in office buildings in Amman and Doha by 2.3 °C and 4.1 °C (i.e., based on the $T_{n(TSV)}$) has resulted in a reduction of 20% and 13% in the annual cooling energy demand, respectively. Overall, this study highlights the inapplicability of the "one size fits all" solution to overcome the gap between the predicted and observed thermal comfort. It shows also that most thermal comfort models that are used in air- conditioned buildings (e.g., PMVg, PMV^*, and Tsens) are not suitable to predict subjects' thermal sensation in the ME. Further, it provides empirical data to be the basis for designers to develop a new and more localised thermal comfort model, that considers the variations in subjects' thermal perception and mitigates the energy demand for space cooling without compromising the occupant thermal comfort in the ME.

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Data Access statement

Data presented in this study are openly available https://doi.org/10.15125/BATH-00967

Disclosure statement

The authors reported no potential conflict of interest.

Appendices

Appendix A

Thermal comfort survey with Arabic-dialects translation (Classical Arabic + Levantine-Arabic)

At present, I feel:

English	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Arabic-classic	بارد جدا	بارد	بارد قليلا	مرتاح	دافيء قليلا	دافيء	حار
Arabic-Levantine	بردان كتير	بردان	بردان شوي	مرتاح	مشوب شوي	دافي	كتير مشوب
	-3	-2	-1	0	+1	+2	+3

Your clothes at present: (Please tick)		What is your activity during the past 15 minutes? (Please tick)	
Short Sleeve shirt/blouse		Sitting (passive work	

Long sleeve shirt/blouse		Sitting (active work)	
Vest		Standing relaxed	
Trousers/long skirt		Standing working	
Shorts		Walking indoors	
Dress		Walking outdoors	
Pullover		Other………………	
Jacket			
Long socks			
short socks			
Tights			
Tie			
Boots			
shoes			
sandals			
head wear			
barefoot			

Appendix B

Summary of surveyed buildings in this study; $\mathrm{n_{buildings}} = 31; \mathrm{n_{subjects}} = 1{,}101$. (M.M indicates mixed mode ventilation).

City	ID	Green certification	Sector	Operation mode	Bldg. Type	Subjects (n)	Participant type
Amman	JO1	na	Private	M.M	Offices	26	Employees
Amman	JO2	na	Private	M.M	Offices	27	Employees
Amman	JO3	na	Private	M.M	Offices	37	Employees
Amman	JO4	na	Private	M.M	Offices	20	Employees
Amman	JO5	na	Private	M.M	Offices	10	Employees
Amman	JO6	Green	Private	HVAC	Offices	102	Employees
Amman	JO7	Green	Private	HVAC	Offices	24	Employees
Amman	JO8	Green	Private	HVAC	Offices	47	Employees
Amman	JO9	Green	Private	HVAC	Offices	45	Employees
Amman	JO10	Green	Private	HVAC	Offices	48	Employees
Amman	JO11	na	Private	HVAC	Offices	35	Employees
Amman	JO12	na	Private	HVAC	Offices	41	Employees
Amman	JO13	na	Private	HVAC	Offices	40	Employees
Doha	QS1	na	Public	HVAC	School	45	Staff
Doha	QS2	na	Public	HVAC	School	7	Employees
Doha	QO1	na	Private	HVAC	Offices	34	Employees
Doha	QO2	na	Private	HVAC	Offices	15	Employees
Doha	QO3	na	Public	HVAC	Offices	28	Employees
Doha	QO4	na	Private	HVAC	Offices	30	Employees
Doha	QO5	Green	Public	HVAC	Offices	26	Employees
Doha	QO6	na	Private	HVAC	Offices	67	Employees
Doha	QO7	na	Private	HVAC	Offices	30	Employees
Doha	QO8	na	Private	HVAC	Offices	74	Employees
Doha	QO9	Green	Public	HVAC	Offices	21	Employees
Dubai	D1	Design award	Public	HVAC	Mosque	23	Prayers
Dubai	D2	Design award	Public	HVAC	Mosque	79	Prayers
Dubai	S1	na	Public	HVAC	School	27	Staff
Dubai	S2	na	Public	HVAC	School	10	Staff
Dubai	S3	na	Public	HVAC	School	14	Staff
Dubai	S4	na	Public	HVAC	School	17	Staff
Jeddah	H	Environment award	Public	HVAC	Hospital	52	Employees

Appendix C

The instruments used to monitor indoor thermal conditions in surveyed buildings in the ME.

