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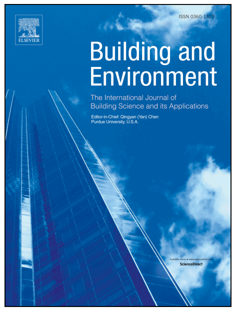

Effects of indoor humidity on building occupants’ thermal comfort and evidence in terms of climate adaptation

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PII: S0360-1323(19)30143-X

DOI: https://doi.org/10.1016/j.buildenv.2019.02.039

Reference: BAE 5998

To appear in: *Building and Environment*

Received Date: 29 November 2018

Revised Date: 9 February 2019

Accepted Date: 25 February 2019

Please cite this article as: Kong D, Liu H, Wu Y, Li B, Wei S, Yuan M, Effects of indoor humidity on building occupants’ thermal comfort and evidence in terms of climate adaptation, *Building and Environment* (2019), doi: https://doi.org/10.1016/j.buildenv.2019.02.039.

Effects of indoor humidity on building occupants' thermal comfort and evidence in terms of climate adaptation

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Abstract

Similar as temperature, air humidity may affect people's thermal comfort and humidity adaptation may happen when people changing their living conditions. To provide evidence on both effect from humidity on people's thermal comfort and their humidity adaptation, a comparative study has been conducted in a controlled climate chamber. During the experiment, the air temperature was set as 25 °C and 28 °C respectively and the relative humidity was changing between 20% and 90%. There were twenty four participants involved in this experiment, with half living in High Humidity (HH) regions of China, such as Chongqing, for over 20 years, and another half recently moved to Chongqing from Low Humidity (LH) regions in northwestern China. During the experiment, mean skin temperature was measured as objective an important parameter and subjective questionnaires were used to subjectively collect people's sensations with respect to heat, humidity and sweating. The data collected demonstrated that people living in HH regions showed a better adaptive ability to humidity changes than those came from LH regions. Climate adaptation also reduced the sensitivity of HH subjects' thermal responses. When air humidity was over 70%, subjects started to show stronger thermal responses. Based on these results, an upper limit of humidity of 17 g/kg has been proposed for Chongqing, China. The results from this study will help to broaden the adaptive thermal comfort theory and can provide important references regarding to humidity control for buildings.

Keywords:

Air humidity, climate adaptation, humidity responses, thermal sensitivity, humidity limits

Abbreviations

HSCW	Hot summer and cold winter	**BMI**	Body mass index
HSWW	Hot summer and warm winter	**Tsk**	Skin temperature
PMV	Predicted mean vote	**MTsk**	Mean skin temperature
LH	Low humidity region	**CLO**	Clothing insulation
HH	High humidity region	**MTSVs**	Mean thermal sensation votes
Ta	Ambient temperature	**MHSVs**	Mean humidity sensation votes
RH	Relative humidity	**Va**	Air velocity
SET*	Standard effective temperature, °C	**△TSV**	Variation in thermal sensation vote with humidity change

1. Introduction

With its vast territory, China has distinctive climatic regions with respect to both temperature and humidity. Based on humidity, the regions can be classified as humid, semi-humid, semi-arid, and arid [1]. People from these various climates may have different responses to their surrounding environmental conditions [1, 2]. For example, Turpan is one of the hottest cities in China and experiences very high temperatures, but the average relative humidity (RH) is only 31% in the summer [2, 3]. In contrast, the relative humidity in Chongqing, which is located in a hot summer and cold winter (HSCW) climate zone, often experiences > 70% RH [4-7]. Thus, people who visit Chongqing from other climate zones may often feel uncomfortable in this high humidity environment [8]. These differences in the perception of the thermal environment can be explained by thermal adaptation theory. This theory has resulted in the formation of an important thermal comfort prediction model, namely, the adaptive model, which has been included in many important standards such as ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) 55 [9], CIBSE (Chartered Institution of Building Services Engineers) Guide A [10], and EU 15251 [11]. Humidity is one of the main factors affecting thermal comfort. However, the effects of humidity on adaptive thermal comfort have not been specified in the standards. In particular, an upper humidity limit of 12 g/kg given in current standards for health considerations about mold prevention may fail to satisfy occupants' adaptive comfort requirements in some areas. Additionally, strict humidity demands can lead to increases in building energy consumption for dehumidification [12]. Thus, adaptive thermal comfort in regard to humidity should be studied more thoroughly to enrich thermal adaptation theory and to help ensure that appropriate humidity limits are set for different climatic regions.

Extensive real-world building studies have identified the phenomenon of the "scissors difference" [13-17], which refers to the difference between the predicted mean vote (PMV) of thermal sensation and the actual thermal sensation vote in buildings. Therefore, a large research project, RP-884, was conducted worldwide to develop a thermal comfort model, as first proposed by De Dear [18]. Compared to the PMV model [19], thermal adaptation theory simulates people's positive interactions with their surrounding thermal environment [9, 20]. In this theory, thermal history has been suggested as a key factor that affects people's environmental preferences [21] and is based on data collected from both climate-controlled chambers and field surveys, with considerations given to people's behavioral adjustments, physiological acclimatization, and psychological adaptations [18]. Extensive on-site studies have been conducted to enrich the adaptive thermal comfort in different climatic zones [2, 7, 13, 15, 21-29]. Yan et al. [30] conducted a year-round field investigation in different climatic regions in eastern China and proposed an individual thermal adaptive model for naturally ventilated environments. Some researchers have reported on seasonal differences in clothing adjustments, changes implemented with respect to air movement, and other physiological or psychological variations as adaptive mechanisms [4, 6, 31]. With the use of indoor cooling or heating, some studies [21, 32] have shown that indoor thermal history can be an important factor that determines human thermal sensation. Luo et al. [32] explored the adaptation process of subjects that migrated from southern China to northern China and uncovered physiological changes regarding their skin temperatures. Those studies mainly emphasized the correlations between outdoor temperatures and people's thermal adaptation. However, few studies have considered the effects of the subjects' humidity exposure history on thermal adaptation.

According to Fanger's thermal comfort model [19], air humidity is an important factor for people's thermal sensation. In real buildings, however, the humidity level does not change as significantly as the air temperature, and people are also not very sensitive to the humidity change within a certain range, such as 40% to 70% [10]. Therefore, humidity has not received much attention. When the air temperature, air speed, and radiation temperature are in a comfortable range, humidity has little effect on human thermal comfort [12, 33-37]. With an increase in the temperature [38-41] and metabolic rate [42] of the human body, the effect of high humidity on thermal comfort becomes more obvious.

One study that investigated 72 combinations of temperature and humidity showed that the acceptable air temperature could be increased by 0.3 °C when decreasing the relative humidity by 10% [33]. Besides building environments, dynamic humidity changes are also universal in aircraft cabins. For example, the RH in aircraft cabins is about 80% at ground level [43] and then drops to 20–25% at cruising altitude [44]. Li et al. [45] used heat transfer analysis to simulate the effects of an air humidity cycle from 80% to 20% and back to 80% on aircraft at 20 °C and 28 °C. The results indicated that the humidity affected both human heat storage and skin temperature due to changes in evaporative heat loss. In addition, aircraft passengers may come from different climatic zones; however, there is scarce literature that considers their climate adaptation levels.

Furthermore, the role that humidity plays in the process of adaptation has not been sufficiently investigated. Until now, there has been little confirmative evidence of the effects of air humidity on people's thermal comfort. Thus, different humidity limits exist in the current thermal comfort standards. For example, the humidity limit is 12 g/kg in ASHRAE55-2013, 40–70% RH in CIBSE Guide A [10], and I: 30–50%, II: 25–60%, III: 20–70%, and less than 12 g/kg in EN (European Committee for Standardization) 15251 [11]. Currently, on-site surveys [3, 5, 46-50] in warm indoor environments with high humidity, such as those in Zhang et al. [5], have shown that people from warm climates have higher thermal neutral responses than those from cold climates. Jin et al. [38] suggested that subjects in hot and humid areas would have stronger adaptation responses to warmth and high humidity than subjects in other climate zones, which highlights the noteworthy effect of climate adaptation. A field study that tracked migrants from cold regions to hot summer and warm winter regions of China was conducted by Liu et al. [51]. The results indicated that migrants were more thermally sensitive to humid-hot environments than were the local residents, particularly in the first two days. To date, however, the effects of humidity on adaptation have not been addressed well.

