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Thermal adaptation of the elderly during summer in a hot humid area: Psychological, behavioral, and physiological responses

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Abstract

Elderly demand for thermal comfort and energy conservation in senior citizen centers is increasing in an aging society. To reveal the thermal responses of the elderly in a warm summer environment, a field study involving experimental measurements was conducted in Chongqing, China. The study included 333 subjects in 17 residential buildings and 119 subjects in 6 elderly nursing homes; it showed that elderly persons as passive users of air conditioners preferred cooling by natural ventilation. The mean thermal sensation vote was lower than estimates obtained from the PMV model in warm environments. The physiological responses of eight elderly subjects (65 ± 3) were measured in a climate chamber at 18 °C and 34 °C and compared with those from eight college students (22 ± 1) and eight middle-aged subjects (50 ± 5). In this chamber, oral temperature, blood pressure, and heart rate of elderly and middle−aged persons were determined to be almost constant as the air temperature

was changed to a hot/cold environment for 30 min, a different result from that of the young subjects. However, the skin temperature for all age groups showed variation with air temperature, suggesting skin temperature as an optimal monitoring parameter for the entire population.

Keywords   **Thermal adaptation; elderly; natural ventilation; skin temperature; hot climate.**

Nomenclature

ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineer
PAO	proportion of air conditioners on
PFU	proportion of fans used
PWO	proportion of windows opened
PMV	predicted mean vote
TSV	thermal sensation vote
ASV	air movement sensation vote
HSV	humidity sensation vote
HSCW	hot summer and cold winter
V_a	indoor air velocity, m/s
V_{out}	outdoor air velocity, m/s
RH_a	indoor relative humidity, %
RH_{out}	outdoor relative humidity, %
T_a	room air temperature, ℃
T_{out}	outdoor air temperature, ℃
AC	air-conditioned

ACs	air conditioners
NV	natural ventilation

1 Introduction

According to the Population Division of the Department of Economic and Social Affairs of the United Nations (UN DESA) [1], the population of the elderly will account for 16.9%, 23.8%, and 32.8% of the overall population in China in 2020, 2030, and 2050, respectively. The elderly spends most of their time at home and are more susceptible to the thermal environment. The demand for specialized service facilities for the elderly has increased with the aging of the population. Thus, the establishment of thermal environment criteria is important to the well-being of the elderly [2]. As a result of thermal adaptation [3] [4] [5], there are differences in the thermal sensation associated with different seasons [6-13], building types [14-16], climates, and cultural differences around the world [15-17]. Thus, an adaptive model [18, 19] was incorporated in ANSI/ASHRAE Standard 55 [20] and other existing standards [21] [22]. However, to date, the important issue of adaptive thermal comfort of the elderly has neither been adequately addressed nor incorporated into any international standards.

According to ASHRAE Handbook (1967) [23], the desired effective temperature is 1 °F higher for men and women above 40 years than for those below this age. However, in the studies of Rohles [24], there was not a significant difference between the elderly and college students with respect to thermal comfort. The idea was supported by Fanger [25] and the current ASHRAE standard [26], that there is no difference in thermal sensation between persons of different ages in a moderate temperature environment. However, it was noted that special human thermal adaptation occurs in the elderly in warm environments [15]. Usually, human thermal adaptation is affected by three factors: behavioral adjustment (e.g., changing clothes), physiological acclimatization, and psychological (expectation and habituation) adaptation [27]. However, as special human groups, the elderly and young children are more susceptible to the thermal environment [28]. Generally, in a warm environment, the elderly are

less sensitive to thermal conditions [29] and express fewer complaints than younger persons [30, 31]. However, elderly people are believed to be less comfortable [31, 32] [33] and suffer greater health risks [34-36] in cold environments; therefore, they need a warmer thermal environment in all seasons [23] [37-39] [40, 41]. In terms of physiological characteristics, elderly people have a lower metabolic rate than young people do [42]. They tend to have poorer health [43], and all three major cold mitigation functions (shivering, vasoconstriction [44, 45], and thermal perceptions of cold or temperature difference [46] [47]) are compromised by aging. This implies that thermal comfort standards based on experimental data involving college students may not be suitable for elderly subjects and might lead to energy waste and discomfort.

