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Thermal comfort and adaptive behaviors in office buildings: A pilot study in Turpan (China) during summer

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ABSTRACT

Nowadays, evaporatively cooled office buildings commonly observed in dry hot areas in summer of China. However, few dedicated studies to record the local residents' thermal comfort and adaptability in these buildings. The contribution of adaptive comfort theory on thermal perception still remains unclear for optimizing office building design parameters. Hence, to deeper probe the adaptive thermal comfort of the related indoor environment, a field study of office buildings during summer considering evaporative cooling air conditioned (ECA) and naturally ventilated (NV) mode was conducted in Turpan, China. Based on 931 valid datasets collected from questionnaires, we found that the neutral temperature (T_n) of 28.4 °C in ECA group, 0.6 °C lower than NV group (29.0 °C). A lower air temperature (T_a) and higher humidity (RH)/air-velocity (V_a) were expected in two modes, and V_a has a stronger influence than RH on mean thermal sensation votes (MTSV). Meanwhile, occupants can adapt to current indoor environment through physiological, psychological and behavioral adjustments, while the clothing regulation had limited effect on MTSV unless the outdoor temperature exceeds 38 °C. Whether in ECA or NV mode, the predicted mean votes (PMV) model overestimated actual thermal sensation when operative temperature (T_{op}) beyond 28 °C. Adaptive models were also proved varied from that in current standards, which indicated that they were not suitable for evaluating the studied buildings in Turpan. Above findings could suggest us a better understanding of the occupants' thermal adaptability, thereby providing the reference of design parameters revision and passive strategies for local newly/renovated buildings.

1. Introduction

1.1. Motivation

Reformation of building technology inevitably ignored the coupling relationships among energy consumption, thermal comfort and

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environmental protection. To be specific, Heating, Ventilation and Air Conditioning (HVAC) systems have been largely adopted to guarantee a more comfortable indoor environment since last century. However, it accounted for more than 20 % of the building energy utilization throughout the world [1]. Moreover, based on the refrigerants of chlorofluorocarbons (CFCs), exceeding 40 % of the greenhouse gases emission were produced by building sector that posing a great threat to the global environment [2,3]. Although a higher temperature set point was deemed as an appropriate strategy to decrease energy demand during cooling period [4], it might sacrifice comfort state to some extent. Therefore, under the background of China's "Double Carbon Goals", how to ensure the thermal comfort of the occupants on the premise of energy saving and environmental protection is particularly significant.

The operation mechanism of evaporative cooling air conditioned (ECA) buildings is based on the distinction between wet and dry bulb air temperature. It through the process of liquid-vapor conversion by water, thereby resulting the temperature reduction in the system [5,6]. Since the cold source (water) is not only affordable and accessible, but also with none of the CFCs utilization, which eliminate the human long-term concern for ozone layer destruction [7]. According to relevant statistics, ECA system has a lower cost of cooling equipment with an initial investment of approximately 50 % comparing to conventional HVAC, as well as promoting the energy saving rate achieve to 70%–80 % [8,9]. However, unlike the AC mode, buildings driven by evaporative cooling systems requires more flexibility in the use of windows and doors. Proper naturally ventilation can better alleviate the discomfort caused by partial vapor pressure on body skin. Based on above advantages, this system has attracted more and more scholars' attention. Meanwhile, it has been widely used in office buildings to improve indoor thermal comfort during the cooling season. Additionally, with the rapid economic development, China, Kazakhstan and other "Belt and Road" (B & R) developing countries are constructing office buildings at an alarming rate. Therefore, some of those cities with typical summer climatic characteristics and largely used ECAs required us more attention seriously.

Turpan is located in Xinjiang Uygur Autonomous Region, the northwest of China. It is an intermountain basin surrounded by Kumtag Desert (between E 87.2–91.5° and N 41.2–43.8°). According to the climate classification by Koppen-Geiger and Chinese code, this region affiliated to cold desert (Bwk) and cold zone (CZ), respectively. It commonly described as dry hot with low humidity in summer and dry cold in winter [10,11]. The average outdoor air temperature during cooling period (mid-May to mid-September) is 32.8 °C with the mean humidity of 23.2 %. In particular, the instantaneous daily maximum air temperature could even reach 47.5 °C [12]. Moreover, the average annual precipitation is only 16.6 mm and evaporation reaches more than 3000 mm (mainly during summer). Low amounts of moisture in atmosphere may result human thermal discomfort and even dehydration. As can be seen, such a unique environment of Turpan is rich in "dry air energy" (air with the capacity to hold more steam). It could efficiently drive the operation of evaporative cooling systems, thereby deeming as a typical and suitable area for current research.

Thermal comfort plays a significant role in building indoor environment. It is defined as the state of mind in which occupants satisfied with surrounding physical environment according to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) [13]. People working efficiency will also be increased by 15 % in comfortable status [14]. Since the formation mechanism of thermal comfort is the coupling result of behavior, psychological and physiological adaption under the long-term experience [15], both external environment and internal microclimate make a difference on human thermal adaptability. As afore-mentioned, the actual indoor condition and occupant responses of ECA buildings may differ from naturally ventilated (NV) mode. Therefore, it is imperative to explore the discriminative features between ECA and NV buildings for creating a desirable indoor thermal environment.

1.2. Literature review

During more than 50 years procession, the studies for thermal comfort can be divided into two stages. One is Fanger's predicted mean vote - predicted percentage of dissatisfied (PMV-PPD) model which based on the theory of steady-state heat balance algorithm [16]. Since conventional AC mode has the ability to create a relatively stable indoor environment and less affected by climate change, it regarded as an ideal assessment condition by adopting PMV model [17,18]. However, some extreme climate condition may cause deviation from thermal neutral point in ECA and NV mode. Meanwhile, the body will unconsciously reduce the influence of discomfort factors from heat acclimatization to thermal adaption [19]. As a result, the other theory namely adaptive comfort model, is carried out under that give-take procession of human-environment and considered as a more reasonable approach to dynamic circumstance [20].

M.A. Humphreys [21,22] firstly proposed the concept of adaptive approach and explained that human actual comfort range exceeding the predicted results by PMV model. De Dear et al. [23] established the adaptive model for AC and NV buildings based on the 21000 sample data in field studies. Through the field investigation of SCATs program, Nicol et al. [24] obtained the control algorithm of the European thermal adaptive model. Furthermore, in Asia [25–27], Australia [28,29] and America [30,31], numerous scholars pointed out that human body is not a passive receiver of the surrounding environment. A variety of adaptability will have a significant impact on thermal comfort, which jointly promote the development of the adaptive theory. Moreover, on the basis of worldwide database, this method had been adopted in many international and local codes such as ASHRAE 55 [13], EN 16798-1 [32] and GB/T 50785 [33], to evaluate the specific operation mode under the complex environment.

China is a vast country with various climatic conditions, life styles and economic levels are both resulting the great differences in occupants' thermal adaptability [19]. For severe cold zone (SCZ), T. Shao et al. [34] conducted field survey in three different latitudes of northeast China to explore the rural residents' adaptive comfort statuses. Analogous study by Z. Wang et al. [35] was presented in Harbin that focus on university classrooms and offices thermal adaptability. In cold zone (CZ), J. Jiang et al. [36] investigated adaptive thermal comfort in controlled/uncontrolled primary and secondary classrooms at the northwest of China during winter, and pointed out the upper limit of neutral temperature was 3 °C lower than the recommend minimum value of current standard. B. Cao et al. [37] surveyed air conditioned (AC) university indoor environment during summer and winter, the results showed that people with a higher tolerance for different seasons through the long-term thermal experience. In hot summer and cold winter zone (HSCW), Z. Wu et al. [38–40] conducted adaptive comfort pilot studies in naturally ventilated (NV)/split air-conditioned (SAC) dormitories and SAC offices in Changsha. They proposed each working condition's acceptable temperature interval based on the investigation results. R. Ming et al. [41] performed thermal adaptive behavior for mixed mode (MM) offices during 5 time nodes in Chongqing, and indicated the neutral temperature mainly distributed between 23.92 °C and 26.23 °C. In hot summer and warm winter zone (HSWW), Y. Zhang et al. [42] and C. Fu et al. [43] by using the field investigation for NV and AC office buildings in Guangzhou, reported that PMV model always significantly overestimate the authentic thermal sensation due to a wider range of adaptions by subjects. For mild zone (MZ), D. Lai et al. [44] observed actual thermal sensation vote (TSV) of urban residential buildings in Kunming could be kept at a relatively stable level across the whole year comparing to other climates. Approximately 61.71 % of the occupants feel neutral due to the stable outdoor environment. As shown above, only by collecting sufficient data from the field investigation can we conduct in-depth quantitative research of occupants' thermal adaptability.

Under such motivation, multiple studies such as in Asia, America and Australia have been further carried out to probe the adaptive thermal comfort based on field investigation [45–56]. The representative studies which including the research methods, paths and techniques adopted are summarized in Table 1. Although these results have laid a good theoretical foundation for current study, there are still some problems: a) In the context of global climate change and individual differences, occupants' requirements on indoor thermal environment of offices have transferred. b) Due to the extensive usage of ECA systems, there are hardly dedicated studies of adaptive comfort conducted specifically in ECA office buildings of China. c) Within no related research in the area of China's dry hot climate, the occupants' actual thermal acceptability and adaptive behaviors in ECA offices cannot be estimated accurately, especially compared to local naturally ventilated buildings. Hence in current research, we selected the ECA and NV office buildings in Turpan to conduct a pilot study during summer from June to September 2021. For one thing, this is helpful to solve the problem of lower office comfort level from a quantitative point of view and put forward corresponding design strategies. For another, it can also enrich the research database of indoor thermal environment of office buildings in China.

1.3. *Objective of this study*

With issues mentioned above, the main objectives of this study were listed as follows.

(1) To survey the actual thermal environment and subjective responses of ECA and NV office buildings under dry hot climate. Meanwhile, to determine the coupling relationships of indoor environmental parameters for each mode.
(2) To understand the differences of thermal behavior adjustments between ECA and NV office buildings.
(3) To establish adaptive models for occupants and verify the applicability of the thermal evaluation models in current standards for such buildings.

2. Methodology

The literature review has suggested a clear need for a study that answers the research questions raised in section 1.1. Hence, we propose the methods adopted to help answer them. In this part, the characteristics of investigated buildings, participants selective

Table 1
Summary of representative studies in the field of indoor thermal environment of offices.