This study was designed to explore the role of humidity adaptations in thermal comfort through comparative experiments with occupants having different levels of climate adaptation (i.e., local residents vs. new migrants). Specifically, their mean skin temperatures and subjective responses to humidity were examined. A climate chamber was used to replicate different humidity levels at acceptable air temperatures.

Objective data and subjective data collected with questionnaires were used to study the influence of climate adaptation on people's thermal comfort with respect to humidity. Based on the results from the above work, useful humidity limits for Chongqing can be appropriately proposed.

2. Methods

2.1 Experimental Subjects

China covers a large area with widespread levels in humidity. Annual rainfall data indicate that China can be separated into four areas based on humidity levels, namely, arid, semi-arid, semi-humid, and humid areas, as shown in Fig. 1. Based on people's exposure levels to humidity, two subject groups were targeted in this study, one consisting of people from arid and semi-arid regions and the other consisting of people from Chongqing, a well-known humid area. Twenty-four first-year college students were ultimately recruited to participate. Half of the group had lived in arid and semi-arid regions for more than 20 years and had migrated to Chongqing within one week prior to the study (noted as the migrant group of low humidity, LH), while the other half came from Chongqing, an area in which they had lived for more than 20 years (noted as the native group of high humidity, HH). The origins of the subjects have been depicted in Fig. 1 as red dots, and their profiles have been summarized in **Table 1** below.

Table 1

Subjects' profiles.

Group	Range of RH in habitat (%)	Clothing	Gender	Number	Age	Height	Weight	BMI[b]

		level			(year)	(cm)	(kg)	
LH	31.0–56.8	0.36	Male	6	22.0±1.1[a]	173.5±5.2	66.8±10.2	22.1±2.1
		0.36	Female	6	22.5±1.0	160.2±3.7	53.6±8.0	20.8±2.5
HH	41.6–98.0	0.36	Male	6	23.3±1.5	173.3±6.0	65.2±8.6	21.6±2.0
		0.36	Female	6	23.2±0.8	161.7±3.1	51.2±8.5	19.6±1.3

[a] Mean value ± standard deviation (S.D.).

[b] BMI = W/(H × H); W-weight, kg; H-height, m.

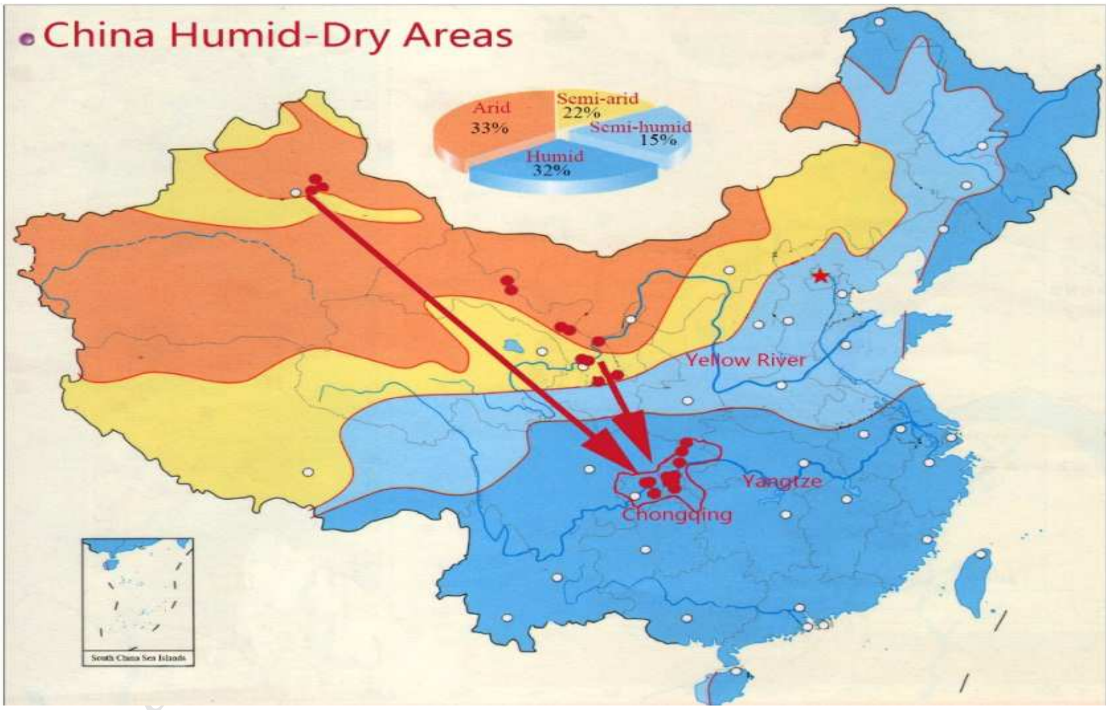

Fig. 1. Map of humid–dry areas in China and origins of the study participants.

2.2 Experimental Apparatus and Conditions

This study was conducted in a climate chamber located at Chongqing University, China. All subjects had experienced their local climate environment throughout the summer before the study started on 15 September 2017. The study lasted for one month. Figure 2 shows the climate chamber with dimensions of 4 m (L) × 3 m (W) × 3 m (H). The climate chamber was separated from the external environment by walls that were 100 mm thick; these walls consisted of a polyurethane filling sandwiched between steel plates. A uniform indoor thermal environment was created by an air-conditioning system, which controlled the temperature and humidity separately; the main system inlet was on the ceiling, and the outlet was located near the floor of a side wall. The control system was able to maintain the indoor air temperature at any point between 5 °C and 40 °C with an accuracy of ±0.30 °C, and the humidity was maintained at 10% to 90% with an accuracy of ±5%. The changing speed of the RH was controlled by adjusting the input power of the wheel dehumidifier and steam humidifier. In addition, there was a preparation room adjacent to the climate chamber, and this was maintained at an air temperature of 26 °C and a RH of 60% to prepare subjects for the study. The sensors (MI6401) were fixed at a height of 1.1 m in the center of the room close to the subjects (points 1 and 2 in Fig. 2)

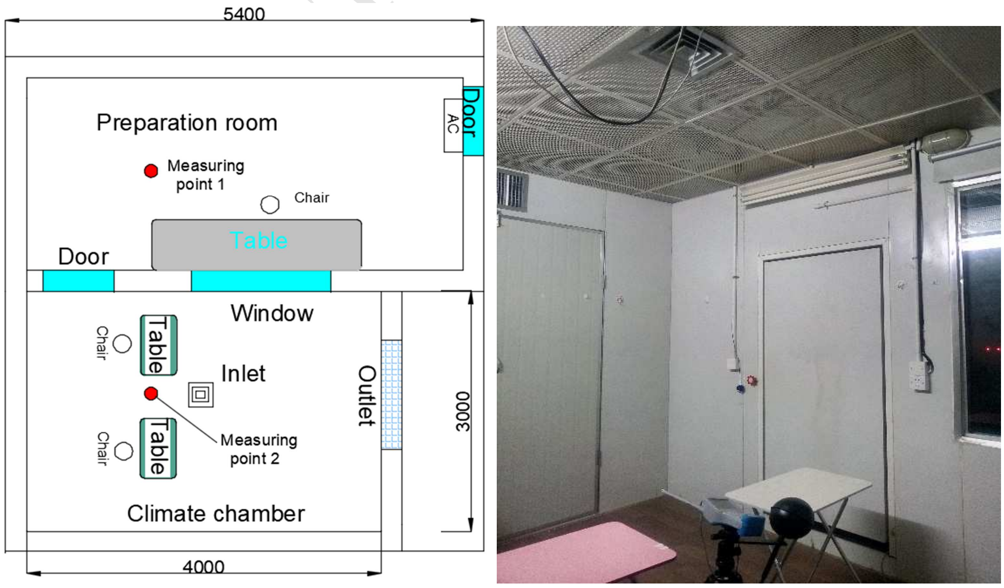

Fig. 2. Diagram of the climate chamber.

Two series of experiments were designed in which the subjects were exposed to a total of four combinations of air temperature and dynamic RH, as listed in Table 2. Because of the larger effect of air humidity and associated human thermal adaptation to humidity in warmer environments, air temperatures in this study were set at 25 °C (neutral temperature) and 28 °C (warm) [45]. As this study was focusing on the effects of humidity in a dynamic environment, we took the discrepancy during RH increasing and decreasing periods into account, and the conditions were set to last for 30 min at 20% and 90% RH and for 15 min at other levels. In order to replicate normal daily humidity levels and ranges, the humidity level was increased (20% to 90% RH) and decreased (90% to 20% RH), as shown in Table 2. The RH changing speed was set to 10% every 15 min, with 30 min for stabilization at the beginning. In addition, the air speed in the chamber was kept to less than 0.10 m/s The thermal environment was controlled by an air-conditioning unit, the wall/floor/ceiling were heated/cooled equally by air, and there were no obvious sources of heat/cold radiation indoors.

Table 2

Environmental conditions during the two series of experiments.

Series	Ta	RH-begin	RH-end
I	25 °C	20%	90%
	25 °C	90%	20%
II	28 °C	20%	90%
	28 °C	90%	20%

2.3 Subjective and Physiological Measurements

During the experiment, air temperature (Ta), RH, and air velocity (Va) were measured by a thermal comfort monitoring device (MI 6401, METREL); some important specifications for this device are listed in Table 3. The sensors were fixed at a height of 1.1 m in the center of the climate chamber and preparation room close to the subjects. These environmental parameters were recorded every 10 s by data loggers. The subjects' skin temperatures (Tsk) were measured at four points, i.e., arm, chest, thigh, and calf, as recommended by Ramanathan [52], by using temperature sensors (UX120-006M). These data were recorded every 2 s. In accordance with the work of Ramanathan [51], the mean skin temperature (MTsk) was calculated by Equation **1**:

$$MT_{sk} = 0.3Tsk_{chest} + 0.3Tsk_{arm} + 0.2Tsk_{thigh} + 0.2Tsk_{calf} \tag{1}$$

Table 3

Instrument specifications.

Parameter	Instrument	Range	Accuracy	Image
Air temperature (Ta)	MI6401	-20–60 °C	±0.2 °C	
Relative humidity (RH)	MI6401	0–100%	±3% RH	
Globe temperature	MI6401	-20–60 °C	±0.2 °C	
Air velocity (Va)	MI6401	0.05–9.99 m/s	±0.05 m/s	
Skin temperature (Tsk)	HOBO U12-006	-20–70 °C	±0.2%	

(1) Thermal sensation

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3

(2) Humid sensation

Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid
☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3

(3) Sweating sensation

No	Slightly	Slightly obvious	Very obvious	Strong
☐0	☐1	☐2	☐3	☐4

Fig. 3. Questionnaire used in the experiments with rating scales.

In this study, subjects' responses to the changing indoor environment were collected by using a subjective questionnaire covering thermal sensations, humid sensations, and sweating sensations. Thermal and humid sensations were quantified by using the ASHRAE 7-point scale [9]. A 5-point scale was designed to evaluate subjects' sweating sensations based on the degree of sweating at the skin surface. The questionnaire was initially designed in Chinese according to the Chinese national standard GB/T 18977 [53] due to the background of participants. A version translated into English is shown in Fig. 3. Before the experiment, the questionnaire was thoroughly explained to all subjects to make sure they fully understood how to use the rating scales.

2.4 Experimental Procedure

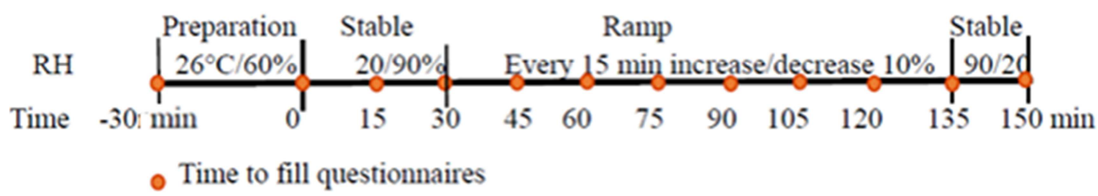

Fig. 4. Experimental procedure.

Given the unequal effects of increased and decreased humidity on both thermal sensation and skin temperature, the 24 subjects involved in the experiments had no idea which humidity changes they were assigned to during the experiment, in order to not bias their votes. Each experiment lasted for 180 min and consisted of 30 min of preparation and 150 min of data collection, as illustrated in Fig. 4. In order to ensure good physical conditions, all subjects were required to avoid alcohol, other stimulating drinks, and strenuous exercise at least 12 h prior to the experiment. Before collecting data, subjects were asked to take a 30 min rest in order to exclude any effects from their experiences before the test, such as walking to the experimental venue. Subjects also used this time to put on uniform clothing, attach the skin thermocouples, and familiarize themselves with both the questionnaire and experimental procedure. Participants' clothing insulation during the experiment was approximately 0.36 clo, and it consisted of a T-shirt, trousers, and a pair of lightweight, "sneaker"-style shoes.

After the preparation period, subjects entered the climate chamber and began to complete their questionnaires. During the experiment, environmental parameters and subjects' subjective assessments of thermal perceptions were recorded every 15 min, as indicated in Fig. 4. Subjects were sedentary with an approximate metabolic rate of 1.1 met. During the experiment, they were allowed to read or talk but could not discuss anything related to their thermal/humid sensations.

2.5 Data Processing and Analysis

This experiment was planned to explore the effects of different humidity levels on thermal comfort, and subjective votes were recorded every 15 min. Data processing adopted the mean value of the thermal/humid/sweating sensation calculated for the same humidity level during the humidity increase and decrease periods for each of the 24 subjects. As these statistical analyses can be seen in Tables 4 and 5 and indicate that there were no significant differences in the values during the humidity increase and decrease periods. To determine whether any significant differences existed between the LH and HH data, an analysis of variance was applied, with the significance levels set at 0.05 (* symbols represent differences at P = 0.05). These data were imported to SPSS V22 software for further analysis.

Table 4

Significant differences in different indicators between humidity increase and decrease periods at 25

Conditions at 25	MTsk	MTSVs	MHSVs	Sweating Sensation
20% RH	0.74	0.13	0.46	0.66
30% RH	0.85	0.11	0.88	0.28
40% RH	0.70	0.12	0.71	0.36
50% RH	0.52	0.22	1.00	1.00
60% RH	0.65	0.41	0.30	0.71
70% RH	0.46	0.36	0.24	0.94

80% RH	0.53	0.65	0.17	0.81
90% RH	0.11	0.11	0.22	0.72

Table 5

Significant differences in different indicators between humidity increase and decrease periods at 28 ℃

Conditions at 28 ℃	MTsk	MTSVs	MHSVs	Sweating Sensation
20% RH	0.54	0.38	0.45	0.20
30% RH	0.32	0.14	0.82	0.53
40% RH	0.53	0.12	0.19	0.29
50% RH	0.15	0.48	0.21	0.90
60% RH	0.26	0.62	0.49	0.66
70% RH	0.25	0.21	064	0.65
80% RH	0.48	0.52	0.20	0.13
90% RH	0.27	0.41	0.85	0.10

3. Results

3.1 Climate Chamber Control

The actual changes in both the temperature and RH in the climate chamber over the entire experimental period are shown in Fig. 5.The changes in humidity at 25°C and 28°C shared nearly the same trend, as all parameters included in Fig. 5 were objective and controlled well by the air-conditioning system. The results clearly illustrate that the temperature was kept fairly stable during the study, with a standard deviation of 0.3 °C. The results clearly illustrate that air temperature was kept fairly stable during the study, with a standard deviation of 0.3°C. Globe temperature also was controlled well (24.96±0.2, 27.98±0.3 at series I and □, respectively). Therefore, the mean radiant temperature calculated by Equation 2 [54], was closed to air temperature. The changing interval of humidity was set at 10% during the experiment, and the change happened after the subjects answered their questionnaire for the current RH level. The results in Fig. 5 indicate that there was good control of humidity during the experiment, which was essential for this work.

$$\bar{T_r} = T_g + 2.44\sqrt{V_a}(T_g - T_a) \tag{2}$$

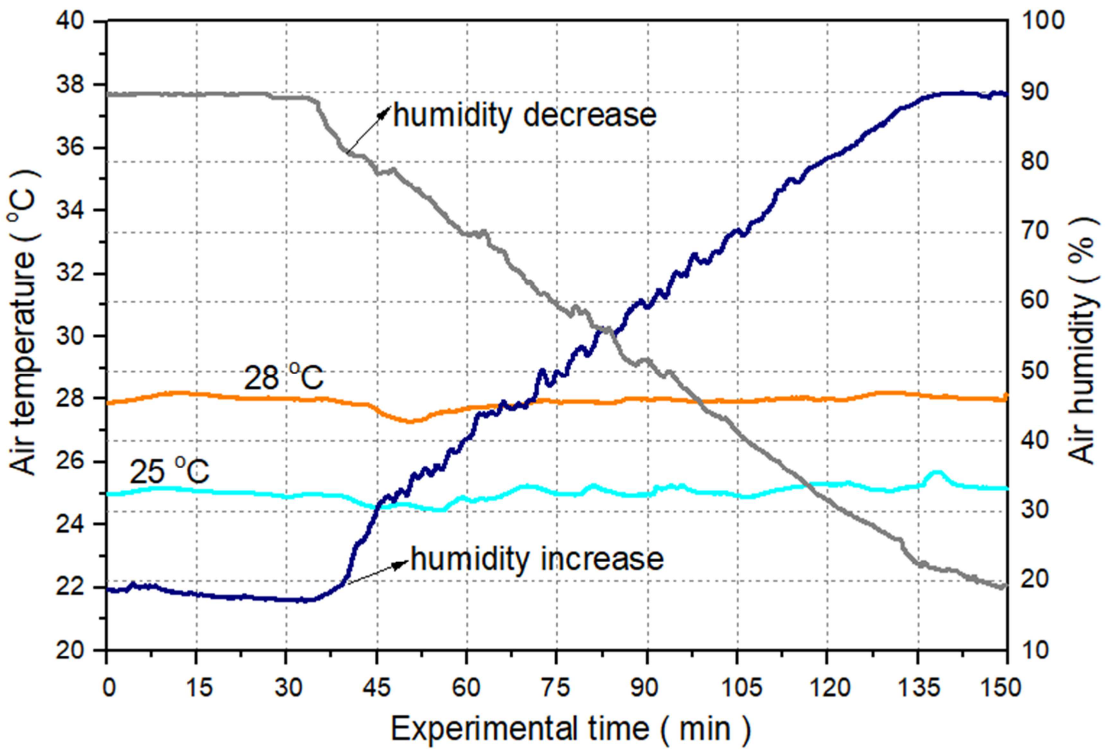

Fig. 5. Air temperature and relative humidity changes over time.

3.2 Mean Skin Temperature (MTsk)

Figure 6 shows the monitored MTsk of occupants with changes in humidity levels at 25 °C and 28 °C. Clearly, when the air temperature increased from 25 °C to 28 °C (air humidity above 70%), the MTsk of HH and LH subjects increased by about 1.0 °C and 1.5 °C, respectively. It was found that the MTsk increased with increasing humidity when the air humidity changed from 20% to 80% RH for both groups, but no further change was noted at 90% RH. Noticeably, the MTsk of the HH and LH subjects increased by 0.37 °C and 0.27 °C at air humidity levels ranging from 20% to 80% RH at 25 °C and by 0.40 °C and 0.45 °C at 28 °C, respectively, as shown in Fig. 6a and 6b. According to Li et al. [39], an increase in skin temperature of 0.5 °C could correspond to an increase in air temperature of 2 °C. Therefore, the changed skin temperatures observed in this study could contribute to new strategies to achieve potential energy savings in buildings. Notably, in Fig. 6, at both temperature levels, the MTsk of all subjects at 80% RH was higher than that at 90% RH, which may have been due to the initiation of sweating, which resulted in evaporative heat transfer at the skin surface [39].

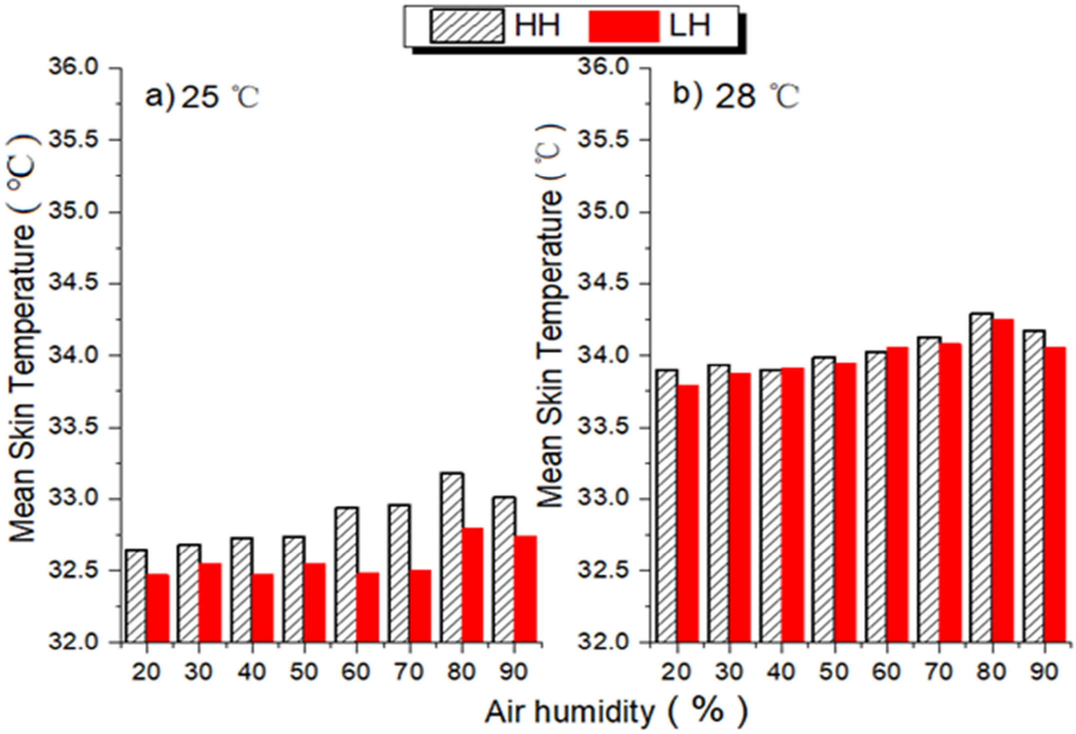

Fig. 6. Mean skin temperature in response to humidity changes at 25 °C and 28 °C.

3.3 Subjects' Thermal Response to Humidity

3.3.1 Mean Thermal Sensation Vote

Figure 7 plots the variation in mean thermal sensation votes for different air humidity levels at 25 °C and 28 °C. At 25 °C, the measured mean thermal sensation votes (MTSVs) for both groups almost fell into the comfort range, which was between -0.5 and +0.5 (as indicated by the red and green lines in Fig. 7), although differences were apparent for the different humidity levels. For 28 °C/20% RH, the thermal sensation vote started to deviate from the comfort zone, and there was a larger slope in the regression relationship between the MTSVs and RH at 28 °C than at 25 °C. These results indicate that the increase in humidity in a warm environment may have greater impacts on MTSVs. There were about 0.7 and 2.0 scale unit increments for both the LH and HH participants when the humidity level changed from 20% to 90% RH at 25 °C and 28 °C, respectively, as shown in Fig. 7a and 7b. It was observed that, at 25 °C, the MTSV of the HH subjects was 0.2 scale units higher than that for the LH subjects, but the differences were not statistically significant. However, at 28 °C, the subjects' MTSVs increased more rapidly with the increasing air humidity, and the increments were about 1.5 and 1.0 scale units from 20% to 90% for the LH and HH subjects, respectively. When the RH was over 70% at 28 °C, 0.5 scale units for the mean thermal sensation votes (MTSVs) of the LH subjects were significantly higher than those of the HH subjects. This phenomenon may have been due to the climate adaptation (i.e., lack of exposure to high humidity and poor thermal adaptation for the LH group), as the subjects from northwestern China were long-term adapted to dry–hot environments but had little experience in humid-hot environments. As a result, it seemed to be particularly uncomfortable for the LH group to adapt to the higher humidity in a warm environment. Table 6 lists the subjects' P values from the two groups in regard to the different humidity levels. When the air temperature was 28 °C, there were significant differences in the thermal sensation votes for the HH and LH subjects between 20% and 70% RH and above. Thus, 28 °C/70% was the critical point for defining a humid and hot environment, which was consistent with the recommendations by Nevins et al. [55].

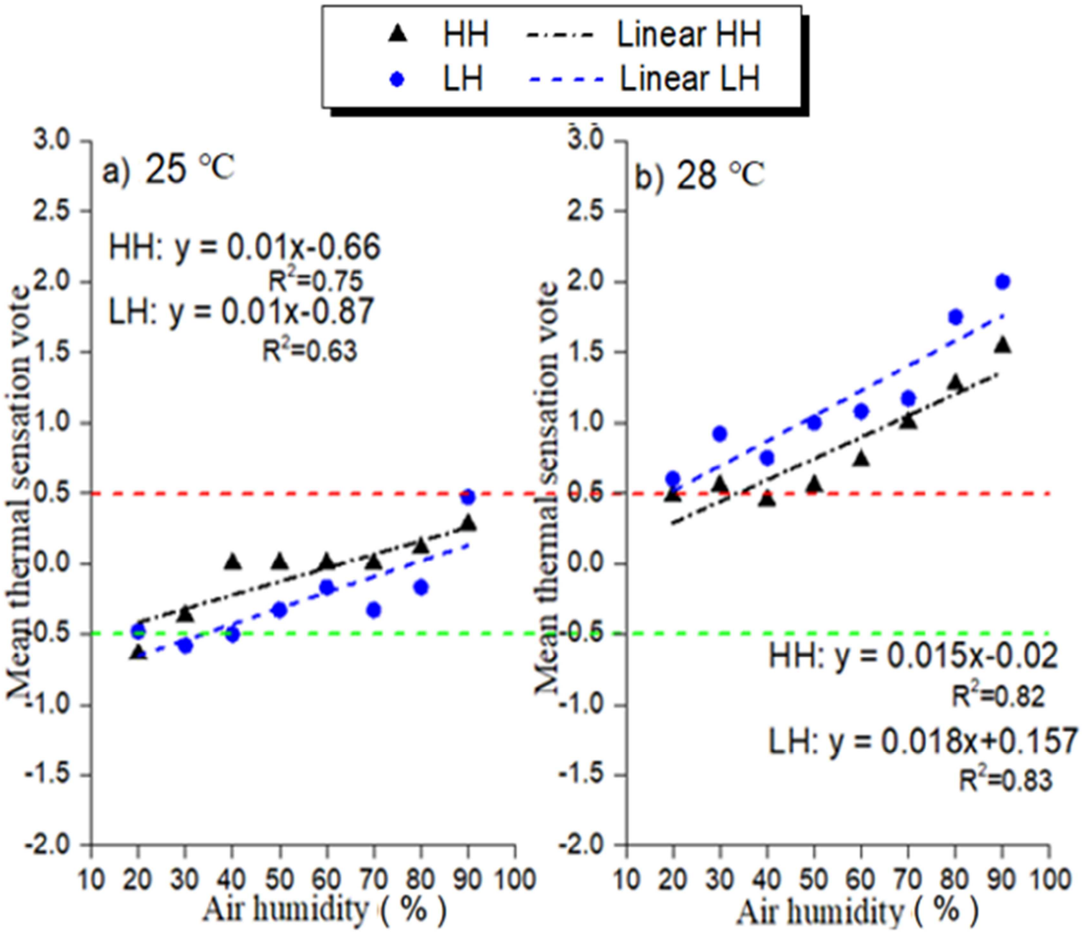

Fig. 7. Mean thermal sensation vote in response to different air humidity levels.

Table 6

Significant differences in mean thermal sensation votes between 20% RH and other humidity levels.

Group	RH / P	30%	40%	50%	60%	70%	80%	90%
25/LH	20%	0.686	0.945	0.546	0.216	0.546	0.216	0.000 [a]
25/HH	20%	0.251	0.025 [a]	0.025 [a]	0.025 [a]	0.008 [a]	0.001 [a]	0.000 [a]
28/HH	20%	0.735	0.895	0.772	0.128	0.007 [a]	0.001 [a]	0.000 [a]
28/LH	20%	0.321	0.634	0.192	0.122	0.048 [a]	0.000 [a]	0.000 [a]

[a] there is a significant difference between the MTSVs at 20% and those at other humidity levels.

3.3.2 Relationship between the Mean Skin Temperature and Mean Thermal Sensation Votes

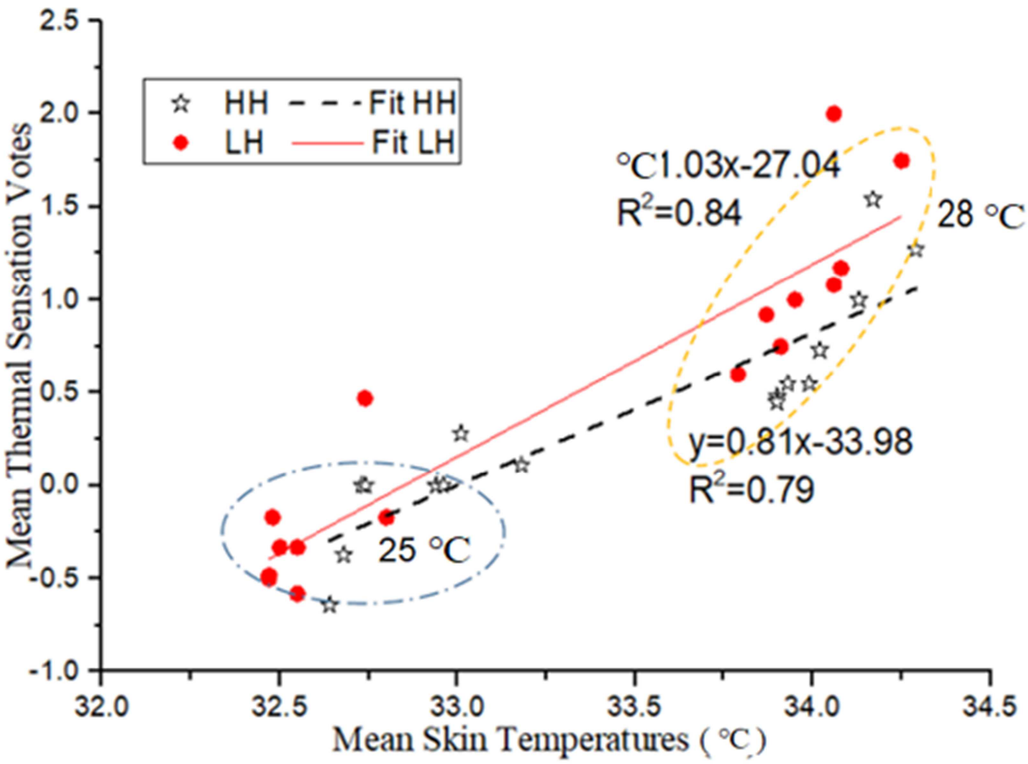

Fig. 8. Relationship between the mean skin temperature and mean thermal sensation vote.

Previous studies [32, 54] have shown that skin temperature is a physiological indicator of thermal comfort. In this study, at a skin temperature of 32.5 °C, the thermal sensations of the HH and LH subjects were almost the same, as shown in Fig. 8. However, when the skin temperature increased to 34.2 °C, the mean thermal sensation votes of the LH subjects were higher than those of the HH subjects. The subjects in this study experienced a warm and high humidity environment, as can be seen in Figs. 6 and 7. At 28 °C, with the increasing humidity, the MTSVs of the LH subjects were higher than those of the HH subjects, even at the same skin temperatures. Therefore, the HH subjects were found to be better adapted to warm and humid environments than the LH subjects.

3.3.3 Mean Humidity Sensation Votes

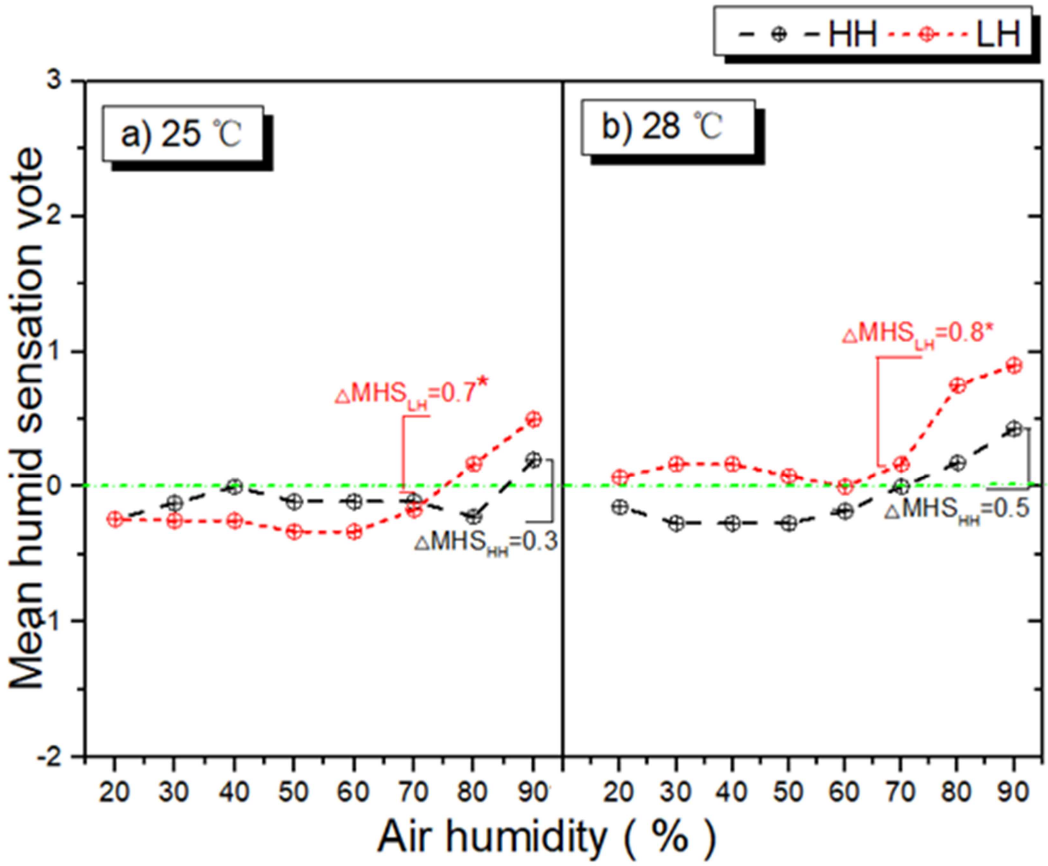

Fig. 9. Mean humidity sensation vote with respect to differences in the air humidity

The variations in subjects' mean humidity sensation votes (MHSVs) under different humidity levels are shown in Fig. 9. Like the MTSVs, increases in the MHSVs of the HH and LH subjects were observed with the increasing air humidity at both 25 °C and 28 °C. However, no significant differences in MHSVs were observed between the HH and LH subjects at all levels of air humidity and temperature. In particular, at 25 °C/28 °C (see Fig. 9), the MHSVs first showed a steady trend when the RH was below 70%, and this was followed by large increases as the RH rose from this point, especially over 28 °C/70%. The MHSVs for the HH and LH votes were observed from 70% to 90% RH with increments of 0.3 and 0.7 scale units at 25 °C and 0.5 and 0.8 scale units at 28°C, respectively. Statistical test results showed that there was a significant difference in the MHSVs for LH subjects between 70% and 90% RH, as shown in Fig. 9. Table 7 compares the P values for the humidity sensation votes between 90% RH and the other humidity levels. There was a significant difference in the humidity sensations of LH subjects between 70% RH and 90% RH when the air temperature was at 25 °C and 28 °C, thus indicating that the effects of humidity on LH subjects below 70% RH were different than those at 90% RH. That is to say, humidity levels over 70% can be considered indicative of a high humidity environment.

Table 7

Significant differences in the mean humidity sensation votes between 90% RH and other humidity levels.

Group	P / RH	80%	70%	60%	50%	40%	30%	20%
25/LH	90%	0.224 [b]	0.050	0.003	0.000	0.000	0.000	0.000
25/HH	90%	0.317 [b]	0.444 [b]	0.444 [b]	0.444 [b]	0.604 [b]	0.454 [b]	0.111 [b]
28/LH	90%	0.520 [b]	0.032	0.018	0.015	0.050	0.024	0.004
28/HH	90%	0.813 [b]	0.555 [b]	0.347 [b]	0.263 [b]	0.239 [b]	0.263 [b]	0.166 [b]

Note**:** [b] there is no significant difference between the MHSVs at 90% and those at other humidity levels.

3.3.4 Sweating Sensation Votes

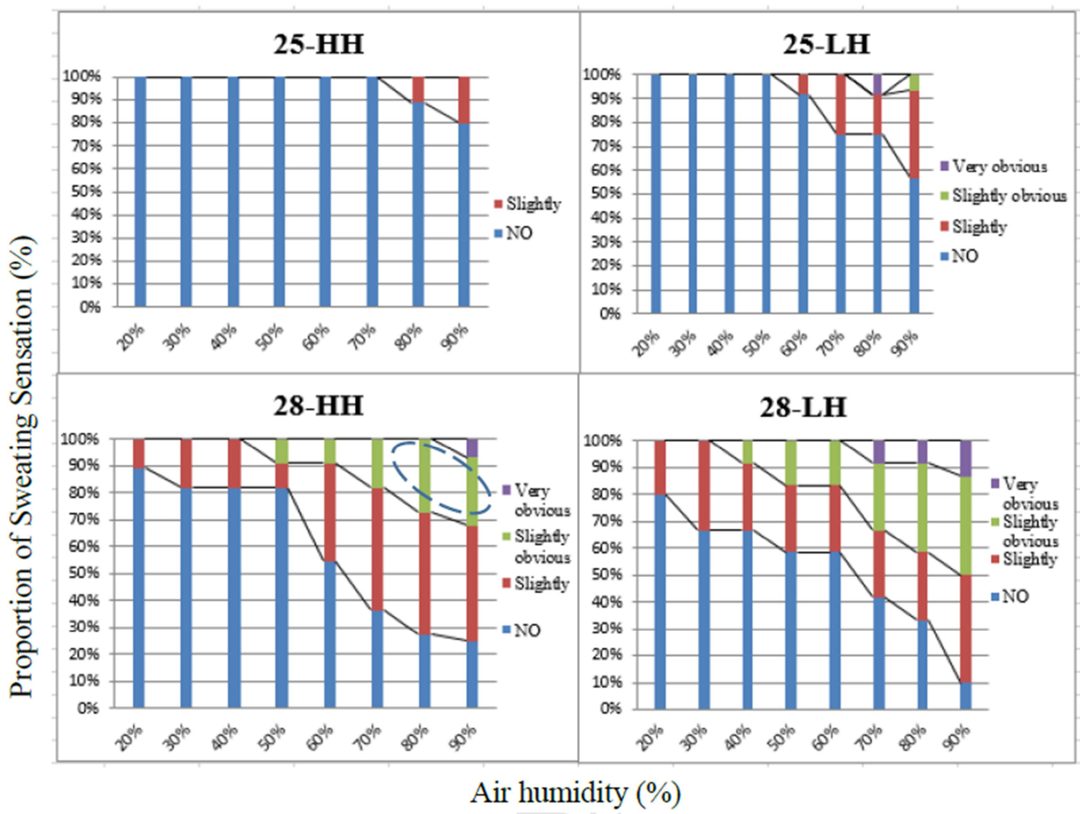

Fig. 10. Sweating sensation vote with respect to differences in the air temperature and humidity.

The sweating sensation votes of the LH and HH subjects at different temperatures and humidity levels are shown in Fig. 10. At 28 °C, the sweating sensation of the two subject groups increased with increases in humidity. In comparison to LH subjects, HH subjects experienced lower sweating sensations at 25 °C/90% RH, with a difference of 20% on the vote of slightly . Notably, the sweating sensation votes of subjects were triggered at 28 °C, which can be seen by the increase in the percentages when the air humidity was above 70% RH in Fig. 10. This increasing trend was similar to the MTSV and MHSV results shown in Figs. 7b and 8b. Therefore, 70% could be considered the demarcation point between neutral and high humidity, which is in line with the findings of existing literature [35, 56].

4. Discussion

4.1 Effects of Adaptive and Thermal Responses to Humidity

The effects of the humidity exposure history on adaptation to humidity has been discussed by the use of ∆TSV and standard effective temperature (SET*) in this study. First, existing studies on the effects of humidity on thermal sensation votes in warm environments were reviewed, and the findings are listed in Table 8. Subjects in the experiment carried out by Jin et al. [38] had weaker responses to increased humidity, and the MTSV of the subjects at 29 °C only increased by 0.48 scale units when the RH increased by 40%. However, subjects from temperate climates showed an increment of 0.7 scale units as for the same humidity increase. At 28 °C, subjects living in HSCW regions for a long time showed similar responses to increased humidity, and the MTSV increased by 0.4 [39] and 0.5 (this study) scale units. In this study, compared to subjects from temperate climates, LH subjects had stronger responses to increased air humidity. For example, a higher increment in the MTSVs for the LH group was observed, i.e., by about 0.7 scale unit, between 60% RH and 80% RH, even at a lower clo value (by 0.24 clo) and lower RH (by 20%). This may have been due to the hot and rainy climate in the summer in Chongqing; thus, local subjects had more exposure to humidity than subjects from the dry-hot–dry zone. Therefore, these findings show that the long-term humidity exposure levels of the subjects affected their thermal perception.

Table 8

Previous studies of the impact of humidity in warm environments.

Year	Reference	Living climate zone	CLO	Air speed (m/s)	Ta (°C)	RH %	∆TSV [a] ($RH_{high}-RH_{low}$)
1987	Tanabe and Kimura [56]	Temperate climate	0.6	0.2	28	80/40	0.7

2018	Li et al. [39]	HSCW	0.37	0.1	28	80/60	0.4
2017	Jin et al. [38]	HSWW	0.6	< 0.1	29	90/50	0.48
2017	This study-HH	Long-term living in HSCW	0.36	< 0.1	28	80/60	0.5
	This study-LH	Long-term living in dry-hot region	0.36	< 0.1	28	80/60	0.7

[a] This value is for the TSV of subjects at a higher RH minus the TSV of subjects at a lower RH.

Figure 11 further compares previous studies (HSCW zone) on humidity with the SET* index. Although the intercepts were not the same, the slopes of the linear regression for the MTSV and SET* models found in existing studies were quite similar. Because of the higher clo levels (by 0.3 clo), a slightly higher MTSV was seen in the experiment carried out by Jin et al. [38] than in those computed by Li et al. [6] and Tan [57]. As was rather clearly seen, the MTSV of the LH subjects changed with the SET* and exceeded the MTSV of the HH subjects. Thus, people with a humid–hot residential history were found to be better adapted to humid–hot environments.

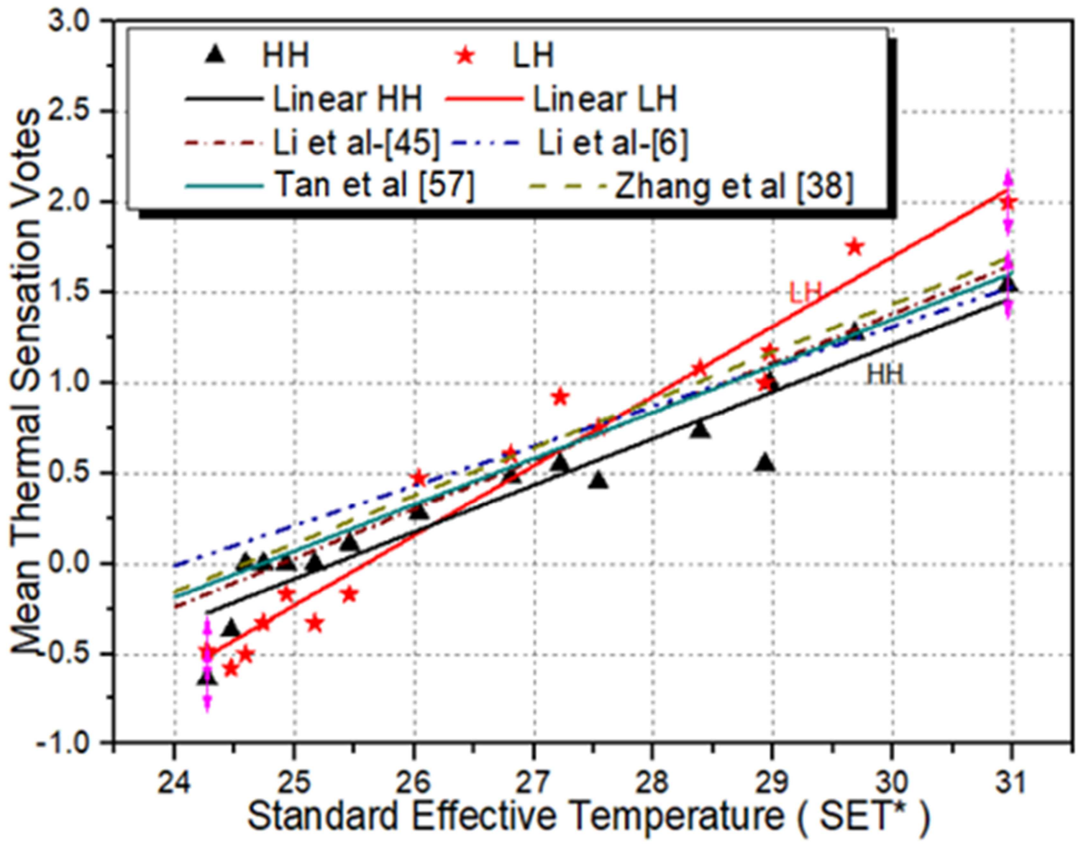

Fig. 11. MTSVs in subtropical areas under SET*.

4.2 Impact of the Experience of Humidity on Adaptation

Previous studies have shown that prior thermal experience can significantly affect thermal sensations [58, 59] and preferences [60], and occupants in different climate zones typically show differences in neutral temperatures, such as 26.2 °C [56] in an HSCW zone and 25.56 °C [2] in Turpan, China in the summer without considering the air humidity. Since a humidity signal exists in the adaptive thermal comfort [61], there is an adaptive difference that climate has on responses to humidity [38]. Mean skin temperatures of the HH and LH subjects to humidity stimuli are identified in this study They were found to provide an important evidence for climate adaptation to high humidity in warm environments. Notably, at 25 °C and at air humidity values above 70%, the MTsk of HH subjects were about 0.4 °C higher than that of LH subjects, although the MTSVs of both the HH and LH were close to neutral, probably because the HH group was adapted for higher skin temperatures as a result of long-term exposure to humid–hot environments. Yu [62] also obtained similar results by comparing occupants with different thermal experiences inside buildings and showing that subjects without air-conditioning exposure in summer had higher mean skin temperatures (about 1 °C) than people who often stay in comfortable building environments.

Moreover, HH subjects were recognized for lower thermal sensitivities, as the MTsk of the HH and LH subjects increased by about 1.0 °C and 1.5 °C with the air temperature increasing from 25 °C to 28 °C (air humidity above 70%), respectively. This finding is consistent with those of previous studies [21, 63, 64], which indicated that experience of high humidity in warm environment contributes to a higher neutral temperature and a lower thermal sensitivity. These results provide important reference data for the design of comfortable building environments.

4.3 Appropriate Limits for Humidity

Humidity is commonly expressed in terms of the relative humidity, humidity ratio, or dew point temperature. Humidity limits in most versions of the ASHRAE standards are based on the humidity ratio. Responses of both the HH and LH subjects over 70% RH tend to be more sensitive to the increase in humidity with increasing temperature in this study. To characterize the MHSVs of subjects with environmental parameters, further analysis on the relationship between the humidity ratio and humidity sensation was done, as shown in Fig. 12. In this study, MHSVs fluctuated slowly when the humidity ratio fell below 12 g/kg. However, the MHSVs of LH and HH subjects increased rapidly by 1.1 and 0.7 scale units, respectively, when the humidity ratio increased from 14 g/kg to 21.8 g/kg, thus indicating that a higher humidity ratio was easier to perceive. The ASHRAE standards have proposed a required maximum humidity ratio of 12 g/kg [9]. However, the humidity sensation of the HH group was slightly lower when the air humidity was 12 g/kg, equal to 50%

RH at 28 °C. In another study conducted by Li et al. [6], it was recommended that the humidity limit be set at 18.8 g/kg with 80% acceptability for the HSCW zone; this was approximately equal to 0.5 scale units of MHSVs in this study.

Most studies have indicated that obvious increases in MTSVs could be found between 70% and 80% RH in warm environments [35, 56]. Dehumidification (below 70% RH) was suggested by Tanabe and Kimura [56] for humid regions, and the acceptable temperature limit can be up to 28 °C [18, 65]. Therefore, 17 g/kg (about 70% RH at 28 □) has been considered an appropriate humidity limit to provide comfort in the HSCW.

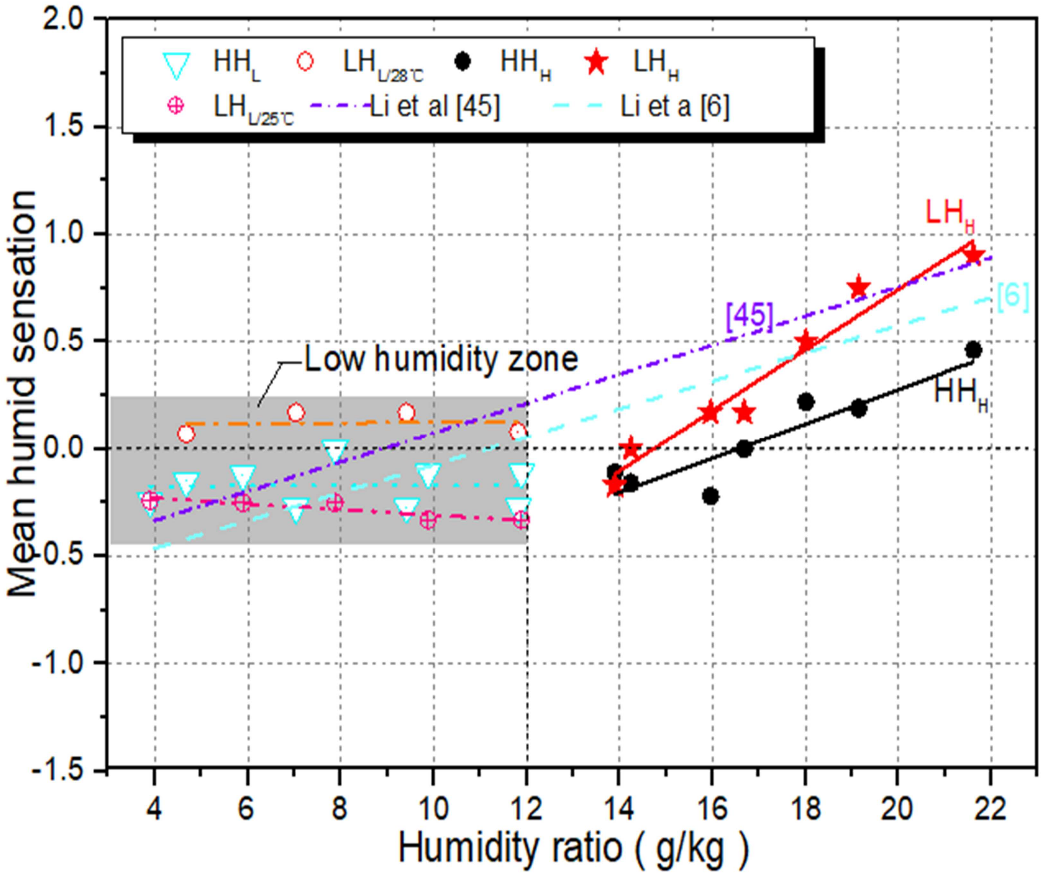

Fig. 12. Humidity sensation vote in relation to the humidity ratio.8

Note**:** HH_L is the MHSV of the HH subjects at 25 °C and 28 °C at low humidity (below 12g/kg); $LH_{L/28}$ is the MHSV of the LH subjects at 28 °C at low humidity; $LH_{L/25}$ is the MHSV of the LH at

25 °C at low humidity; HH_H/LH_H is the MHSV of the HH/LH at high humidity (over 12g/kg).

5. Conclusions

This study has investigated the effect of climate adaptation on people's thermal responses to humidity in buildings. By comparisons between two groups of participants with significantly different living experience in terms of humidity, evidence about humidity adaptation has been provided. Main conclusions of this study have been listed as followings:

(1) The HH group was adapted for higher skin temperatures. When temperature was set as 25 °C, the mean skin temperature (MTsk) of participants from HH regions was 0.4 °C higher than that of those from LH regions. When temperature was set as 28°C, however, the MTsk of participants from HH regions was lower than that of those from LH regions.

(2) Significantly different subjective answers were found between HH and LH participants when RH was over 70%, at both 25°C and 28°C conditions. Participants from LH regions had much higher mean thermal sensation votes (MTSVs) than those of HH regions, demonstrating lower sensitivity and stronger adaptation to warm and high humidity conditions.

(3) 70% can be considered as the changing point between high humidity environment and low humidity environment, as participants showed stronger thermal responses when the air humidity was over 70%.

(4) It has been proposed that the upper limit of humidity for Chongqing could be set at 17 g/kg.

Acknowledgements

This research is supported by the Fundamental Research Funds for the Central Universities (Grant No. 2018CDYJSY0055, 2018CDJDCH0015), the National Key Research and Development Program of China (2017YFC0702700), and the 111 Project (Grant No.B13041).

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HIGHLIGHTS

- Exploring the effect of people's humidity adaptation on their thermal comfort
- People from high humidity areas were easier to be comfortable in humid conditions
- Adaptation alleviated people’s thermal sensitivities to humid and hot environments
- Relative humidity over 70% was considered as high humidity
- 17 g/kg was proposed as upper humidity limit for Chongqing