The thermal discomfort of an occupant is one of the main factors that motivates action, such as turning on AC units, using fans, and opening windows [19, 48], and these behaviors are mainly affected by indoor and outdoor air temperature [49, 50]. Therefore, it should be noted that healthcare of the elderly is another important issue [35]. Because of the extreme outdoor conditions in hot summer and cold winter (HSCW) climate zones, the room air temperature varies over a large range when natural ventilation is used [27]. In such extreme conditions, the morbidity and mortality of the elderly significantly increase [51, 52]. Compared with young people, the core temperature of elderly persons is more unstable. In addition, a higher temperature is needed to induce sweating, and a lower temperature is needed to produce shivering [44]. As such, a more intense environmental stimulus is required for the elderly, compared with that for younger persons [45]. Thus, the elderly should avoid being exposed to cold environments [53, 54]. In warm environments, the reduction in heat dissipation ability is offset by a decrease in the metabolic rate of the elderly. These considerations make it particularly important to design an environment for elderly people that optimizes their well-being and considers their special conditions.

There are many important findings with regard to elderly persons from field studies. In a field study on elderly care centers in Korea [55], it was determined that the elderly prefers warm indoor thermal environments. Based on an investigation involving 119 elderly individuals in two nursing homes in Japan [47], the participants were found to be thermally neutral when the thermal environment was in the range of PMV −0.5 to +0.5 and unable to sense any vertical temperature difference. In another study of 19 nursing homes in Hong Kong, involving 387 elderly persons, the preferred room air temperature was determined to be 1.5–2 °C higher for the age group 80–99 years old than that for the group 60–79 years old [56]. A field study in nursing homes in Shanghai, China [43] also found that elderly with health problems had a thermal sensation vote 0.36 lower than that of healthy elderly persons. In yet another field study in nursing homes in Shanghai, China [57], the common thermal adaptation methods of the elderly persons were determined to be clothing and window adjustments. Hwang and Chen [58] determined that the rate of change for TSV with air temperature thermal sensitivity was higher in the summer (0.39/°C) compared with that in winter (0.28/°C) for the elderly in Taiwan. By investigating 425 elderly individuals in 6 welfare facilities in Portugal, Mendes et al. [59, 60] found that the rate of dissatisfaction in thermal conditions is 48% in the winter and 8% in the summer. All this indicates that the thermal responses of the elderly to the thermal environment in buildings need to be better understood.

This study investigated the psychological, behavioral, and physiological responses of the elderly in a hot climate region. First, a field study was conducted in both residential buildings and nursing homes to investigate the behavioral and psychological responses of the elderly to hot and humid summer conditions. The method and results of the field study are presented in *Section 2.1 Field study* and *Section 3 Results of the field study.* Next, experiments were performed to measure the physiological

responses of the elderly and compare them with those of middle-aged and young persons to cool and hot environments. The method and results of the experimental study are presented in *Section 2.2 Physiological measurement in a climate chamber* and *Section 4. Results of the experimental study in the climate chamber*. In addition, the psychological, behavioral, and physiological responses of the elderly are discussed in *Section 5 Discussion*. The results of experimental study could reveal the characteristics and underlying causes of adaptive behaviors and thermal comfort of the elderly with respect to a warm environment. This study also aims to identify the optimal parameters with respect to thermal sensation of the elderly when thermal adaptation occurs in a building environment, which could contribute to their well-being as well as benefit energy conservation in buildings. Finally, the conclusions are summarized in *Section 6 Conclusions.*

2 Methods

2.1 Field study

To understand the fundamentals of the adaptive thermal comfort mechanism of the elderly in a hot climate, a survey was conducted from June 5 to August 30 in Chongqing, which is located in hot summer and cold winter (HSCW) climate zone , China [61]. Basically, 17 apartment buildings were involved in the survey, distributed in the area showed in Figure 1 in Chongqing. Of the surveyed buildings, 70.6% are reinforced concrete structures, while the rest are old brick-concrete structures; 47.1% of the buildings were built before the 1980s, while 35.3% were built after 2000; the average area of a room within the apartment is approximately 23.5 m^2; and all the surveyed rooms have operable outside windows. In addition, six nursing homes were investigated, with two in the central area of Chongqing, two in the residential community area, and two in the suburb that is close to a forest, as showed in Figure 1. All the buildings of the nursing homes were old brick-concrete structures with single-pane glass windows. The buildings had heights of two to five floors, and all the elderly