Scholars	Location	Season	Mode	Subjective questionaries	Measured physical parameters			Thermal comfort evaluation model		
					T_a	[a] RH	V_a	PMV	TSV	[b] ACM
Wu et al. [45]	Guangzhou	Summer, autumn, winter	[c] AC, [d] NV	✓	✓	✓	×	✓	✓	✓
Singh et al. [46]	Tezpur, Shillong	Autumn	NV	✓	✓	✓	✓	×	✓	✓
Madhavi et al. [47]	Doha	Summer	AC	✓	✓	✓	✓	✓	✓	✓
Peng et al. [48]	Singapore	Summer	[e] MM	✓	✓	✓	✓	✓	✓	✓
Zheng et al. [49]	Guangzhou	Autumn	AC	✓	✓	✓	×	×	✓	×
Mustapa et al. [50]	Fukuoka	Summer	[f] FR, AC	✓	✓	✓	✓	×	✓	×
García et al. [51]	Bogotá	Summer	NV	✓	✓	✓	✓	✓	✓	✓
Kwon et al. [52]	Seoul	Summer, winter	AC	✓	✓	✓	×	✓	×	×
Madhavi et al. [53]	Chennai, Hyderabad	All season	MM, AC, NV	✓	✓	✓	✓	×	✓	×
Khoshbakht et al. [54]	Brisbane, Gold Coast	Summer, autumn, winter	MM	✓	✓	✓	✓	×	✓	✓
Vecchi et al. [55]	Florianópolis	All season	AC, NV	✓	✓	✓	✓	×	✓	×
Liu et al. [56]	Guangzhou	Autumn	AC	✓	✓	✓	×	×	×	×
Current research	Turpan	Summer	[g] ECA, NV	✓	✓	✓	✓	✓	✓	✓

Note: [a] relative humidity; [b] adaptive comfort model; [c] air conditioned; [d] naturally ventilation; [e] mixed mode; [f] free running; [g] evaporative cooling air conditioned.

principle, and methods of subjective and objective data collection were described as below.

2.1. *Description of surveyed buildings*

The investigation study was conducted in 3 ECA and 4 NV office buildings which were all located within 8 km away from Turpan center area. For ECA buildings, nearly all tested rooms were equipped with direct evaporative cooling system and operable windows except for two spaces adopting indirect evaporative cooling system. Occupants could by transforming the set point temperature of air conditioners or open windows to achieve indoor thermal comfort. For NV buildings, none of the mechanical cooling equipment was installed except ceiling fan. Subjects usually adjusted thermal status through changing activity levels, clothing, as well as open windows to enhance the indoor air circulation. Fig. 1 presented the main form of operable windows and evaporative cooling air conditioners in surveyed buildings.

In addition, all surveyed buildings were built at the beginning of 21st century with the construction of steel-framed concrete. Due to the similar constructing order of each material layer, the calculated heat transfer coefficient (U-value) of the envelope were basically identical. Among them, exterior walls were composed of aerated concrete panels with U_{Wall} values approximately by 0.4–0.6 W/(m^2.K). Floors and roofs were made of concrete slabs with U_{Floor} and U_{Roof} of 0.3–0.4 W/(m^2.K) and 0.3–0.5 W/(m^2.K), respectively. Fenestration were adopt single clear or double glazing with a thickness of 2–5 mm vacuum layer, possessing the U_{Glaze} and solar heat gain coefficient (SHGC) around 1.8–2.1 W/(m^2.K) and 0.4, respectively. The detailed information for investigated buildings are shown in Table 2.

2.2. *Participants*

Totally 986 occupants were invited to participate the investigation. It is worthwhile mentioning that the background information revealed 55 of them were non-local residents. Nevertheless, the preconditions for selective adaptation required a long-term thermal experience in study site, and the results of that part would be in an error to some extent. Hence, we decided to reject that 55 samples for further analysis. In this way, 931 valid datasets were received that including 446 for ECA group and 485 for NV group. Meanwhile, all selected subjects were guests and staffs who have been lived in Turpan for over one year and have adapted to local climatic conditions. Table 3 summarized the basic body indexes of the surveyed occupants.

2.3. *Questionnaires*

The subjective questionnaires were distributed to occupants from 12 June to September 16, 2021, during the specific time started at 10:00 a.m. to 20:00 p.m. for surveyed days. The content was designed in simple and colloquial language which mainly including three parts as below. Part-1 collected fundamental data such as gender, age, height, weight, clothing and activity levels etc. The clothing insulation (clo) and metabolic rate (met) were estimated according to the recommended values in ASHRAE 55 [13] based on the survey results (Table 3). Part-2 regarded the occupants' thermal cognitive status that including thermal/humidity/air-velocity sensation vote, thermal/humidity/air-velocity preference vote, thermal/humidity/air-velocity acceptability vote and overall comfort vote. From which 7-point scale (−3 to 3) was adopted to evaluate sensation and preference vote, and 5-point scale (−2 to 2) was for acceptability and overall comfort vote [13,57], as shown in Table 4. Part-3 determined behavior regulation modes to avoid thermal discomfort, containing physical adjustments and adaptive actions. One thing worth noting that, since the personal information is involved, we have explained to the subjects that the open data is only for anonymous statistical analysis. Meanwhile, the informed consent form was signed by all participants before the questionnaire.

2.4. *Environmental measurements*

Physical environmental parameters were measured by calibrated instruments simultaneously with the subjective responses. The sampling time of equipment was approximately 10 min after it became stable. During the investigation, try the best to reduce errors caused by indoor heat disturbance (such as douse the lights and reduce personnel activities etc.). For external parameters, outdoor dry

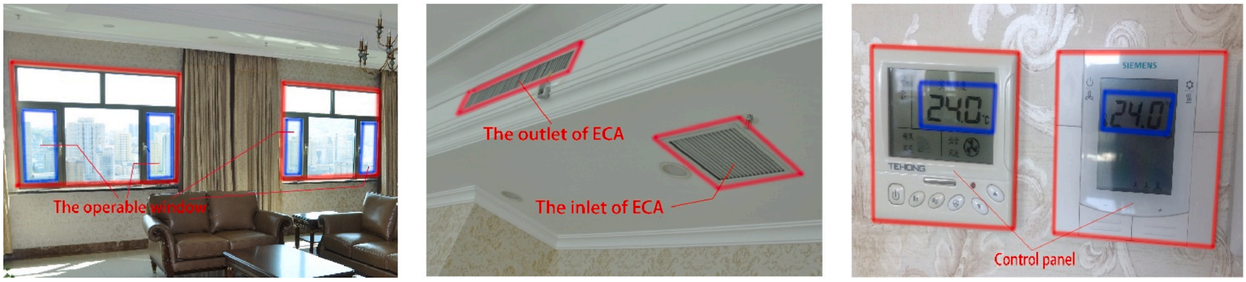


Fig. 1. The main form of operable windows and evaporative cooling air conditioners.

Table 2
Detailed information for investigated buildings.

Mode	Building code	Envelope parameter properties					
		U-floor [W/(m^2.K)]	U-roof [W/(m^2.K)]	U-wall [W/(m^2.K)]	U-glaze [W/(m^2.K)]	[c] WWR	[d] SHGC
[a] ECA	ZFLQ-01	0.4	0.38	0.5	1.8	0.4	0.4
	ZFLQ-02	0.35	0.4	0.5	1.8	0.4	0.4
	ZFLQ-03	0.35	0.46	0.45	1.8	0.4	0.4
[b] NV	ZRTF-01	0.4	0.5	0.55	1.8	0.3	0.4
	ZRTF-02	0.35	0.35	0.6	2.1	0.3	0.4
	ZRTF-03	0.4	0.45	0.45	2.0	0.4	0.4
	ZRTF-04	0.4	0.45	0.52	2.1	0.4	0.4

Note: [a] evaporative cooling air conditioned; [b] naturally ventilated; [c] window-to-wall ratio; [d] solar heat gain coefficient.

Table 3
Background information of investigated subjects.

Type	Gender	Number	Age	Height (cm)	Weight (kg)	[a] CI (clo)	[b] BSA (m^2)	[c] BMI (kg/m^2)	[d] MR (met)
ECA	Male	328	32.2 ± 4.8[e]	174.6 ± 6.6	70.2 ± 9.2	0.30 ± 0.12	1.73 ± 0.16	22.2 ± 2.5	1.1 ± 0.10
	Female	118	28.8 ± 3.6	162.1 ± 5.6	49.8 ± 7.6	0.35 ± 0.10	1.52 ± 0.12	18.8 ± 1.8	1.1 ± 0.20
	Total	446	31.5 ± 4.5	170.5 ± 5.4	63.8 ± 10.2	0.32 ± 0.11	1.68 ± 0.13	20.9 ± 2.3	1.1 ± 0.12
NV	Male	332	29.5 ± 3.9	173.4 ± 6.3	68.5 ± 8.8	0.28 ± 0.07	1.70 ± 0.15	21.5 ± 2.8	1.1 ± 0.15
	Female	153	31.2 ± 2.8	163.5 ± 5.8	51.2 ± 6.5	0.30 ± 0.05	1.54 ± 0.10	19.4 ± 2.0	1.1 ± 0.20
	Total	485	30.0 ± 3.5	169.6 ± 7.8	62.5 ± 9.3	0.28 ± 0.06	1.65 ± 0.15	20.6 ± 2.6	1.1 ± 0.14

Note: [a] clothing insulation; [b] body superficial area; [c] body mass index; [d] metabolic rate; [e] standard deviation.

Table 4
Evaluation indicators and scales of the thermal comfort study.

Indicators		Scales						
		(-3)	(-2)	(-1)	(0)	(+1)	(+2)	(+3)
[a] T	[d] TSV	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
	[e] TPV	Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	Warmer	Much warmer
	[f] TAV	–	Clearly unacceptable	Unacceptable	Slightly acceptable	Acceptable	Clearly acceptable	–
[b] RH	[g] HSV	Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid
	[h] HPV	Much dryer	Dryer	Slightly dryer	No change	Slightly wetter	Wetter	Much wetter
	[i] HAV	–	Clearly unacceptable	Unacceptable	Slightly acceptable	Acceptable	Clearly acceptable	–
[c] AV	[j] ASV	Very low	Low	Slightly low	Neutral	Slightly high	High	Very high
	[k] APV	Much lower	Lower	Slightly lower	No change	Slightly higher	Higher	Much higher
	[l] AAV	–	Clearly unacceptable	Unacceptable	Slightly acceptable	Acceptable	Clearly acceptable	–
Overall	[m] OCV	–	Clearly uncomfortable	Uncomfortable	Slightly comfortable	Comfortable	Clearly comfortable	–

Note: [a] air temperature; [b] relative humidity; [c] air velocity; [d/g/j] thermal/humidity/air-velocity sensation vote; [e/h/k] thermal/humidity/air-velocity preference vote; [f/i/l] thermal/humidity/air-velocity acceptability vote; [m] overall comfort vote.

bulb air temperature ($T_{a\text{-}out}$), relative humidity (RH_{out}) and air velocity ($V_{a\text{-}out}$) were tested by local meteorological station at the shading areas. Solar radiation intensity (SRI) was received by 8-channel data-logger (DaqPRO-5300) that using a circular probe with a diameter of 10 cm attached to the building's façade. For internal indicators, indoor dry bulb air temperature ($T_{a\text{-}in}$) and relative humidity (RH_{in}) were measured by AZ-8829 thermometer recorder at the vertical height of 0.6 m (sitting position) and 1.7 m (standing position) above the ground. Indoor air velocity ($V_{a\text{-}in}$) was determined by Testo 425 anemometer at the same place with $T_{a\text{-}in}$ and RH_{in}. And the globe temperature ($T_{g\text{-}in}$) was recorded by adopting a 45 mm black sphere at the height of 0.6 m with its probe installed in the center of it (WBGT-2010). The detail information of instruments were presented in Table 5, all collected data were proposed for further

Table 5
Detail description of measuring instruments and variables.

Instrument	Variables	Range	Accuracy	Reaction time
Thermometer AZ-8829	Dry bulb temperature	−40 ~ 85 °C	±0.3 °C	60s
	Relative humidity	0 ~ 99 %	±5 %	60s
Anemometer Testo 425	Air velocity	0 ~ 20 m/s	±0.03 m/s	≤3s
Thermometer WBGT-2010	Globe temperature	0 ~ 80 °C	±0.3 °C	≤5min
Pyranometer DaqPRO-5300	Solar radiation intensity	0 ~ 2000W/m^2	±3 %	≤5s

analysis.

3. Results

3.1. Objective thermal environments

3.1.1. Distribution of outdoor environment

In Fig. 2, it can be observed that the outdoor air temperature during surveyed period ranged from 24.2 °C to 41.4 °C with the daily mean values exceeding 30 °C for most of the time. The peak point approximately occurred from 21 July to 25 July. Meanwhile, due to the intense short-wave solar radiation and accompanied by a large amount of evaporation, the daily average relative humidity was extremely low that oscillated between 16.3 % and 27.5 %.

M.A. Humphreys [21] firstly pointed out that the outdoor temperature is a significant index to predict indoor comfort status and established thermal adaptive model. Allowed for time variability in comfort conditions, the prevailing mean outdoor air temperature (T_{pma}) was adopted in this study instead of using measured data directly. This parameter takes the human thermal history (within 7 days) into account. The specific algorithm is presented as follows Eq. (1):

$$T_{pma\ (today)} = (1 - \alpha)\left(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \ldots + \alpha^6 T_{od-7}\right) \tag{1}$$

where $T_{pma\ (today)}$ is prevailing mean outdoor air temperature on today (°C); $T_{od\text{-}1}$ is mean daily outdoor air temperature on yesterday(°C); $T_{od\text{-}2}$ represents mean daily outdoor air temperature on the day before yesterday, and so on. αis a constant varying from 0 to 1, which reflects the response degree of continuous mean change for outdoor temperature and assigns the maximum weight to the most similar day (comparing to today). The recommended values ofαin ASHRAE-55 varied from 0.6 to 0.9, and a lower value of 0.6 may be a more reasonable choice for dry hot climates [13]. Therefore, T_{pma} can be calculated during the investigation period that ranged from 27.4 °C to 39.6 °C, with the mean value and standard deviation of 34.4 ± 2.0 °C.

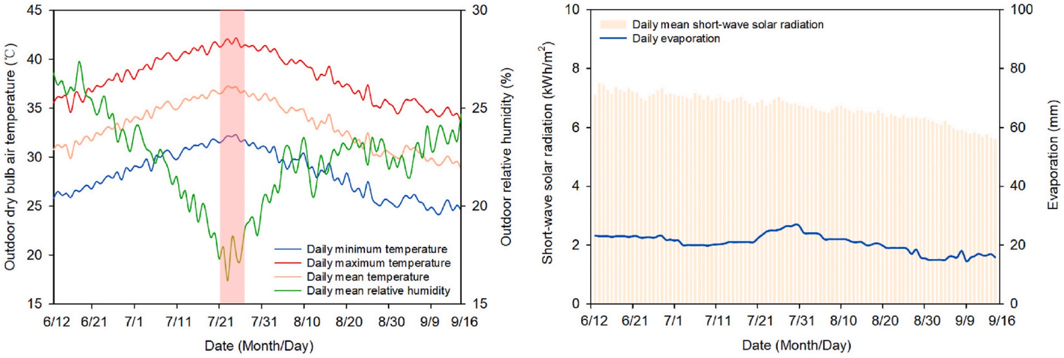
3.1.2. Distribution of indoor environment

Table 6 summarized the distribution of indoor measured data. The mean air temperature with standard deviation in ECA and NV buildings were 29.2 ± 1.8 °C and 32.4 ± 1.3 °C, respectively. The average relative humidity in ECA buildings (63.6 ± 10.8 %) was double higher than that in NV buildings (32.8 ± 11.2 %). It mainly due to the former was accompanied by humidifying effect in cooling process, while the latter was more affected by outdoor environment. The mean air velocity in ECA and NV buildings were 0.15 ± 0.22 m/s and 0.29 ± 0.28 m/s, respectively. About 70 % of the time for both modes were under 0.2 m/s that lower than the upper limit specified in ASHRAE-55 [13]. One thing should be pointed out that the statistic results of air velocity for different vertical heights (0.6 m and 1.7 m) were nearly identical except for NV mode. The reason is occupants may use ceiling fans to enhance indoor air flow that resulting the higher place with larger values.

For searching a more precisely evaluation indicator, the operative temperature (T_{op}) was selected in this research for further analysis because it takes both air temperature (T_a) and mean radiant temperature (T_{mrt}) into consideration. Meanwhile, M.A. Humphreys [58] also confirmed that the actual thermal sensation (TSV) was perfectly correlated with T_o. Thus, firstly we calculated the T_{mrt} through T_a, T_g and V_a. Then can obtained T_{op} via T_a and T_{mrt} of 29.6 ± 1.8 °C for ECA buildings and 32.6 ± 1.5 °C for NV buildings, shown in Table 6. The overall process is listed as Eqs. (2) and (3) [59]:

$$T_{mrt} = [(T_g + 273)^4 + 2.5 \cdot 10^8 \cdot V_a^{0.6} \cdot (T_g - T_a)]^{0.25} - 273 \tag{2}$$

$$T_{op} = (T_a + T_{mrt})/2 \tag{3}$$



(a) (b)

Fig. 2. Outdoor environmental parameters during investigation period: (a) dry bulb air temperature and relative humidity; (b) short-wave solar radiation and evaporation.

Table 6
Indoor environmental parameters during investigation period.

Type	Category	Variables					
		[a] T_a (°C)	[b] RH (%)	[c] V_a (m/s)	[d] T_g (°C)	[e] T_{mrt} (°C)	[f] T_o (°C)
ECA	Mean	29.2 ± 1.8 [g]	63.6 ± 10.8	0.15 ± 0.22	29.6 ± 1.8	29.6 ± 1.9	29.6 ± 1.8
	0.6 m	29.1 ± 1.8	62.5 ± 10.6	0.12 ± 0.21			
	1.7 m	29.4 ± 2.0	65.2 ± 11.2	0.16 ± 0.25			
NV	Mean	32.4 ± 1.3	32.8 ± 11.2	0.29 ± 0.28	32.5 ± 1.5	32.5 ± 1.4	32.6 ± 1.5
	0.6 m	32.4 ± 1.4	33.2 ± 11.8	0.18 ± 0.32			
	1.7 m	32.6 ± 1.0	30.7 ± 11.5	0.34 ± 0.21			

Note: [a] air temperature; [b] relative humidity; [c] air velocity; [d] globe temperature; [e] mean radiant temperature; [f] operative temperature; [g] standard deviation.

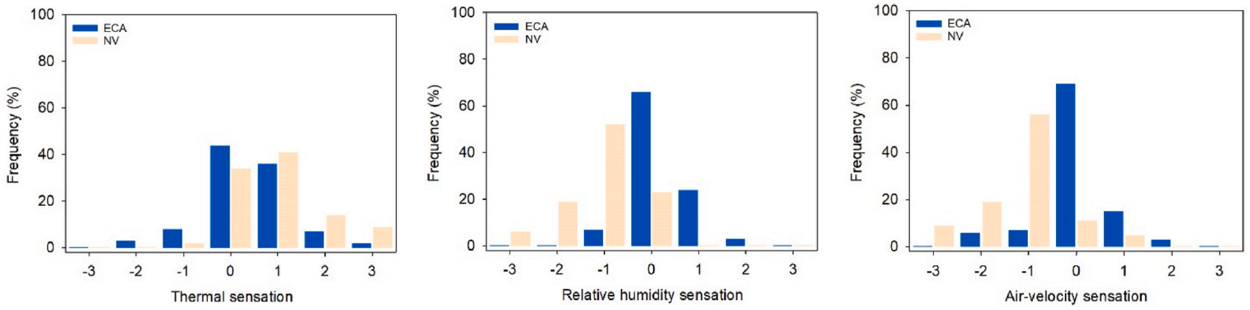
where T_{mrt} is mean radiant temperature (°C); T_a is indoor air temperature (°C); T_g is black globe temperature (°C); T_{op} is operative temperature (°C) and V_a is air velocity (m/s).

3.2. Subjective thermal responses

3.2.1. Sensation, preference and acceptability

The frequency of sensation votes for indoor air temperature, relative humidity and air-velocity were counted on ASHRAE 7-point scale (Table 4), as presented in Fig. 3. For ECA buildings, approximately 88 % of the occupants voted in the range of ±1 for thermal sensation scales. 97 % and 91 % of the total responses lied between ±1 interval for relative humidity and air-velocity sensation scales, respectively. As for NV conditions, about 63 % of the votes between 1 and 3 for thermal sensation scale. Meanwhile, the proportion of humidity and air-velocity sensation in −1 ~ -3 range were approximately of 77 % and 84 %, respectively. The phenomenon indicated that the majority of subjects felt indoor environment hot, dry and without blowing sensation in NV rooms.

Furthermore, the cross-tabulated summary of sensation compared with preference and acceptability votes for each operating mode are shown in Figs. 4 and 5. In ECA mode, it can be observed that, when occupants voted for "slightly cool" (−1) or "cool" (−2) thermal sensation, the preference votes (the sum of "no change", "slightly cooler" and "cooler") were still account for 68 % and 35 %, respectively. About 54 % and 22 % of the subjects who voted for this sensation ("slightly cool" and "cool") deemed indoor environment to be "slightly acceptable". It demonstrated that a bit cooler indoor temperature may be a better choice. Due to the use of ECA was accompanied by air humidification, the willingness of "slightly wetter"/"wetter"/"much wetter" were mainly distributed on the "slightly dry" (−1) humidity sensation scale for approximately 52 %. The voters considered indoor RH "slightly acceptable" and "acceptable" for most of the time. The air speed preference votes were evenly distributed across each air-velocity sensation scale, illustrated that the air circulation in ECA mode could basically meet the needs of occupants' comfort status. More than 70 % of the occupants in the comfort air-velocity sensation scale (±1) reflected to be "slightly acceptable", "acceptable" and "clearly acceptable". In NV mode, the performance of above three subjective responses was poor. Only 36 % of the subjects thermal sensation votes were located in "neutral" status. Out of which 72 % preferred indoor temperature to be a litter cooler and approximately 30 % voted "unacceptable". For RH sensation votes, all the results oscillated between 0 ~ -3 scale indicated that the free-running mode causing the indoor humidity maintain a relatively low level. The majority of the occupants preferred wetter indoor environment. More than 75 % of votes occurred on "unacceptable" and "clearly unacceptable" when HSV less than 0. Although the mean air-velocity in NV condition was higher than ECA buildings, the high temperature with low humidity still resulting the subjects feel uncomfortable. Over 50 % of them desired higher air movements, and surpass 80 % of the people voted "unacceptable" and "clearly unacceptable" on the range of −1 ~ -3 air-velocity categories.



(a) (b) (c)

Fig. 3. Subjective responses on 7-point scales: (a) thermal sensation votes; (b) relative humidity sensation votes; (c) air-velocity sensation votes.

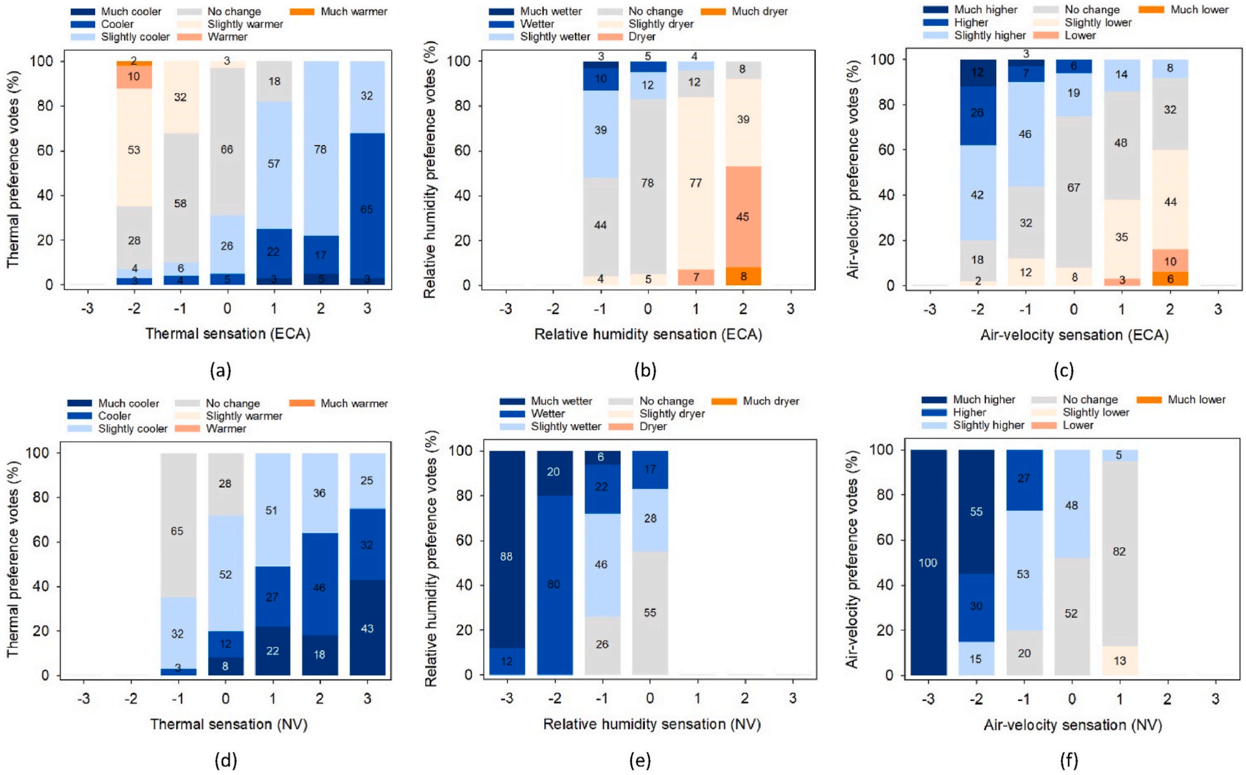

(a)
(b)
(c)
(d)
(e)
(f)

Fig. 4. Cross-tabulated summary: thermal sensation and thermal preference votes, relative humidity sensation and relative humidity preference votes, air-velocity sensation and air-velocity preference votes in ECA and NV buildings.

3.2.2. *Overall comfort*

The overall comfort votes that considered the coupling effect of indoor temperature, relative humidity and air-velocity were recorded based on 5-point comfort scale, see Fig. 6. For ECA group, the majority of subjects (4.6 % "clearly comfortable", 42.5 % "comfortable" and 34.3 % "slightly comfortable") were satisfied with current indoor environment. While the opposing situation was occurred in NV group, approximately 65.7 % and 12.4 % of the subjects could not accept the indoor environment and voted "uncomfortable" and "clearly uncomfortable". It further revealed that the local dry hot climate in summer have a significant impact on indoor environment in naturally ventilated buildings.

3.3. *Assessment of indoor thermal parameters*

In this section, linear regression and Giffiths method were conducted between indoor thermal parameters and subjective comfort votes. Firstly, the comfort (neutral) temperature was determined when TSV equals zero. Secondly, the acceptable range of indoor temperature, relative humidity and air velocity were observed at the intersection of the regression line with votes falling on each central three categories (±1, refer to 80 % base line).

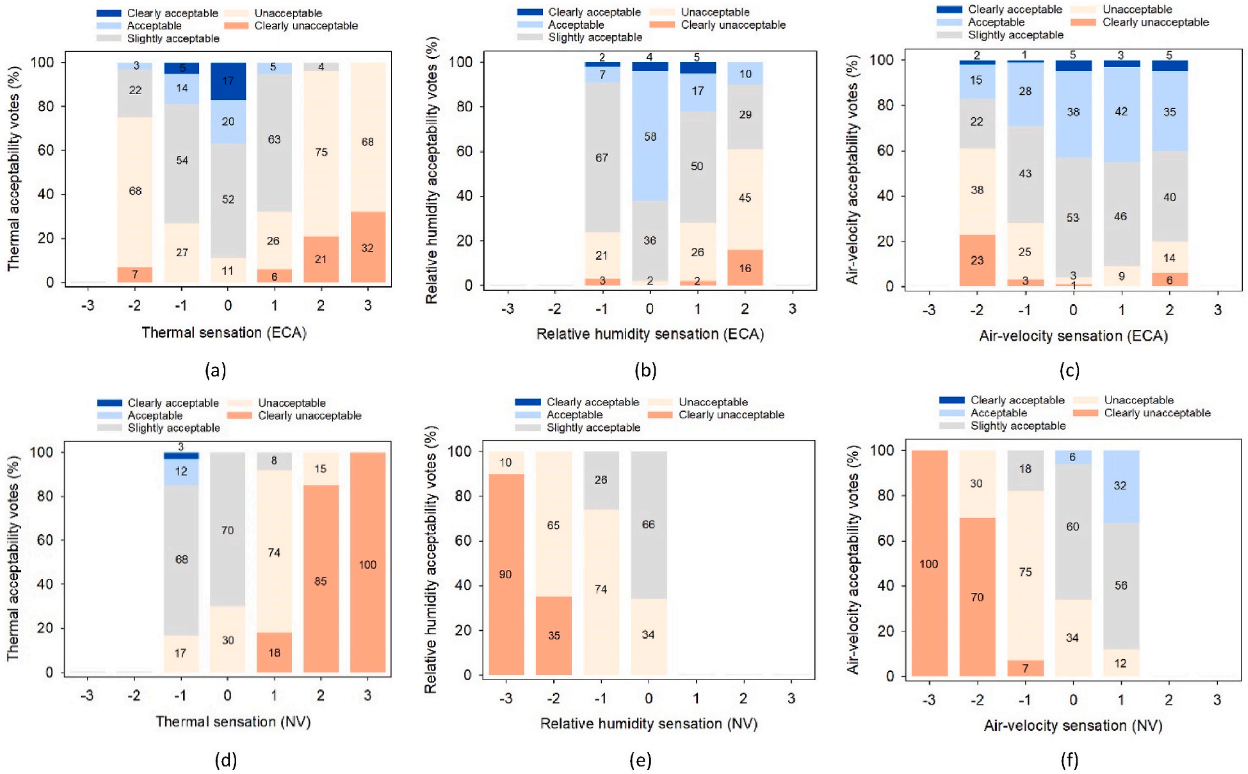
3.3.1. *Neutral and acceptable temperature*

Thermal neutrality described a state that occupants feel neither too cold nor too hot. In other words, it referred to the operative temperature (also called neutral temperature or comfort temperature) at which the thermal sensation votes equals zero. Linear regression method was adopted by numerous researchers to determine the neutral temperature [40,42,60,61]. In present study, this method was used to perform the analysis between physical measurements and comfort votes. Fig. 7 showed the linear regression relationship between thermal sensation and indoor operative temperature. The regression equations of the ECA group and NV group were listed as Eqs. (4) and (5):

$$\text{ECA: TSV} = 0.47T_{op} - 13.35\ (R^2 = 0.29,\ p < 0.001) \tag{4}$$

$$\text{NV: TSV} = 0.46T_{op} - 13.36\ (R^2 = 0.34,\ p < 0.001) \tag{5}$$

It can be observed that the results of ECA group was significantly different from NV group. Neutral temperature of 28.4 °C was found in ECA group, 0.6 °C lower than that of NV group (29.0 °C). Due to the slope of the two equations were almost the same, which indicated that both groups had the uniform thermal sensitivity to operative temperature. In addition, acceptable temperature range



(a) (b) (c)

(d) (e) (f)

Fig. 5. Cross-tabulated summary: thermal sensation and thermal acceptability votes, relative humidity sensation and relative humidity acceptability votes, air-velocity sensation and air-velocity acceptability votes in ECA and NV buildings.

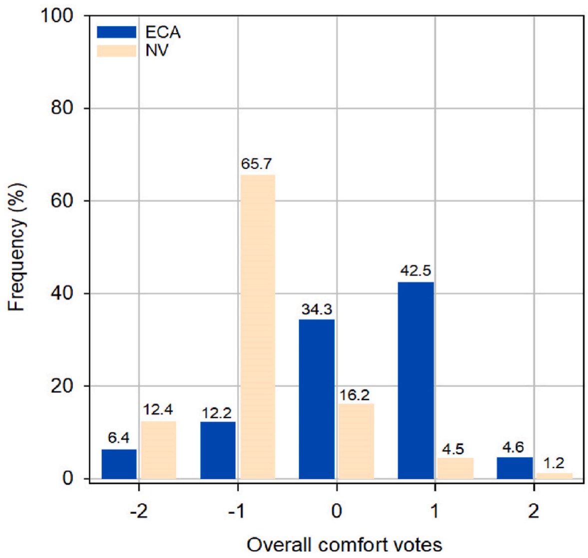


Fig. 6. Frequency of overall comfort votes in ECA and NV buildings.

was given by the intersection of the regression line with the "-1" and "1" sensation votes. In this way, two intervals of 26.32°C–30.58 °C and 27.13°C–31.52 °C were obtained for ECA and NV group, respectively. The upper limit of the ECA was 0.94 °C lower than NV group, illustrated that the perennial living conditions have improved the heating resistance of local residents in summer.

However, some studies revealed that the regression method neglected the occupants' behavior adaptation, so as to reduce the regression coefficient [62,63]. Therefore, this research applied Griffiths constant (a calculation method to avoid mistakes due to the small sample size) to further calculate the neutral temperature. The algorithm shown as Eq. (6):

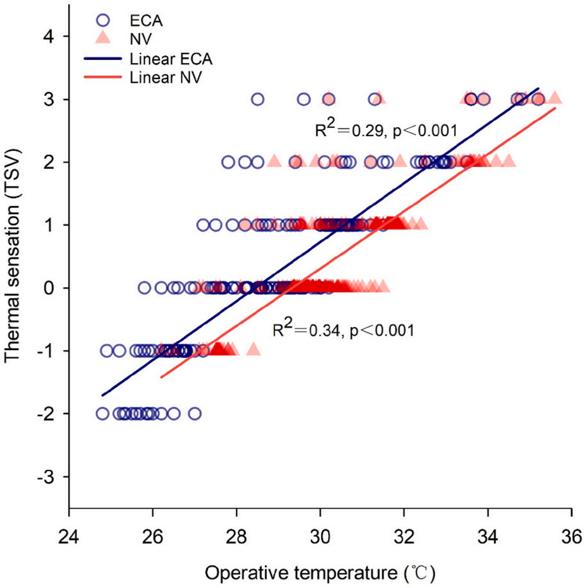


Fig. 7. Thermal sensation against operative temperature.

$$T_c = T_{op\text{-}mean} + (0 - MTSV)/G \quad (6)$$

where T_c is comfort temperature (°C); $T_{op\text{-}mean}$ is mean operate temperature (°C); MTSV represents mean thermal sensation vote; G is Griffiths constant. While adopting Griffiths method, three empirical values of G (0.25, 0.33 and 0.50) have been probed in multiply previous studies [40,62,64,65]. The mean comfort temperatures determined by these values were listed in Table 7. In current study, the value of 0.33 was adopted for further calculation mainly because there was almost no difference between mean globe temperature (TSV = 0) and mean comfort temperature. In Fig. 8, adopting 0.33 as the Griffiths' slope, the mean comfort temperature (ECA: 28.7 °C, NV: 29.2 °C) was nearly the same as that calculated using regression method (ECA: 28.4 °C, NV: 29.0 °C).

3.3.2. *Acceptable relative humidity and air-velocity*

As revealed in Fig. 9, by conducting the regression analysis between humidity sensation votes (HSV) and physical humidity measurements, acceptable interval of indoor relative humidity was obtained of 42.5%–76.2 % ($R^2 = 0.31$) for ECA group and 35.2%–51.6 % ($R^2 = 0.33$) for NV group, respectively. Dhaka [60] and Tewari [65] both reported that the acceptable humidity range for evaporative cooling air-conditioned buildings was oscillated between 35 % and 80 %. The results in this study was found close to previous studies.

With the same method above, the acceptable range of indoor air-velocity was observed for ECA and NV group by 0.06 m/s - 0.31 m/s ($R^2 = 0.35$) and 0.35 m/s - 0.76 m/s ($R^2 = 0.29$), respectively, as shown in Fig. 10. Occupants reported the acceptable air movements in ECA group having a mean value of 0.19 m/s closest to zero, 0.35 m/s lower than that in NV group (0.54 m/s). This also suggested that a moderate increase in air speed could compensate for the discomfort caused by high temperatures. Furthermore, the mean measured indoor air velocity in ECA and NV group (ECA: 0.15 ± 0.22 m/s; NV: 0.29 ± 0.28 m/s, see Table 6) were found closely to the speed corresponding to "0" air-velocity sensation votes (ASV) obtained through linear regression. S. Kumar [66] deemed 0.62 m/s as the preferred indoor air velocity during summer in NV buildings, which including in the scope of the findings for this research.

3.3.3. *Effect of relative humidity and air-velocity on neutral temperature*

To probe the influence of indoor relative humidity on neutral (comfort) temperature, we calculated the mean comfort temperature

Table 7
Comfort temperature calculated by Griffiths constant method.

Operation mode	N	[a] T_c (°C)	[b] G		
			0.25	0.33	0.5
[c] ECA	446	Mean	28.1	28.7	29.2
		[e] SD	2.8	2.2	3.0
[d] NV	485	Mean	28.6	29.2	29.7
		SD	3.8	2.5	2.2

Note: [a] comfort temperature; [b] Griffiths constant; [c] evaporative cooling air conditioned; [d] naturally ventilated; [e] standard deviation.

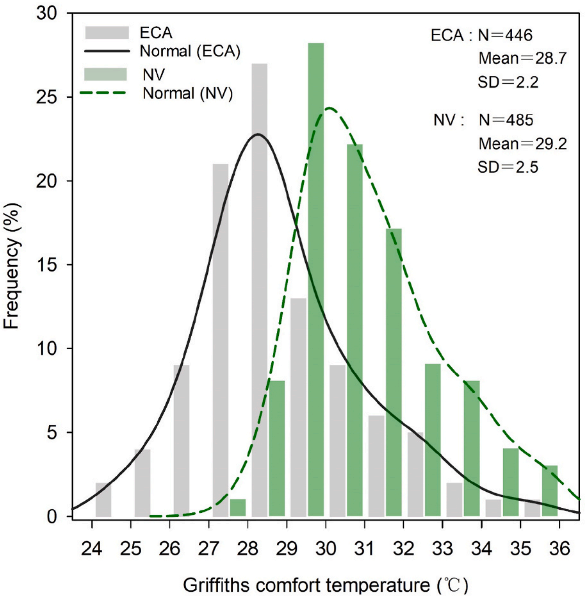


Fig. 8. Frequency of Griffiths comfort temperature.

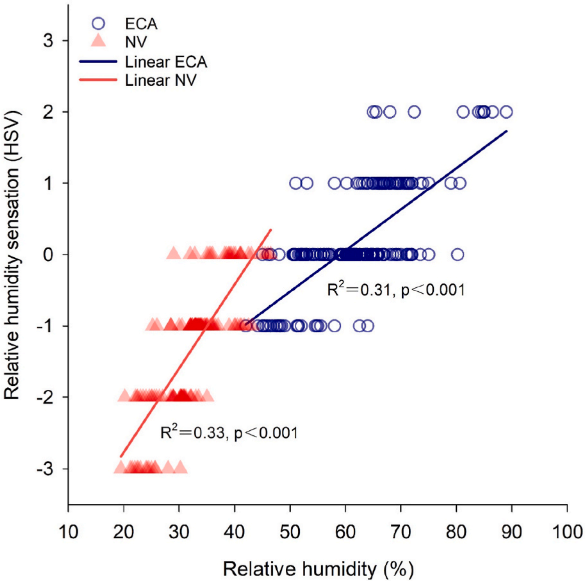


Fig. 9. Relative humidity sensation against relative humidity.

for all humidity sensation categories presented on ASHRAE 7-point scale. Fig. 11 shows the comparison of the humidity levels and calculated T_c, taking the humidity sensation votes (HSV) as a reference. It can be observed that the variation trend of T_c and relative humidity is proportional to each other in both mode. This is contrary to the results reported by P. Tewari [65] and L.A. López-Pérez [67], further indicated that local occupants with a willingness of low temperature and low humidity levels during the long-term experience. In current research, for ECA mode, the highest T_c and RH that can be reached without affecting the thermal comfort standard are 27.5 ± 1.8 °C and 71.2 ± 8.7 %, respectively. In NV mode, the values were 28.1 ± 2.4 °C and 32.6 ± 6.5 %.

Fig. 12 illustrated the comparison between indoor air speed and comfort temperature adopting air velocity votes (ASV) as a reference. It can be found that the T_c increased with the air movement goes up. Similar observations were presented by López-Pérez et al. [67] in an educational buildings operating in air conditioned (AC) and naturally ventilation (NV) under the hot-humid climate. In this study, for ECA mode, the highest T_c and V_a that can be obtained without occupants feeling discomfort are 28.5 ± 1.6 °C and 0.42 ± 0.12 m/s, respectively. In NV mode, the values were found to be 29.6 ± 2.5 °C and 0.52 ± 0.24 m/s.

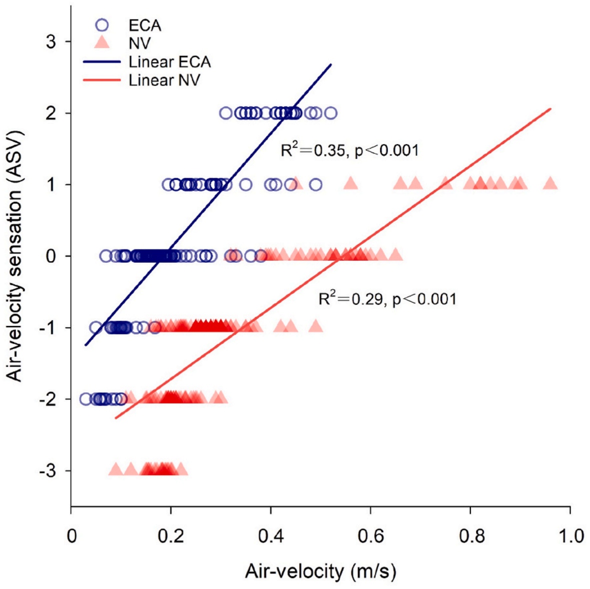
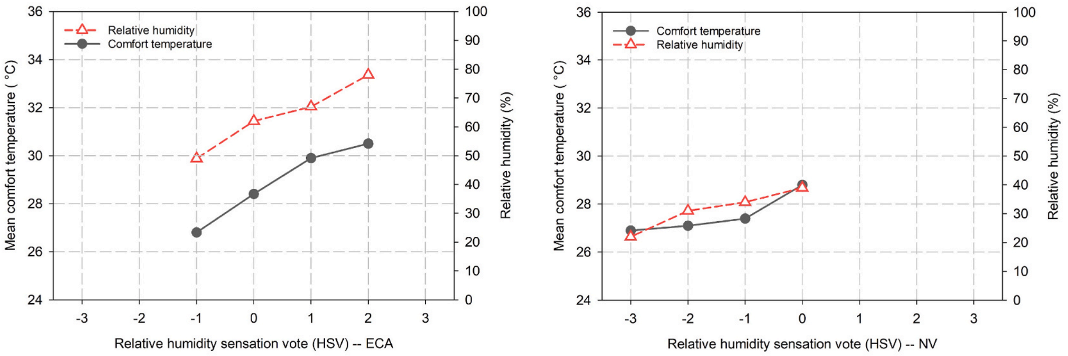


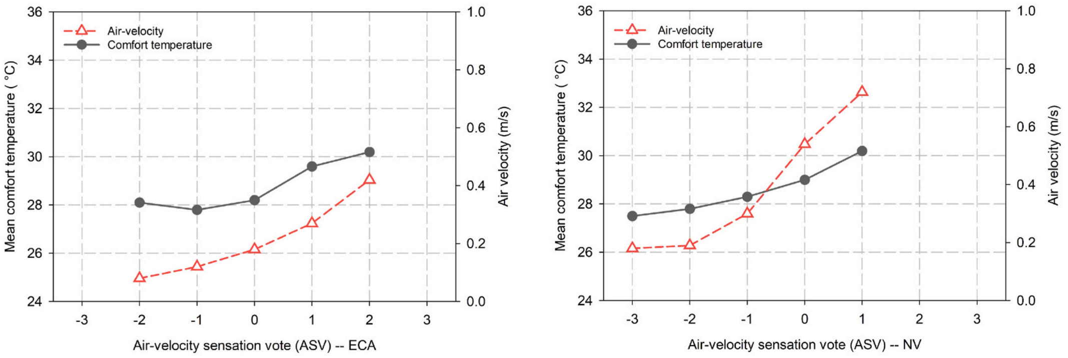
Fig. 10. Air-velocity sensation against air-velocity.



(a)

(b)

Fig. 11. Relationship between indoor mean comfort temperature and relative humidity sensation vote: (a) ECA mode; (b) NV mode.



(a)

(b)

Fig. 12. Relationship between indoor mean comfort temperature and air-velocity sensation vote: (a) ECA mode; (b) NV mode.

3.4. Assessment of thermal behavior adjustments

Generally, when surrounding environment exceeds the acceptable range, subjects may take advantage of physiological, psychological and behavior adjustments to improve their thermal comfort [68,69]. These regulatory mechanisms can be divided into individual adjustments (such as clothing insulation and metabolic rate) and adaptive strategies (such as open a ceiling fan, drink cold beverage, etc.).

3.4.1. Clothing insulation

In current research, clothing insulation for each mode were observed through questionnaires. The dress worn by occupants varied in ECA and NV modes, as well as by gender. Staffs in ECA spaces mostly dressed in the combination of long-thin pants, T-shirt, short-sleeve dress shirt and leather shoes. While in NV mode, the clerks dressed in the combination of shorts, skirts, short sleeve, canvas shoes or sandals for most of time.

To probe the regulation of clothing condition, Fig. 13 showed the average value of clo level with standard deviation for binned operative temperature in two groups (male versus female). In general, the clothing insulation tended to decrease as the operative temperature increased, regardless of indoor operation mode and gender. According to the recommended value in ASHRAE 55 [13], the average value of clothing insulation in ECA and NV groups were 0.32 ± 0.11 clo and 0.28 ± 0.06 clo, respectively. Furthermore, the clo level of female were slightly higher than male for both modes, and the totally value of NV conditions was approximately by 0.04 clo lower than ECA conditions. Due to the unique dry hot climate in Turpan, the mean value of clothing insulation in this study was slightly lower than the research by X. Wang [70] and M. Shrestha [71].

It is widely known that clothing behaviors under NV conditions would be strongly affected by outdoor climate during peak seasons [72]. Additionally, H. Wang [73] and R. Yao [74] also emphasized that the clothing conditions were more correlated to the outdoor air temperature rather than indoor operative temperature. Therefore, a linear regression was carried out in NV groups to explore the relationship between clothing insulation and outdoor air temperature. Firstly, we classified all clothing insulation into 1 °C binned data of outdoor air temperature. Then the average values of clo within each temperature interval were calculated. Fig. 14 showed the comparison result, from which can be seen that two parameters presented inverse tendency. As outdoor air temperature increased, the occupants seem to decrease their clothing insulation. Among those thirteen mean points, the former eleven generally ranged from 0.28 clo to 0.31 clo with little downward slope. While the other two plots corresponding to 39 °C and 40 °C showed a sharp drop with the average clo level were much lower than before. This phenomenon demonstrated that the local subjects adapt to thermal environment in offices by transforming their clothing when the mean outdoor air temperature exceeds 38 °C.

3.4.2. Metabolic rate

Due to the dry hot climate, the majority of subjects performed low-intensity activities indoors during the field study. Based on the results of questionnaires, the main activities including sleeping (0.7 met), napping (0.8 met), seated quiet/reading/writing (0.9–1.0 met), typing/eating (1.1 met), standing relaxed (1.2 met), walking (1.4–1.7 met) and lifting/packing (1.8–2.1 met) [13,75]. The metabolic rate of each segment for different groups and genders were summarized in Table 8. It's not difficult to spot that the highest proportion of metabolic rate were distributed in 1.0–1.2 met regardless of indoor operation modes (ECA: 62.9 %, NV: 58.8 %). Moreover, in ECA groups, the rate of moderate-intensity activity (1.2–2.0 met) was higher in male (30.3 %) than female (17.0 %). Whereas the two values were similar in NV conditions (male: 24.6 %, female: 23.1 %).

To further explore the change rule of metabolic rate against surveyed working time, we also collected the data sorted into bins with 1 h of the daytime. Fig. 15 showed the mean value of metabolic rate within each time interval (i.e. the points corresponding to 10:00 was the mean values between 9:30 and 10:30). During the morning period, the activity level for both modes were similar which mainly in the range of 1.0–1.1 met. However, the opposite phenomenon appeared in the afternoon that resulting the values were higher than

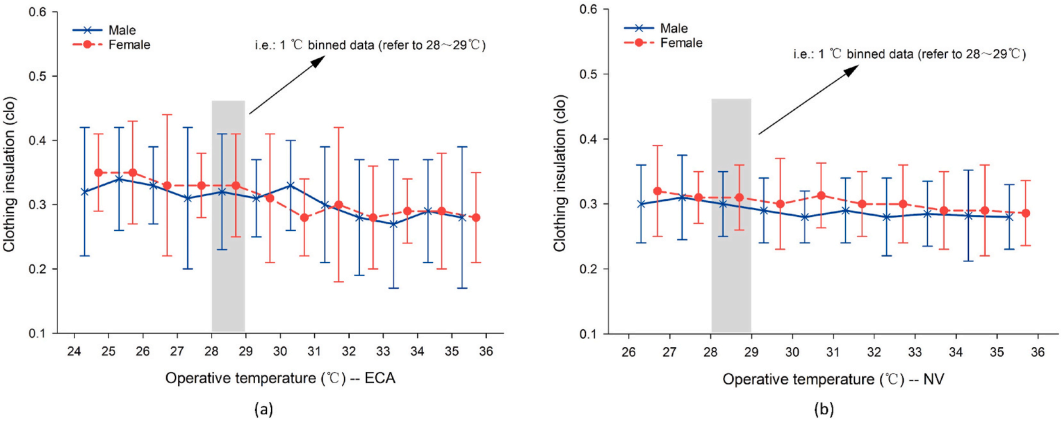


Fig. 13. Relationship between clothing insulation and operative temperature: (a) ECA mode; (b) NV mode.

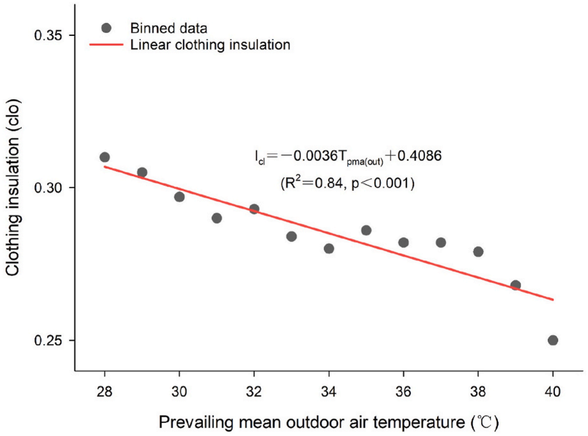


Fig. 14. Relationship between clothing insulation and prevailing mean outdoor air temperature.

Table 8
Frequency of metabolic rate in ECA and NV buildings.

Metabolic rate (met)	Frequency (%)					
	ECA			NV		
	Male	Female	Overall	Male	Female	Overall
0.6 - 0.8	5.3	3.1	4.2	4.4	9.7	7.2
0.8 - 1.0	7.8	11.2	9.6	8.5	9.6	9.1
1.0–1.2	56.6	68.7	62.9	62.5	55.4	58.8
1.2 - 1.4	10.7	4.0	7.2	15.4	10.9	13.1
1.4 - 1.6	3.0	8.8	6.0	2.6	4.4	3.5
1.6 - 1.8	12.4	2.7	7.3	3.5	7.8	5.7
1.8 - 2.0	4.2	1.5	2.8	3.1	0.0	1.5
> 2.0	0.0	0.0	0.0	0.0	2.2	1.1

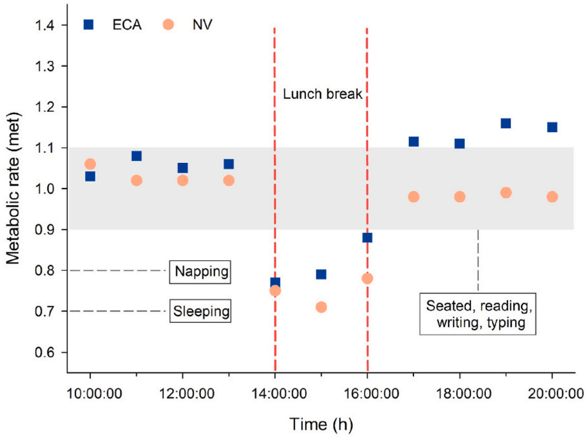


Fig. 15. Transformation in mean metabolic rate against working time for ECA and NV buildings.

1.1 met in ECA groups and lower than 1.0 met in NV groups. Owing to the plenty time for lunch break, subjects experienced a transient change in temperature after their basic metabolic rate decreased in a cooler environment. This may lead to energetic with higher activity levels in the afternoon for occupants in ECA spaces. While in NV environments, with the sense of fatigue increased after waking up, the activities continually remained at a lower level over a period of time.

3.4.3. Adaptive strategies

During the field investigation, various thermal adaptive strategies were carried out by local occupants when feeling hot or discomfort, which contained opening windows/doors/ceiling fans, using hand fans, taking a shower and drinking cold beverage, etc.

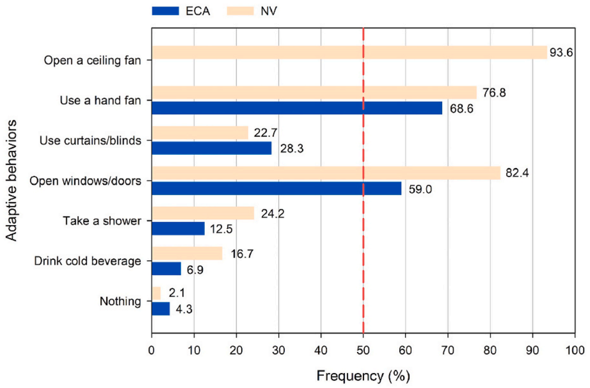


Fig. 16. Frequency of adaptive behaviors in ECA and NV buildings.

Fig. 16 showed the frequency of such adaptive behaviors in different operative environments. In ECA mode we observed a preference for using hand fans and opening windows/doors as the regulative strategies. The reason is that the circulation of air flow can carry away the water vapor in the evaporative cooling process. As in the NV situations, opening the ceiling fans, windows and adopting hand fans were considered to be the effective ways for more than 70 % of the subjects.

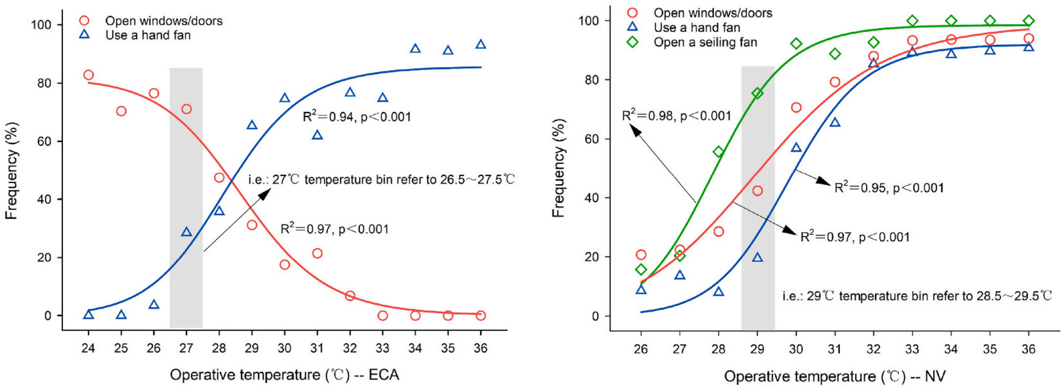
In addition to that, multiple scholars adopted logistic regression to predict the preference for adaptive behaviors in thermal comfort research [70,76,77]. Hence in this study, the strategies that exceeding 50 % choice base line were selected to compare with the indoor operative temperature. The logistic regression equations can be expressed as Eqs. (7) and (8):

$$\text{logit}\ (p) = \log\ [p/(1 - p)] = bT + c \tag{7}$$

$$p = \exp^{(bT + c)} / [1 + \exp^{(bT + c)}] \tag{8}$$

where p is the probability that an adaptive behavior occurs; exp is the base of natural logarithm; b is the regression coefficient and c is the constant.

Fig. 17 showed the relationship between indoor operative temperature and frequency of opening windows/doors/ceiling fans and using hand fans. In Fig. 17 (a), when the indoor operative temperature was from 28 °C to 34 °C, the proportion of using hand fans increased from 40 % to 90 %. While the percentage of opening windows/doors was negatively correlated to the operative temperature in ECA environment. This suggested that occupants prefer higher relative humidity with the windows closed to higher indoor air temperature. In Fig. 17 (b), it can be seen that the proportion of turning on ceiling fans suddenly increased from 20 % to 90 % when operative temperature between 27 °C and 30 °C. The fan switch-on rate reached 100 % when the temperature rised to 33 °C, and then does not increase with temperature. Compared with the HVAC systems, trying to increase the circulation of air flow seems to be a feasible measure to relieve the thermal discomfort in NV spaces.



(a)　(b)

Fig. 17. Frequency of windows/doors/ceiling fan opened and hand fan used: (a) ECA mode; (b) NV mode.

4. Discussion

4.1. Comparison with PMV model

Up to now, various international comfort standards adopting Fanger's PMV/PPD model to evaluate the indoor ventilated, heated and cooled environment, such as ASHRAE 55 [13], EN 16798-1 [32] and GB/T 50785 [33]. In order to verify whether the PMV model can be used to assess the indoor thermal environment of ECA and NV buildings in Turpan, the PMV values were calculated by MATLAB for each mode according to EN 16798-1 [32]. Meanwhile, the relationship among predicted mean votes (PMV), mean actual thermal sensation votes (MTSV) and indoor operative temperature (T_{op}) were built by using the 1 °C binned data, as presented in Fig. 18.

Results showed that a clear "scissors difference" was observed between PMV and MTSV models in two modes, from which the NV situation was more obvious (Fig. 18). Due to the specific dry hot climate in Turpan, the indoor operative temperature in NV mode was more likely to be affected by outdoor climate, even resulting the PMV values reached its peak at 4.71. Moreover, MTSV values were lower than the corresponding PMV in each 1 °C binned interval, indicated that the occupants can adapt to local climate through physiological, psychological and behavioral adjustment. While in ECA buildings, it is actually a mixed mode as the subjects can control the windows and doors freely. The PMV equation overestimated occupants' actual thermal sensation when operative temperature exceeded 28 °C, and the MTSV model was more tended to be neutral than PMV. This phenomenon also illustrated that the PMV model is more sensitive than MTSV to predict the change of subjects' thermal sensation. Overall, the findings above revealed that the PMV model can not evaluate the actual thermal sensation accurately in neither ECA nor NV buildings.

4.2. Comparison with adaptive model

Adaptive model described the relationship between indoor comfort temperature and outdoor temperature. At present, Griffiths' method was widely adopted to probe the study of adaptive thermal comfort, from which the neutral temperature can be calculated by the actual thermal sensation votes at measured climate data [40,68,78]. In this section, the ECA and NV adaptive models were established by linear regression between Griffiths comfort temperatures and prevailing mean outdoor air temperature. The calculation process can be expressed as Eqs. 9 and 10. Meanwhile, Figs. 19 and 20 displayed the comparison results of adaptive models with the ASHRAE 55 [13], EN 16798-1 [32] and GB/T 50785 [33] standards.

$$\text{ECA: } T_n = 0.01T_{pma} + 27.75 \ (p > 0.05) \tag{9}$$

$$\text{NV: } T_n = 0.48T_{pma} + 15.29 \ (p < 0.001) \tag{10}$$

Obviously, there was no correlation between indoor comfort temperature and outdoor temperature in ECA buildings ($p > 0.05$). The slope of the ECA adaptive model almost equals to zero. However, in NV buildings, a significant positive correlation was observed between T_c and T_{pma} ($p < 0.001$). It manifested as the neutral temperature increases with the raise of the outdoor temperature, which basically similar to those findings by H. Yan [78] and J. Kim [79]. Moreover, the slope of the NV adaptive model was slightly higher than that recommended in ASHRAE 55 [13] and EN 16798-1 [32]. Due to the extreme climate in Turpan, most comfort scatters (blue and red dots in Figs. 19 and 20) were beyond the comfort zone of the three codes whether in ECA or NV mode.

In addition to this, the frequency of neutral temperature for each mode within the band of comfort zone was also listed to better quantify the data division, as shown in Table 9. The results showed that there is no specification that can accommodate more than 50 % of the neutral temperatures. In ECA and NV buildings, ASHRAE 55 has the highest ratio of the three standards. In which 45.8 %/40.6 % and 22.7 %/16.5 % of the comfort scatters were within the 80 %/90 % acceptable temperature interval. However, due to the large part of the prevailing mean outdoor air temperature in Turpan was beyond the upper limit of the EN 16798-1 (30 °C) and GB/T 50785 (32 °C), few dots located within the comfort band especially for NV situation (less than 10 %). Therefore, the recommended models in

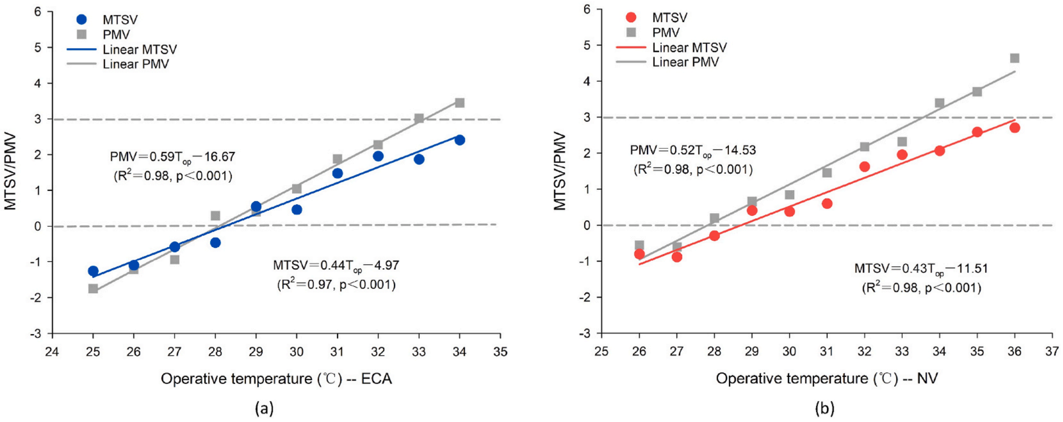
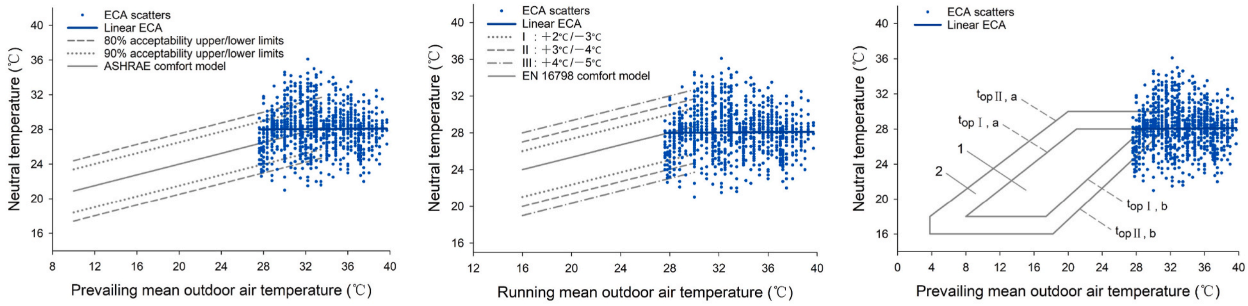
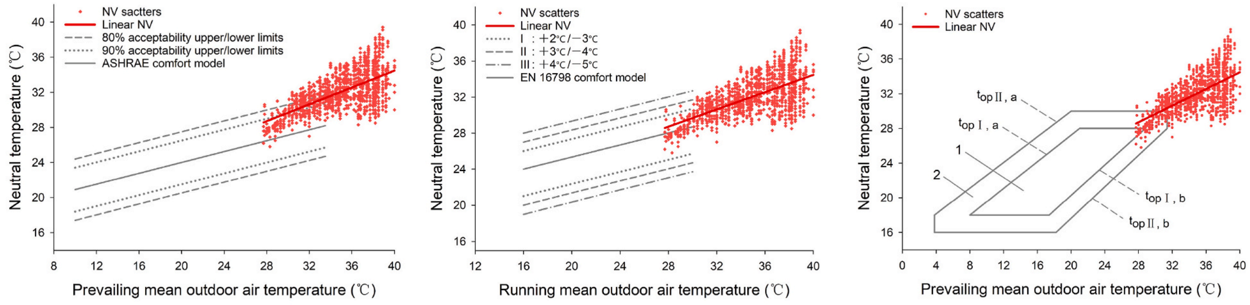


Fig. 18. Comparison of mean thermal sensation votes (MTSV) and predicted mean votes (PMV): (a) ECA mode; (b) NV mode.



(a) (b) (c)

Fig. 19. Comparison of neutral temperature (T_n) and various codes for ECA mode: (a) ASHRAE 55; (b) EN 16798-1; (c) GB/T 50785.



(a) (b) (c)

Fig. 20. Comparison of neutral temperature (T_n) and various codes for NV mode: (a) ASHRAE 55; (b) EN 16798-1; (c) GB/T 50785.

Table 9

Frequency of the neutral temperature within various thermal comfort codes.

Operating mode	ASHRAE 55		EN 16798-1			GB/T 50785	
	90 %	80 %	I	II	III	1	2
ECA	40.6 %	45.8 %	14.1 %	17.8 %	19.6 %	1.2 %	12.2 %
NV	16.5 %	22.7 %	8.9 %	9.2 %	9.4 %	0.9 %	7.1 %

Table 10

Summary of existing studies for office buildings in summer.

Scholars	Year	Location	Mode	^{a} T_n (°C)	$T_{n\ (range)}$ (°C)
Wu et al. [40]	2019	Changsha	^{b} MM	27.0	24.2–28.4
Ming et al. [41]	2020	Chongqing	MM	26.17	24.7–29.0
Zhang et al. [42]	2010	Guangzhou	^{c} NV	25.4	23.5–27.4
Fu et al. [43]	2020	Guangzhou	^{d} AC	26.2	–
Dhaka et al. [60]	2017	Jaipur	AC	27.5	23.89-28.01
Tewari et al. [65]	2019	Jaipur	^{e} ECA	28.15	24.5–31.8
Guo et al. [69]	2022	Urumqi	ECA	27.3	26.4–30.3
Yan et al. [80]	2022	Zhengzhou/Jiaozuo	^{f} SAC	26.8	–
Indraganti et al. [81]	2013	Tokyo	AC	27.1	–
Indraganti et al. [82]	2013	Hyderabad/Chennai	NV	29.0	–
Tse et al. [83]	2019	Cardiff	MM	19.3	14.7–23.8
Manu et al. [84]	2016	India	NV	–	19.6–28.5
Rijal et al. [85]	2017	Japan	^{g} CL	–	23.9–26.9
			^{h} FR	25.0	23.3–26.7
Current research	2021	Turpan	ECA	28.4	26.32-30.58
			NV	29.0	27.13–31.52

Note: ^{a} neutral temperature; ^{b} mixed mode; ^{c} naturally ventilated; ^{d} air conditioned; ^{e} evaporative cooling air conditioned; ^{f} split air conditioned; ^{g} mechanical cooled; ^{h} free running.

current standards have a large deviation to comparing with this study. They were not applicable for evaluating ECA and NV office buildings in Turpan.

4.3. Comparison with existing studies

It is no doubt that the actual thermal sensation was affected by various climate zones, local cultures, living habits, thermal history and age/gender of the occupants [38,70,76]. Turpan is located in severe cold zone of China, with the climate performed by dry cold in winter and dry hot in summer. This may lead to the results of current research differing from other studies. Thus, we conducted a summary of thermal comfort studies in office buildings during summer with different regions, seeing Table 10.

Regardless of indoor operating mode (AC, NV or MM) in various previous studies, several regularities can be obtained. Specifically, both the neutral temperature and the upper limit of acceptable temperature varied from geography and climate. It being higher in warmer regions, and vice versa. The neutral temperatures found in Turpan (current research) during summer (ECA: 28.4 °C, NV: 29.0 °C) were 9.1–9.7 °C higher than that of Cardiff (MM: 19.3 °C) [80]. Which mainly due to the difference of prevailing mean outdoor air temperature in two regions in summer beyond 10 °C. Meanwhile, the T_n in other regions of China, such as Changsha [40], Chongqing [41] and Guangzhou [42,43], were slightly lower than study site. Moreover, the difference between the upper limit temperature and neutral temperature in ECA buildings (2.18 °C) was slightly lower than NV buildings (2.52 °C) in current study, indicated that NV occupants are more tolerant than HAVC of the environmental changes caused by deviations from neutral temperature. In other words, when people exposed to a dry hot environment, they have lower psychological expectation regarding the cool temperature and high humidity than other areas. In this process, behavioral adjustments may play a significant role in shaping the thermal history of residents in their perennial lives.

4.4. Potential application

As mentioned above, during the long period of thermal adaption, occupants in dry hot areas can endure the higher temperature behaviorally in summer. The following guidelines are carried out and can be adopted by architects or designers to create a comfort office environment in similar climatic zones. Meanwhile, the implementation of these findings will also contribute to a better quality indoor environment for clerks in their offices which will enhance their productivity and wellbeing.

a) Firstly, the acceptable range of T_a, RH and V_a in current research may enhance the promotion of good practices to design newly/renovated offices spaces for the clerks, or to evaluate existing ones in similar climate regions by checking whether a given thermal environment meets the comfort criteria during summer. b) Additionally, from the subjects' adaptive behaviors, operating windows and increasing inner air flow are most simple and efficient ways for subjects to adapt to surrounded environment in both modes. Further practice should focus on the improvement of design guidelines, such as adjustment of building functional layout, improving fenestrations and enhancement of appropriate natural ventilation. c) Moreover, results revealed that RH has no obvious influence on thermal sensation of occupants in ECA mode, but possessed the increased expectations in NV buildings. Thus in the future design, the NV buildings should pay more attention to improving the issue of low indoor humidity in summer. Indoor humidification equipment, such as green plants, ecological fish tanks, humidifiers and flowers can be added timely to solve it. d) Lastly, we found that most of the surveyed buildings were not adopting shading devices, resulting in a large amount of solar radiation into the rooms. This not only caused high energy consumption in ECA buildings, but also leaded to high temperatures in NV rooms. Therefore, proper designing of shading device is a significant measure to reduce the summertime building energy demand and improve indoor thermal comfort.

4.5. Limitations and future challenges

Although this study probed human responses and adaptive behaviors of ECA and NV thermal conditions. There were also some limitations: a) Firstly, it is the limited season selection. The investigation of this research mainly focus on summertime, while the winter and transition season are also important processes that shape the thermal history of residents. Further studies with larger samples are planned to explore the indoor thermal environment in Turpan's offices. b) Secondly, only two indoor operation modes (ECA and NV) were discussed in this study. However, the indoor thermal environment created by conventional mechanical air conditioned and ECA is different, and the variation of human targeted thermal feedback in that two conditions are still unclear. Thus we intend to conduct a comparative study of various working conditions in next step. c) Thirdly, within the participants, age segment and health conditions were not assessed in detail as personal characteristics. Future work will also concentrate on the influence of individual health conditions on thermal adaptation at different age segment.

5. Conclusion

This paper presents a pilot study of the thermal comfort and adaptive behaviors for healthy adults in Turpan during summer. To explore the impact of different operating modes on thermal responses, 446 and 485 data sets were collected in 3 ECA and 4 NV office buildings, respectively. The main achievements could be summarized as follows.

(1) During summer in Turpan, the mean indoor air temperature in ECA and NV buildings were 29.2 and 32.4, respectively. And the relative humidity in ECA mode was approximately double higher than NV mode. As for air-velocity, about 70 % of the time for both modes were under 0.2 m/s, lower than the upper limit required in ASHRAE 55.

(2) Thermal responses of the two modes expressed a significant disparity. For ECA buildings, 88 % of the occupants satisfied with present condition, but there was still a desire for them to have a cooler T_a and higher V_a. However, in NV buildings, approximately 78.1 % of the subjects could not accept current indoor environment, which indicated that the thermal satisfaction of the occupants needs to be improved.

(3) The neutral temperature of 28.4 °C was found in ECA group, 0.6 °C lower than NV group. 80 % acceptable interval of 26.32°C–30.58 °C and 27.13°C–31.52 °C were obtained for ECA and NV buildings, respectively.

(4) Statistical analysis showed that the RH and V_a in two modes were proportional to T_n. And the V_a has a stronger influence than RH on thermal sensation when comparing with T_n in both modes.

(5) Residents can adapt to current indoor environment through physiological, psychological and behavioral adjustments. They would rather endure high RH with the windows closed than high T_a in ECA environment. Nevertheless, sprinkling water and increasing the circulation of air flow may be the effective way in NV mode.

(6) Whether in ECA or NV mode, the scissors difference was observed between PMV and MTSV models. The PMV model overestimated occupants' actual thermal sensation when T_{op} beyond 28 °C. This revealed that the perennial living conditions have improved the heating resistance of local residents.

(7) It found to be the adaptive models in this research were different from ASHRAE 55, EN 16798-1 and GB/T 50785. Most comfort scatters in two groups were beyond the standards' comfort zone. It illustrated that the recommended models in current codes cannot be adopted to predict the subjects' thermal perception in Turpan.

(8) Occupants' thermal adaptability should be taken into account seriously in the design of passive strategies. The approach of "one-size-fits-all" not only results in a large amount of unnecessary energy waste and economic costs, but also at the expense of health and thermal comfort for local residents.

Author contribution statement

Yuang Guo: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; wrote the paper. Hao Tang, Yali Gao, Yuxin Wang: performed the experiments; analyzed and interpreted the data; wrote the paper. Xi Meng, Gangwei Cai: analyzed and interpreted the data; contributed reagents, materials, analysis tools or data. Jingyuan Zhao, Bart Julien Dewancker, Weijun Gao: conceived and designed the experiments; contributed reagents, materials, analysis tools or data.

Data availability statement

The authors do not have permission to share data.

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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.

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