Instrument	Variable	Unit	Valid range	Accuracy
SWEMA [47]	T_g	℃	[0, 50]	±0.1
	T_a	℃	[10, 40]	±0.3
	RH	%	[0, 100]	±1.0

	V_a	ms^{-1}	[0.05, 1.0]	±0.03	
Delta 32.3 [48]	T_g T_a RH V_a	℃ ℃ % ms^{-1}	[-10, 100] [-40, 100] [0, 90] [0.1, 5]	±0.1 ±0.1 ±1.5 ± 0.2	
Heat stress wet bulb globe thermometer	T_g T_a RH	℃ ℃ %	[0, 80] [0, 50] [1, 99]	±0.6 ±0.8 ±3.0	
Hot wire thermo-anemometer	V_a	ms^{-1}	[0, 25]	±0.01	

Appendix D

Energy modelling details.

Design Element	Specification	
Model	Office Model	Hospital Model
Floor Area (m^2)	4,982	22,422
Aspect Ratio	1.5	1.3
No. of Floors	3	5
Floor to Ceiling Height (m)	2.74	4.27
Glazing Fraction	0.33	0.15
Roof Construction (U-Value)	Built up roof and insulation above deck (0.063 W/(m^2·K))	Built up roof and insulation above deck (0.063 W/(m^2·K))
Wall Construction (U-Value)	Steel frame (0.704 W/(m^2·K))	Mass wall (3.293 W/(m^2·K))
Window Overall (U-Value)	Fixed window (1.22 W/(m^2·K))	Fixed window (1.22 W/(m^2·K))
Air Distribution	Multizone variable air volume	variable air volume with reheat
Cooling System	Packaged air-conditioning unit	chiller - water cooled
Heating System	Furnace	Boiler

Appendix E

Summary statistics of the results in the new dataset created using aggregated data from meta-analysis and our results in present study, the reported values represent the mean scores, (Present) indicates current thermal comfort studies done by the authors, T_n represents neutral temperature, $n = 2{,}649$.

Location	Source	Season	Subject (n)	Bldg. Type	μ(PMV)	μ(TSV)	$\mu T_{n(PMV)}$ (°C)	$\mu T_{n(TSV)}$ (°C)
Saudi Arabia								
	[40]		281	Mosques	0.01	-0.19	21.5	22.3
	[41]	Summer	120	Hospital	-0.50	0.32	25.6	22.7
	Present		52	Hospital	-1.11	-0.52	25.4	22.6
Kuwait								
	[37]		111	Homes	0.13	-0.28	23.3	25.2
	[39]	Summer	140	Mosques	0.19	-0.26	23.3	26.1
	[42]		136	Campuses	0.50	0.11	18.9	22.9
Qatar								
	[35]	Summer	828	Offices	0.04	-0.23	23.7	24.1

Jordan	Present		377	Offices	0.43	-0.38	20.7	24.7
UAE	Present	Summer + Winter	502	Offices	0.30	-0.01	19.6	23.0
	Present	Winter	102	Mosques	0.03	1.49	-	-

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Highlights

1. A meta-analysis and thermal comfort surveys in the Middle East (ME) were done.
2. The PMV model fails to predict the thermal sensation of 94% of occupants in the ME.
3. Contrary to PMV prediction, 39% of occupants expressed cold discomfort in summers.
4. Occupants in AC buildings in the ME had higher comfort temperature than expected.
5. Using the PMV model increased annual energy demand for space cooling up to 20%.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: