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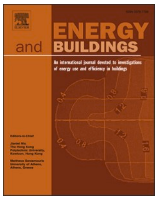

Thermal comfort of students in naturally ventilated secondary schools in countryside of hot summer cold winter zone, China

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ABSTRACT

People experience four seasons every year, and their thermal comfort usually changes with the season. However, a little is known about the dynamic characteristics of secondary students' thermal comfort in the countryside under different seasons. This study aims to investigate thermal comfort of students in the countryside under various seasons and reveal the underlying mechanism. One year long-term field study was conducted in a countryside secondary school in Hengyang City, located in the hot summer and cold winter zone of China. A paper questionnaire was used to collect subjective thermal comfort. The surrounding physical environment was also measured. A total of 450 subjects voluntarily participated and returned 2349 valid datasets. The results indicated students had the lowest acceptance rate with temperature (71.9 %), humidity (74.9 %), and velocity (70 %) in summer season. Neutral temperature was 25.7 °C in summer, 19.2 °C in transition, and 14.9 °C in the winter. An inverted U relationship was found between perceived air quality and air temperature. Cold extremities (53.0 %), shivering (37.2 %), and stuffy nose (60.4 %) were prevalent in winter. Adaptive comfort model was only effective in the summer in naturally ventilated secondary school buildings. Estimated learning performance was the highest in transition and lowest in summer. Behavioral adaptation was determined by the relationship between air velocity clothing insulation and operative temperature. The findings of this study provide fundamental knowledge of thermal environment, subjective comfort, and health status in naturally ventilated educational buildings in countryside area. Engineers and designers can use professional comfort indicators to guide their future construction or renovation.

1. Introduction

Educational buildings are the main space for student learning and working, where they spend around 30 % of their time [1]. A comfortable indoor thermal environment is vital for students' comfort, work performance, and health [2,3]. As societies experience rapid economic growth, educational facilities have garnered increasing attention for their essential role in shaping future generations. Investigating the thermal conditions and students' thermal comfort within these educational buildings becomes imperative to ensure optimal learning performance.

1.1. Research background

From the 1960s, numerous field studies [4–9] have examined the thermal environment in educational buildings. These studies have covered educational buildings with various education levels, geographic, climatic, seasons, and ventilation types. Educational buildings differ significantly from residential and office buildings in terms of the occupants' age, metabolic rate, clothing, adaptation opportunity, and occupancy density [10]. Such divergence has led to observable differences between the subjective thermal comfort reported by students and the predictions of Predicted Mean Vote-Percentage People Dissatisfied (PMV-PPD) model [11,12]. More than 50 % of students evaluate their surrounding thermal environment within a typical thermal comfort range (i.e., slightly cool, neutral, and slightly warm) [4,13–15]. Despite the outdoor environment is relatively hot (i.e., Japan [16], Taiwan [17] or cold [18,19], some students still have neutral thermal sensation. Neutral temperature [20,21], a typical thermal comfort indicator, is used to analyze human subjective comfort in the field study. Students usually have lower neutral temperatures than adults in office buildings [22–24]. The reasons for such discrepancies have been concluded as follows, 1) the high metabolic rate [25] leads to higher preference and acceptability for the cooler environment; 2)

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students have higher tolerance [26] to thermal environment. Students' neutral temperatures are also dependent on outdoor weather [8] and local climate [10,27], especially in naturally ventilated educational buildings. Students in relatively cold climates have lower neutral temperatures. For example, students in cold climates, such as England [4,22], have lower neutral temperatures (16–20 °C) compared to those in warmer subtropical regions (24–27 °C in Australia [28] and Hawaii [29] and hot tropical climates (28–29 °C in Singapore [26] and Taiwan [17]. The strong correlation between neutral temperatures and outdoor temperatures aligns with the adaptive comfort models, which have been validated with field studies of adults. However, existing standards, including ASHRAE 55-2020 [30], EN 16798-1 [31], and ISO 7730 [32], rely on findings from studies involving adults, raising questions about their applicability to secondary school students.

Elevated temperature could result in acute health symptoms [33–35] (i.e., headache and difficulty in concentrating) and negatively affect cognitive performance [36]. A comprehensive series of studies in Sweden [37,38] found that the schoolwork performance of 9–12 years old children is significantly lower at 27 and 30 °C compared to 20 °C. The magnitude of the negative effect of temperature on performance was for some tasks as great as 30 %. Eighteen university students in Romania have optimal performance at 27–28 °C for the Prague test and at 25–26 °C for the Kraepelin test [39]. Seppänen [40,41] fitted an inverted-U relationship by summarizing 24 previously published studies. The fitted model shows a performance peak at 21.6 °C, then decreases in temperatures beyond 22 °C. ASHRAE Handbook [42] and REHVA Guidebook [43] show a bell-shaped performance curve centering at the optimum comfort temperature. Associated with arousal theory [44,45], the relationship between thermal environment and cognitive performance follows an inverted U shape [41,46].

China has the largest educational system with nearly 260 million students in the world [47]. Approximately 20 % of these students attend schools in rural areas, where educational facilities often lack air conditioning systems. Classrooms in these regions typically rely on natural ventilation and ceiling fans, leaving students with limited means to adapt to the thermal environment. With the rapid development of economy, people are demanding improved living, working, and learning environments. Hengyang, located in the hot summer and cold winter (HSCW) zone of China, has the same climate as Changsha, where the researchers have conducted field studies with dormitory and office buildings [20,21,48–50].

1.2. Research gaps and objectives

Despite prior research in hot and humid regions of China, there is a significant shortage of thermal comfort field studies in secondary educational buildings, particularly in rural areas and among teenagers. Most studies in the HSCW zone have predominantly targeted adults, overlooking the unique thermal comfort considerations of teenagers. To fill in these gaps, this study endeavored to investigate students' thermal comfort in secondary schools located in the countryside of Hengyang, China, across all seasons. This research seeks to answer critical questions: How does the thermal environment fluctuate with the seasons, and how does students' thermal comfort differ from established adaptive thermal comfort models? The novelty of our study lies in the first year-long field study within secondary educational buildings in rural areas, specifically among teenagers in hot summer and cold winter zone of China. Our research revealed the seasonal variations in students' thermal comfort, filling a crucial gap in the existing literature. In pursuit of above questions, a year-long thermal comfort field study was conducted. As the continuous work of previous studies in office and residential buildings [20,21,48–50], this work will provide systematic insight into students' thermal comfort in secondary school at the whole year level. For the reasons explained above, this thermal comfort field study was conducted with the following objectives:

1. To investigate the thermal comfort in countryside naturally ventilated secondary schools based on a year-long seasonal field study in the HSCW zone, China
2. To determine the neutral temperature, preferred temperature, and acceptable temperature range of students in different seasons in countryside naturally ventilated secondary school
3. To evaluate the applicability of existing thermal comfort models (i.e., adaptive thermal comfort model) in countryside naturally ventilated secondary school

2. Research methods

2.1. Location, climate, and buildings

From January to December 2018, a field study was conducted at a secondary school located in the countryside of Hengyang City, China. Hengyang is a typical city in the HSCW zone of China. This city has a humid subtropical climate in terms of the Köppen-Geiger climate classification [18,19]. The hottest monthly could be 30 ± 2.0 °C and the coldest monthly average temperature is 7.2 ± 2.2 °C. All investigated students learned in a three-story building. The school building was built in the last century, with 240 mm brick walls, wood-frame windows, and single-glazed glass. The windows were installed on the southern and northern sides, and two doors were placed on the front and backward of the northern wall. The window/wall ratio was about 0.5 on both the southerz hn and northern sides. Each floor had two classrooms. There was an external corridor connected to the northern side of classrooms. Each classroom had about 60 seats, and the room size was 6 m*8 m (width*length). All these classrooms were naturally ventilated and each classroom had two ceiling fans. Students could adjust their clothing insulation, close or open windows or doors, and control the ceiling fans.

2.2. Measurement

The outdoor temperature and humidity were monitored with HOBO-U23 attached to an outside pillar of the investigated buildings (Fig. 1a). The Delta Comfort instrument was used to measure indoor air velocity, air temperature, globe temperature, and relative humidity. Students in each classroom were divided into four groups (Fig. 1b). The classroom layout consisted of ten desk lines separated by two aisles (Fig. 1c). To capture accurate data, the instruments were strategically positioned at two points located at the intersection of each aisle. Subsequently, the classroom area was divided equally into four quadrants, with students indicating their assigned group number on a questionnaire. In each group, a single measurement of the indoor parameters was conducted. The stable measurement values displayed on the instrument screen was diligently documented by manually recording them on paper. The instrument was always took inside 30 min before the measurement to ensure the stable values of indoor measurement. The instrument was held to a tripod at a height of 0.6 m. All instruments were calibrated and met the requirement of ISO 7726 [51]. Operative temperatures were calculated based on ASHRAE Standard 55-2020 [30] for further data analysis. Table 1 shows the details of instrument information.

2.3. Subjects

Four hundred fifty subjects (238 males, 212 females) in 8 classes voluntarily participated in this field study. 2349 valid questionnaire datasets were finally collected. In detail, 912 datasets were collected in transition, 1018 datasets in summer, and 419 datasets in winter. Table 2 summarizes the anthropometric information of subjects. Their age ranged from 11 to 16. The mean height was 156.5 cm, and the weight was 44.0 kg. All students grew up in the investigated town. Their experience was representative of climatic adaptation and the built environmental experience of local inhabitants.

Fig. 1. Physical measurement of (a) outdoor thermal environment, (b) indoor thermal environment and (c) the classroom layout.

Table 1
Detailed information of related instruments.

Environment	Parameters	Instrument	Range	Accuracy
Indoor	Air temperature	HD32.3	−40–100 °C	± 0.1 °C
	Globe temperature		0–50 °C	± 0.6 °C
	Relative humidity		5–98 % RH	± 2 % RH
	Air velocity		0.00–5 m/s	0.05 m/s
Outdoor	Air temperature	HOBO-U23	−40–70 °C	± 0.25 °C
	Relative humidity		0–100 % RH	± 2.5 % RH

Table 2
The information of respondents.

Gender	N	Age	Height (cm)	Weight (kg)	BMI (kg/m^2)
Female	212	13.1 ± 1.2[a]	153.6 ± 6.9	41.6 ±6.8	17.6 ± 2.3
Male	238	13.4 ±1.9	159.2 ± 10.0	46.1 ±12.2	18.2 ±5.6
Total	450	13.3 ±1.1	156.5 ±9.1	44.0 ±10.3	20.6 ±3.2

[a] Standard deviation

2.4. Questionnaire

Survey was usually conducted in the classroom during the self-studying time (17:00–18:00) because students were only available during such time duration. The survey was usually arranged every half month but also dependent on the availability of the students. The survey was not arranged during the vacation and examination period. In the beginning, the practice session of the survey was conducted where all the questions and subjective scales were explained to the students. Students could request help from us if they encountered problems with the questionnaire. The paper questionnaire used a similar design as our previous study [49]. Personal characteristics, thermal perceptions, and perceived air quality were surveyed by questionnaire. Personal information included the subjects' gender, height, weight, age, activity level, and clothing types. Subjective evaluation was investigated with air temperature, relative humidity, and air velocity for thermal perceptions. ASHRAE seven-point scale (−3 Clod; −2 Cool; −1 Slightly cool; 0 Neutral; 1 Slightly warm; 2 Warm; 3 Hot) was used to collect thermal sensation evaluation. In addition, subjective thermal preference, comfort, and acceptability were evaluated. Humidity and velocity perception were also investigated with a similar scale of thermal perception. All scales were also presented in related figures in results. Clothing insulation was determined by summing each value of clothing items and a normal chair (ASHRAE Standard 55-2020 [30]).

2.5. Data analysis

R studio software was used to perform data analysis and figure construction. The normality of data was examined with the Shapiro-Wilk test. One-way ANOVA or independent *t*-test was conducted for normally distributed data and the nonparametric Kruskal-Wallis or Mann-Whitney for non-normally distributed data. In Section 3.3, all the dependent variables were binned with every 0.5 °C of operative temperature. All the relationships presented in figures are significant. The black line in all regression relationship figures indicated the whole year level. The regression correlations were determined with one-way ANOVA test. The significant value was set as 0.05.

3. Results

3.1. Thermal environment

Fig. 2 shows how the outdoor and indoor environments change over time. During the study period, the average daily outdoor temperature was 27.4 °C in summer, 16.2 °C in transition, and 7.4 °C in winter. The average daily relative humidity was 76 % in summer, 82 % in transition, and 79 % in winter. The hottest month was July, and the coldest month was December.

Seasons were classified with pentad (five days) average temperature. In detail, the winter season was when the pentad average temperature was lower than 10 °C; the summer season was when the pentad average temperature was higher than 22 °C; the transition season was when the pentad average temperature ranged from 10 °C to 22 °C. Table 3 presents the statistical results of the outdoor and indoor environments in three seasons. The running mean outdoor temperature (T_{rm}) [30] and prevailing mean outdoor temperature (T_{pm}) [31] were also calculated to predict the indoor comfort temperature from the climate.

3.2. Subjective evaluation

Fig. 3 shows the frequency distribution of thermal perceptions in three seasons. The highest percentage of thermal sensation is "Neutral" in summer (44.3 %), "Neutral" in transition (55.7 %), and "Slightly cool" in winter. The mean thermal sensation was 0.5 in summer, 0.1 in transition, and −0.7 in winter. 41 % of subjects felt warm in summer, and 54.9 % of subjects felt cool in winter. The largest proportion of subjects preferred "No change" in summer (39.9 %) and transition (57 %) season and "Slightly warm" in winter (44.7 %). The proportion of cooler preference votes was remarkably higher than the warmer preference votes in the summer, while the situation was the verse in the winter. The thermally uncomfortable percentage was 37.7 % in summer, 25.7 % in transition, and 41.2 % in winter. The proportion of thermal acceptability was 71.9 % in summer, 81.8 % in transition, and 79.3 % in the winter season.

Table 3
The statistical results of the outdoor and indoor environments in three seasons.

Season	T_{out} (°C)	RH_{out} (%)	T_{in} (°C)	RH_{in}	MRT_{in}	$T_{g(in)}$	$V_{(in)}$
Summer	27.4 ± 3.4	76 ± 10	28.2 ± 3.5	71 ± 12	28.2 ± 3.5	28.2 ± 3.5	0.31 ± 0.3
Transition	16.2 ± 4.3	82 ± 12	19.8 ± 3.3	69 ± 14	19.9 ± 3.4	19.8 ± 3.4	0.07 ± 0.1
Winter	7.4 ± 4.0	79 ± 16	8.9 ± 2.2	76 ± 5	8.8 ± 2.3	8.9 ± 2.2	0.04 ± 0.0

Fig. S1 shows the frequency distribution of velocity perceptions in three seasons. The highest percentage of subjects had "Neutral" velocity sensation in summer (54.5 %). A higher proportion of subjects had "low" velocity sensation than "high" velocity sensation in all three seasons. Also, most subjects prefer "no change" with velocity in all seasons. More subjects prefer higher velocity than lower velocity in summer and transition seasons. The percentage of velocity acceptance was 70 % in summer, 81 % in transition, and 80.7 % in winter. Fig. S2 presents the frequency distribution of humidity perceptions in three seasons. The highest proportion of subjects had "Neutral" humidity sensation in summer (59 %), transition (66.1 %), and winter (53.9 %). More subjects have dry sensation than wet sensation in all three seasons. Most subjects prefer "no change" with humidity in summer (56.4 %), transition (67.4 %), and winter (50.6 %). The acceptable rate is 74.9 % in summer, 83.7 % in transition, and 82.5 % in winter.

3.3. Comfort temperature

3.3.1. Neutral temperature

This study used the linear regression method to determine neutral temperature. Fig. 4a shows the linear regression relationship between thermal sensation and operative temperature in different seasons. The neutral temperature was defined as the temperature interpoint of the regression line when thermal sensation was equal to zero. The neutral temperature was determined as 25.7 °C in summer, 19.2 °C in transition, and 14.9 °C in the winter. Subjects had almost the same thermal sensitivity to indoor temperature in summer and winter.

3.3.2. Acceptable temperature

80 % acceptable temperature range is the classical thermal comfort

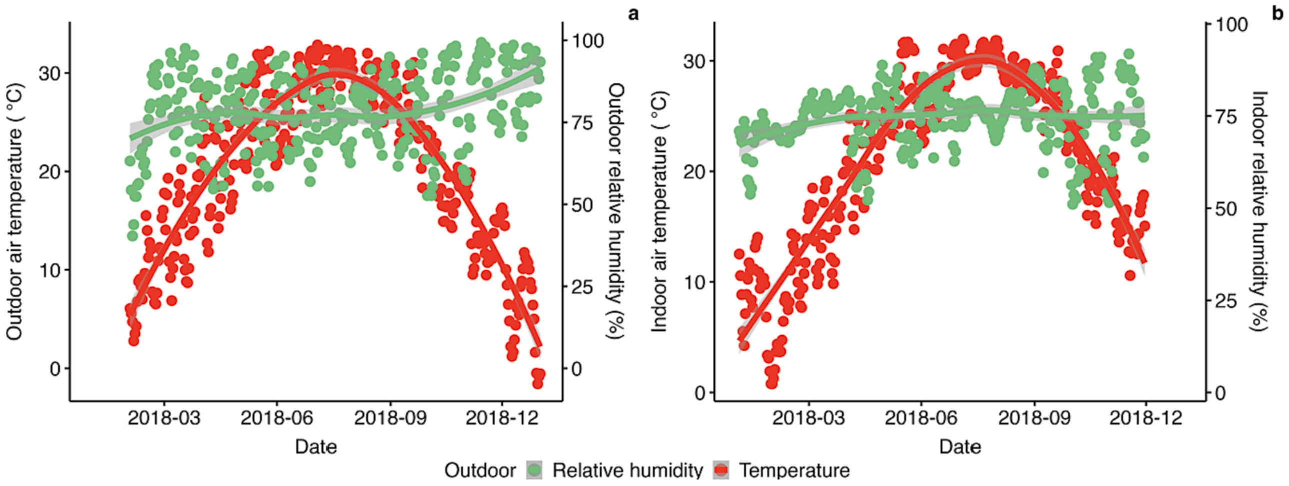

Fig. 2. Time series of (a) daily outdoor temperature and relative humidity, (b) daily indoor temperature and relative humidity in three seasons.

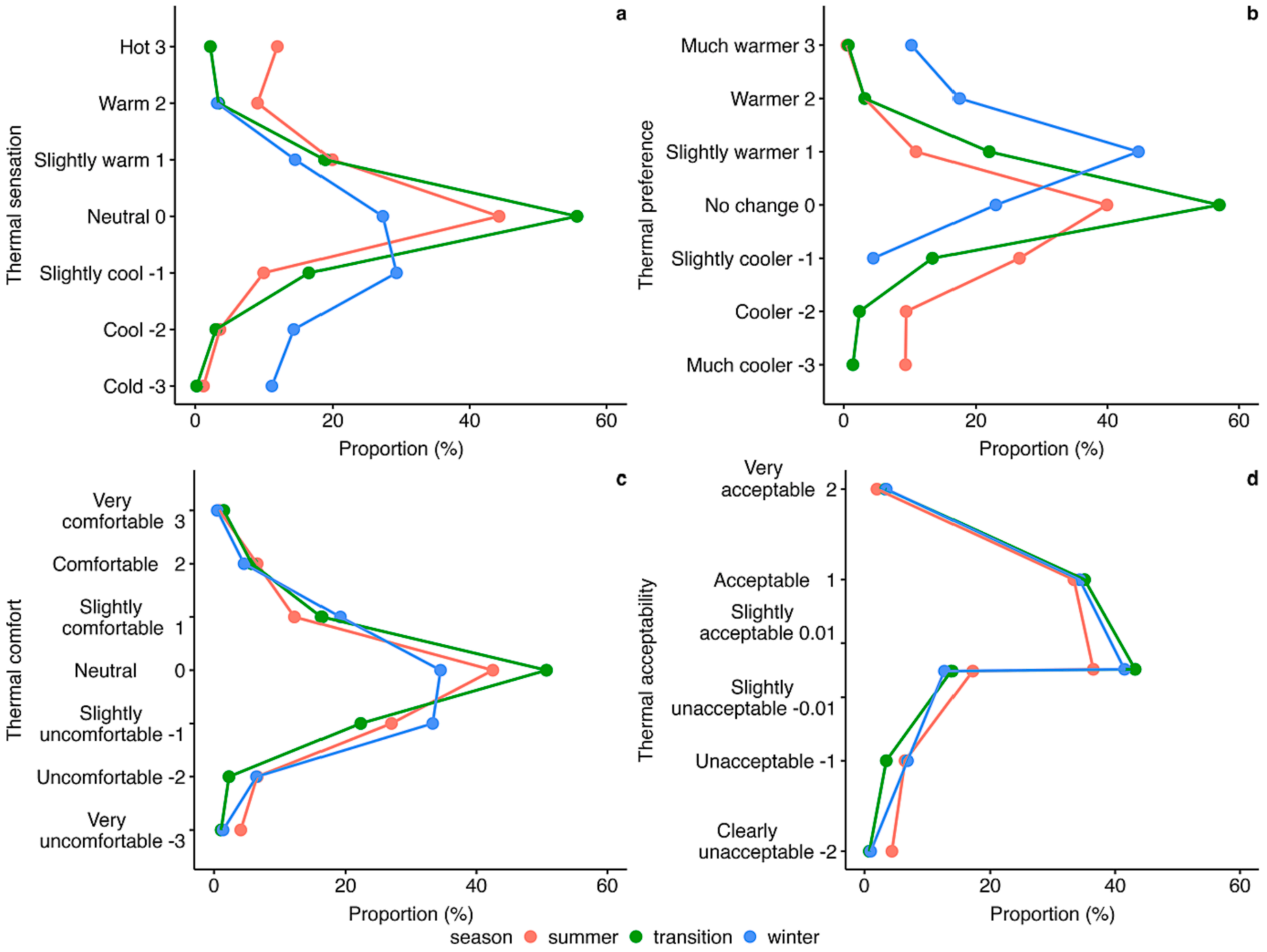

Fig. 3. The frequency distribution of (a) thermal sensation, (b) thermal preference, (c) thermal comfort, and (d) thermal acceptability under three seasons.

indicator. This study defined the actual acceptable rate with the thermal acceptance votes. Fig. 4b presents the acceptable temperature ranges of subjects in three seasons. A second-order function was determined between the actual acceptable rate and operative temperature. The results indicate that summer's upper limit of 80 % acceptable temperature range is 27 °C.

3.3.3. *Preferred temperature*

The preferred temperature is useful to determine what temperature subjects expect in many studies [52–54]. In this study, the preferred temperature was determined by using probit analysis. the thermal preference votes were arranged in binary form: "prefer warmer" and "prefer cooler". Then the probit regression model was used to determine the lowest probability of preferring a cooler or warmer environment. Consequently, the preferred temperature was found where a preference for no temperature change. Ordinal regression was used and the operative temperature was defined as the covariate and the probit as the link function. Fig. 4**c** shows the preference proportions in different seasons. All the probits were transformed into proportions by using the following function:

$$\text{Probability} = \text{CDF.NORMAL}\ (\text{quant},\ \text{mean},\ \text{S.D.}) \tag{1}$$

where CDF.NORMAL is the cumulative distribution function; quant is the operative temperature.

The preferred temperature was determined as the intersection point of the "prefer warmer" and "prefer cooler" curves. The results indicated that the preferred temperature was 22.5 °C in transition and 25.4 °C in summer.

3.4. *Perceived air quality, sick building syndrome symptoms and estimated performance*

3.4.1. *Perceived air quality*

Fig. 5 shows that the percentage of subjective acceptability with air quality is 76.9 % in summer, 81.8 % in transition, and 74.6 % in winter. An "inverted-U" relationship was found between the acceptable rate of perceived air quality and operative temperature. Subjective satisfaction with air quality was positively correlated to operative temperature and reached the maximum (83.1 %) satisfaction when operative temperature was 20.1 °C; Then, subjective satisfaction with air quality decreased with operative temperature.

3.4.2. *Estimated performance*

Previous studies [35,41,43] have determined an "inverted U" shape between work performance and temperature or thermal sensation. As the main space for learning, the indoor thermal environment is vital for the student's learning performance. Several studies [42,43,46] have determined the relationship between relative performance and thermal sensation. Therefore, in this study, the relative learning performance was estimated using the relationship model of Lan et al. [46]. The relationship is shown as follows,

$$RP = -0.0351TS^3 - 0.5294TS^2 - 0.215TS + 99.865$$

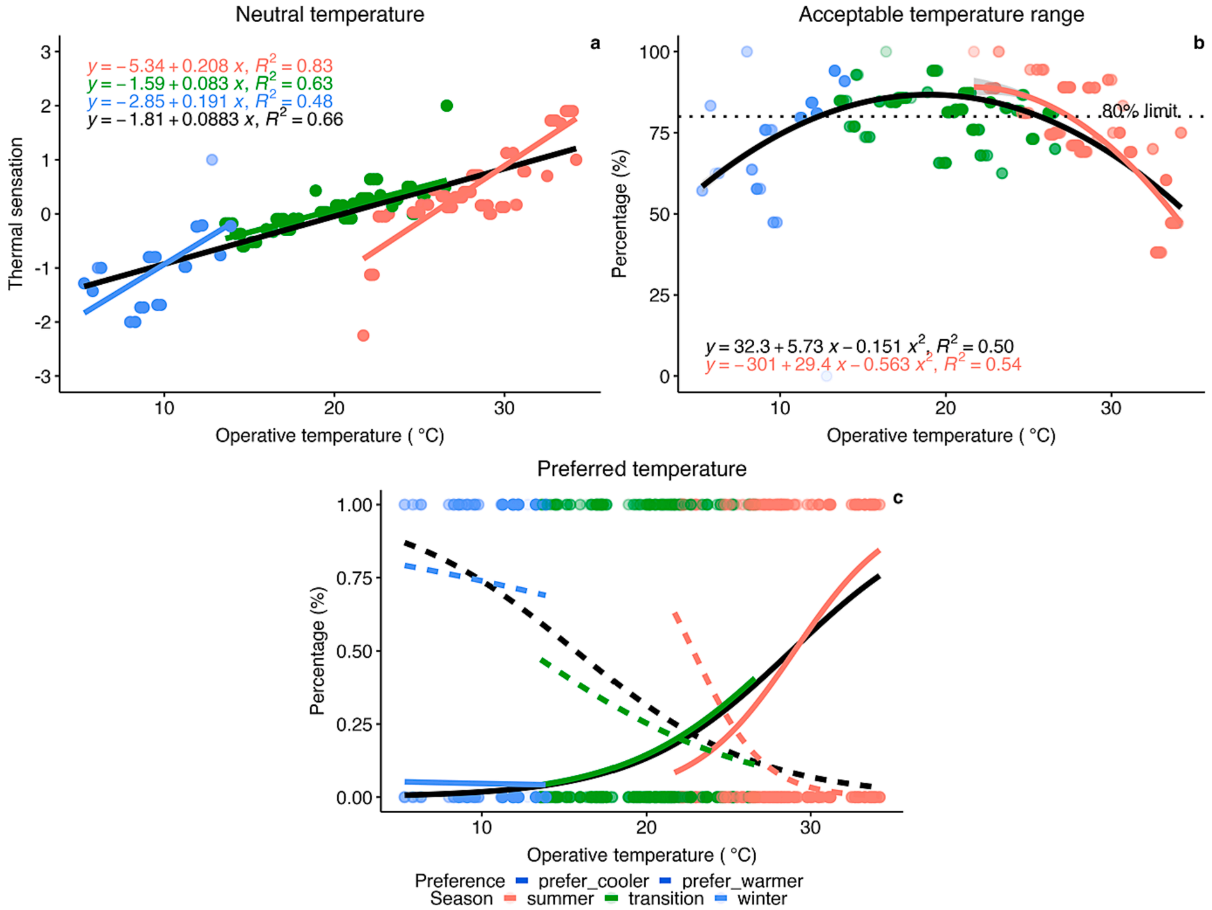

Fig. 4. (a) Neutral temperatures, (b) acceptable temperature ranges and (c) preferred temperatures in summer, transition and winter seasons.

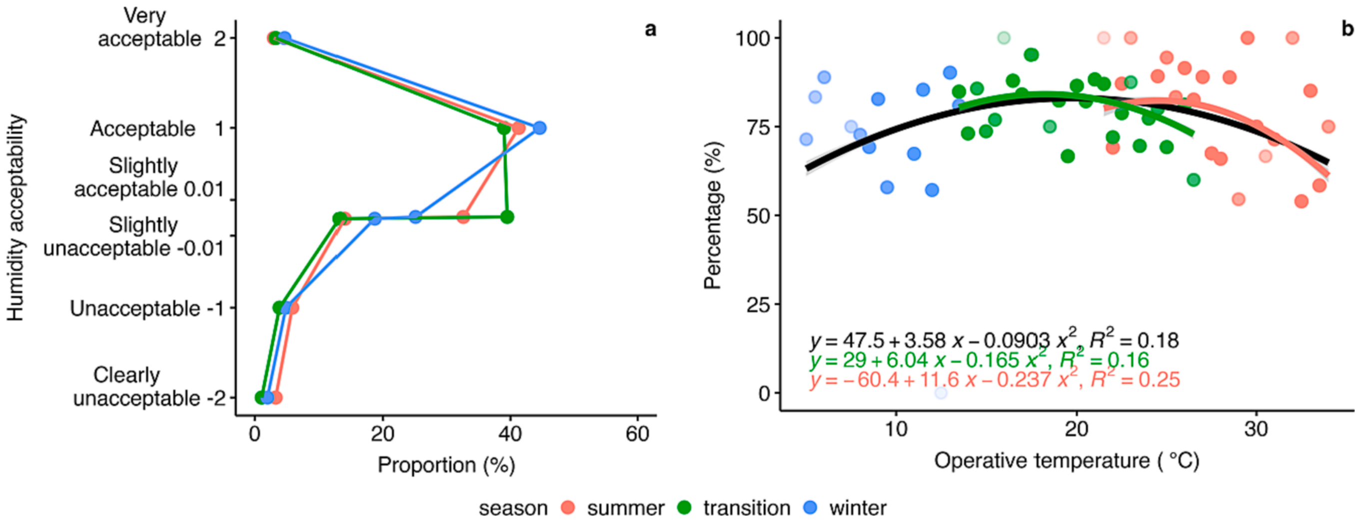

Fig. 5. The (a) frequency distribution of perceived air quality, and (b) the change of acceptable rate of perceived air quality with operative temperature under three seasons.

where RP is the relative performance and TS is the subjective thermal sensation votes.

The estimated relative learning in the transition (99.4 ± 1.1 %) season was significantly higher than those in winter (99.0 ± 1.0 %) and summer (98.6 ± 2.1 %) (Fig. S3).

3.5. Adaptation behavior

Fig. 6a shows the tendency between air velocity and operative temperature. The mean air velocity was very low in transition (0.08 ± 0.1 m/s) and winter (0.03 ± 0.0 m/s), while it was high in summer (0.32 ± 0.3 m/s). Operative temperature did not affect air velocity in winter and transition seasons. There was a positive linear relationship between

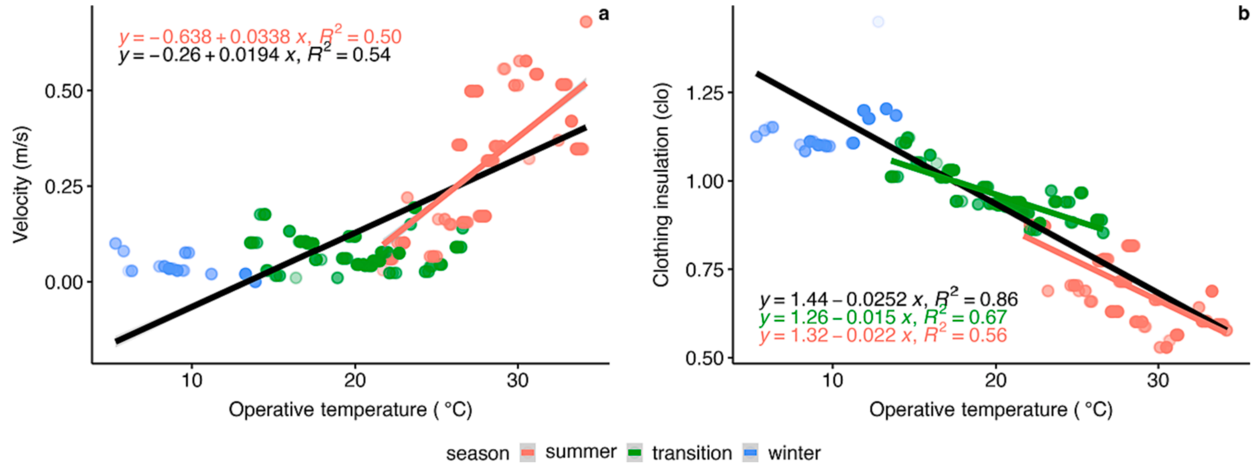

Fig. 6. (a)The change of air velocity with operative temperature under three seasons, and (b) the frequency distribution of clothing insulation under three seasons.

air velocity and operative temperature in summer; 1 °C increase in operative temperature led to 0.03 m/s decrease in summer. Fig. 6b shows the tendency between clothing insulation and operative temperature. The mean clothing insulation was significantly higher in winter (1.2 ± 0.2 clo) than in transition (1.0 ± 0.2 clo) and summer (0.7 ± 0.2 clo). Clothing insulation was almost constant and did not change with operative temperature in winter, while the clothing insulation decreased linearly with operative temperature in transition and summer.

4. Discussion

Existing standards have widely used outdoor temperature to evaluate indoor comfort temperature bands. Based on the adaptive comfort model, ASHRAE Standard 55-2020 [30] adopts running mean outdoor temperature (T_{rm}), and EN 16798 [31] uses prevailing mean outdoor temperature (T_{pm}). In section 2, both T_{rm} and T_{pm} were calculated. Previous studies always compare the adaptive comfort band with Griffiths' neutral temperatures, which are also theoretically estimated. However, this method is less accurate than subjective comfort votes. In this study, the temperatures were compared where subjects were subjectively thermal comfort (TC >= 0). Existing standards only apply the adaptive comfort model in summer and transition seasons and limit the applicability to specific temperature ranges (ASHRAE: 10–33.5 °C; EN16798: 10–30 °C). EN 16798 applies the same temperature limit in winter season as buildings with mechanical cooling systems because there is central heating in Europe. The investigated school is naturally ventilated in all three seasons. Therefore, the applicability of adaptive comfort model was also tentatively explored in winter season. In summer, 77 % of comfort temperatures are located within the adaptive comfort band of ASHRAE Standard 55-2020 [30] (Fig. 7); in transition, however, only 53 % of comfort temperatures are consistent with the comfort band; in winter, no comfort temperatures is complying with the comfort band. the adaptive comfort model (ATC_{school}) was further developed, relating comfort temperatures with outdoor temperatures. The change rate between comfort temperatures and outdoor temperature is sharper than the ASHRAE in all seasons. This means subjects are more sensitive to outdoor temperature than the defined ASHRAE model, which underestimates the effect of outdoor temperature on indoor thermal comfort. In summer and transition, the ATC_{ashrae} underestimated the comfort temperature for high outdoor temperatures and

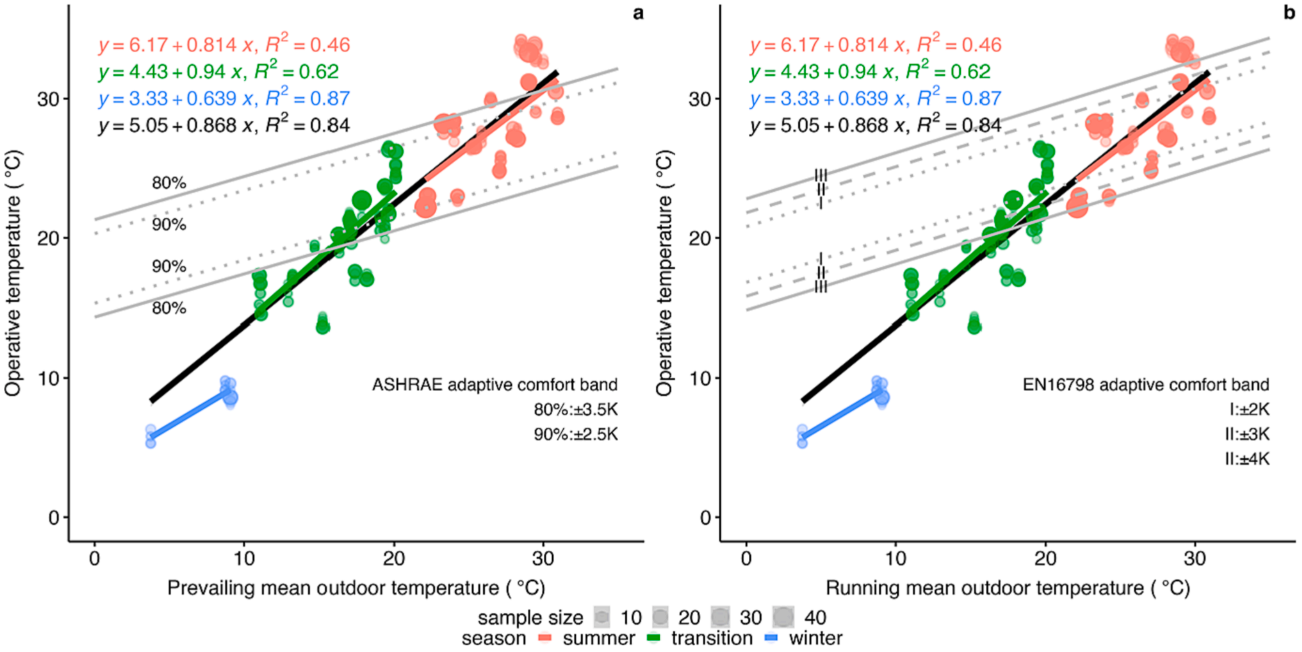

Fig. 7. The comparisons between thermally comfort temperatures with adaptive comfort band in ASHRAE 55 and EN 15251 under three seasons.

overestimated the comfort temperatures for low outdoor temperatures. The differences ranged from −5.5 °C to 2.5 °C in summer and varied from −2.5 °C to 7.5 °C. However, the ATC_{ashrae} consistently overestimated the comfort temperatures in winter, and the differences were higher than 8 °C.

This study demonstrated the behavioral adaptation by the strong relationship between occupants' clothing insulation or velocity and indoor temperature. Existing knowledge always advocates the application of adaptive comfort model in naturally ventilated and mixed-mode buildings. This is consistent with other studies [20,55]. However, the percentage of thermal comfort in both summer (62.3 %) and winter (58.8 %) was extremely low. Such low comfortable percentage was far from the comandary requirement in existing standard [56]. This could also be reflected by the large discrepancy between neutral temperature (i.e., 25.7 °C in summer and 14.9 °C in winter season) and actual mean indoor temperature (28.2 °C in summer and 8.9 °C in winter season). It was inferred that people cannot maintain comfort through adaptation because the indoor temperature exceeded the upper comfort limit in summer and the lower comfort limit in winter.

This study found an "inverted-U" relationship between the acceptable rate of perceived air quality and operative temperature. Improved perceived air quality at lower air temperature was supposed due to the cooling effect of air on the mucous membranes in the upper respiratory tract [57,58]. The inhaled air could cool the mucosa when lower than the mucosal temperature of 30 °C [59,60]. This finding was also observed in previous studies [2,61] when the temperature was higher than about 20 °C. Perceived air quality was correlated with ambient air enthalpy and was related to the evaporative and convective cooling of the mucous membranes in the upper respiratory tract (revise). It was further found the perceived air quality decreased with air temperature when air temperature was lower than 20 °C. The stuffy nose (60.4 %) was more prevalent in winter than in transition and summer seasons. As indicated above, the average monthly indoor temperature in winter was 8.9 °C, which was significantly lower than those in transition (18.9 °C) and winter (28.2 °C). It was inferred that the extremely cold air in winter induced rhinitis, which is a common complaint of individuals with chronic allergic or nonallergic rhinitis and those without chronic nasal disease [62]. Then the rhinitis would decrease the subjects' acceptable rate with perceived air quality.

This study indicated that the neutral temperature of students was 19.2 °C during the transition, 25.7 °C in summer, and 14.9 °C in winter. Students preferred higher temperature in transition and lower temperature in summer. Such findings in summer were consistent with previous studies [21,49] with adults. Table 4 presents a summary of previous thermal comfort field studies conducted in primary and secondary schools in China. The summary range was limited to primary and secondary schools due to similarities in subjects' age, occupancy density, and classroom conditions. Despite variations in ventilation type, climate, and geography among the studies, it was observed that neutral temperatures exhibited seasonal fluctuations. Specifically, the neutral temperature was higher in summer compared to winter, which aligns with the findings of Liang et al. [63]. Moreover, our study revealed that in the summer, the neutral temperature in Hunan was 3.6 °C lower than that of Taiwan [63]; in the winter, it was 1 °C higher than that in Shanxi [64] and 7.5 °C lower than that in Taiwan [63]; in the transition, the neutral temperature in Hunan was 4–5 °C lower than that in Taiwan [17]. Notably, the average monthly temperature in Hunan during summer (27.4 °C) was lower than the corresponding values in Taiwan (29.8 °C). It was worth mentioning that Shanxi [64] and Liaoning [65] regions had a temperate climate, with the lowest average monthly outdoor temperatures observed in summer and winter. These results further supported the notion that neutral temperatures were influenced by climate zones [49,66]. This indicated that students tend to have higher neutral temperatures in warmer climates. However, an exception was observed in the study conducted by Ma et al. [65], where central heating was available, resulting in indoor temperatures ranging from 17.06 to 24.29 °C. In this case, students may have experienced a relatively warmer long-term thermal history indoors. Previous studies [20,67] have indicated that subjects tend to have higher neutral temperatures when exposed to warmer indoor thermal conditions, which is in line with the findings of Ma et al. [65] and Jing et al. [64].

This study investigated objective thermal environment, subjective thermal comfort, and health at the whole year level. The findings of the distribution of thermal perception and thermal indicators can provide fundamental knowledge for building design or renovation in the countryside area. Meanwhile, the quantitative assessment of estimated learning performance can help educators thoroughly understand the relationship between the thermal environment and learning performance. This study tells engineers what kind of thermal comfort models they can use and how much they should adopt them. However, this study was conducted with only students in secondary school. Usually, there is a larger proportion of students in kindergarten schools in the countryside area. Meanwhile, other indoor environmental domains are also important, except thermal comfort, such as lighting and acoustic environment. Other indoor environmental parameters were not explored, which should be further measured and investigated.

5. Conclusions

This study explored students' thermal comfort, perceived air quality and estimated performance in countryside secondary buildings in hot summer and cold winter zone, China. The following conclusions can be drawn:

(1) The thermally uncomfortable percentage was the highest (41.2 %) in winter, 3.5 % higher than that in summer and 15.5 % higher than that in transition. The existing indoor thermal environment was far from the comandary thermal comfort requirement in the existing standard.

(2) Students had the lowest neutral temperature in winter (14.9 °C), 4.3 °C lower than that in transition and 10.8 °C than that in summer. Students preferred "warmer" temperature (3.3 °C higher than neutral temperature) in transition and "cooler" temperature (0.3 °C lower than neutral temperature) in summer.

Table 4
Summary of thermal comfort field studies conducted in primary and secondary schools in China.

Study	Location	Climate	Season	School	Ventilation type	Sample size	Neutral temperature (°C)
Hwang et. al (2009) [17]	Taiwan	Tropical	Autumn	Primary	NV	944	23–24
Liang et. al (2012) [63]	Taiwan	Tropical	Whole year	Primary and secondary	NV	1614	22.4 (Jan)29.28 (Sep)
Jing et. al (2020) [64]	Shanxi	Temperate	Winter	Primary and secondary	NV	345	13.9
Ma et. al (2020) [65]	Liaoning	Temperate	Winter	Primary	Central heating	835	18.5
This Study	Hunan	Subtropical	Whole year	Secondary	NV	Transition: 903 Summer: 1018 Winter: 419	Transition: 19.2 Summer: 25.7 Winter: 14.9

* NV: Naturally ventilated.

(3) The adaptive thermal comfort model [68] that forms the basis of ASHRAE Standard 55-2020 [30] underestimated the thermal adaptability of school students in this study in naturally ventilated secondary school buildings in the Chinese countryside during summer, transition, and winter seasons. That is, the current sample of school children were more thermally adaptable than the model and standard suggest.
(4) There is an inverted U relationship between perceived air quality and indoor temperature. Estimated performance was the highest in transition season, 0.4 % higher than that in winter and 0.8 % higher than that in summer.

CRediT authorship contribution statement

Zhibin Wu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Andreas Wagner:** Writing – review & editing, Supervision.

Declaration of competing interest

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.113891.

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