surveyed in this study lived on the ground or second floor.
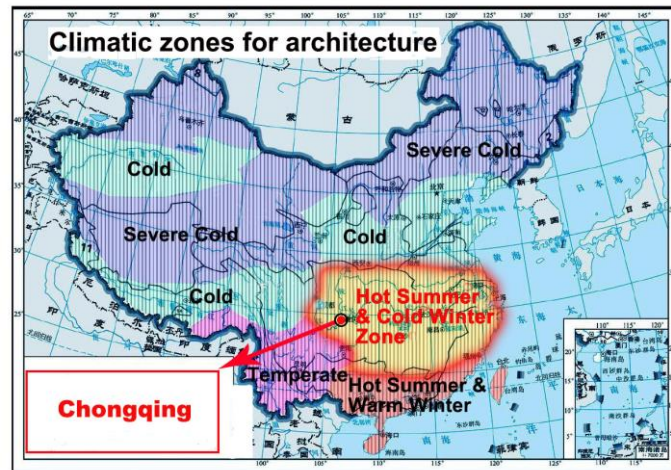
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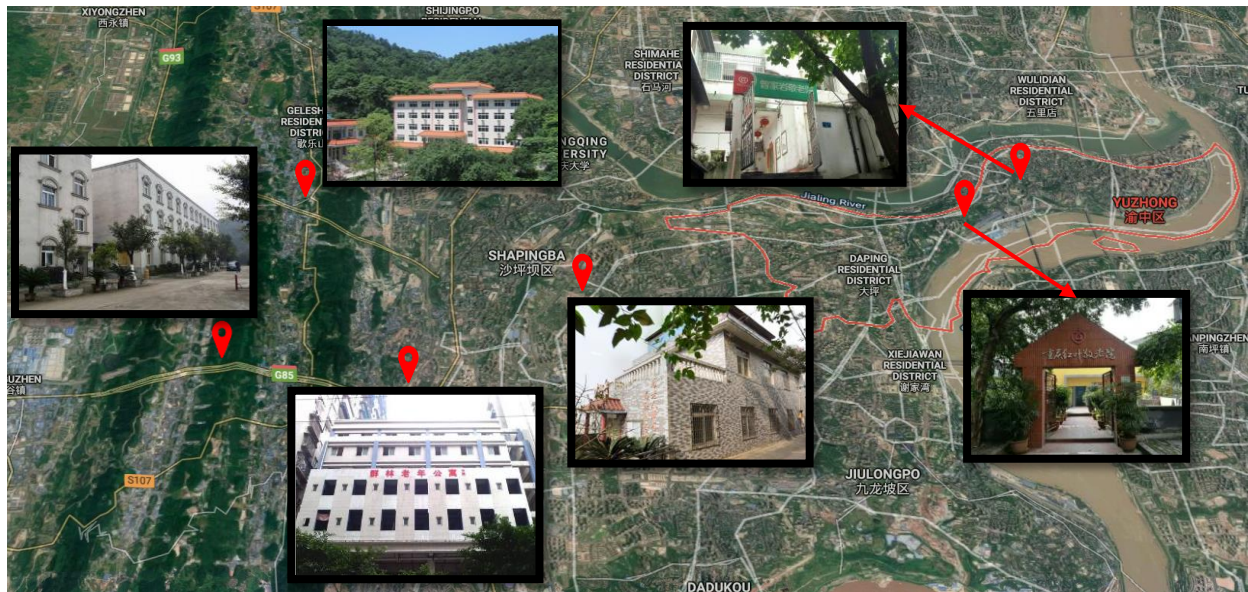
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Fig. 1 (a) The location of Chongqing in China; (b)The surveyed area of residential buildings and location of nursing homes in Chongqing (note: the zone marked by red line – central area of Chongqing); (c) Representative appearance

of a residential building; (d) Picture of indoor survey

The elderly in the residential buildings were recruited when they were outside of their residential quarters, and their home addresses were recorded so that the researchers could investigate them in a subsequent time when they were at home. Although the elderly in nursing homes were investigated directly, during the study, together with the thermal comfort survey, physical measurements of indoor and outdoor conditions were conducted. The physical measurement data were collected during the daytime from 08:30 to 17:30 from 333 elderly persons older than 60 years, who participated in the survey in 17 residential buildings, in addition to 119 elderly persons in 6 nursing homes. The duration of visits at the residences of the elderly participants was approximately 30 min to ensure that all the measurements reached stable values, and the entire questionnaire was answered properly. All samples included were valid data, as any invalid data were checked and redone immediately in the field; otherwise, they were not included in our final data statistics.

The survey included an overall thermal satisfaction vote, thermal sensation vote (TSV), humidity sensation vote (HSV), and air movement sensation vote (ASV). The overall thermal satisfaction was evaluated using a five-point scale: −2 dissatisfied, −1 slightly dissatisfied, 0 acceptable, 1 slightly satisfied, and 2 satisfied. The reasons for dissatisfaction were also investigated when the survey participants selected dissatisfied or slightly dissatisfied. The thermal sensation vote of the elderly was assessed using the ASHRAE seven-point thermal sensation scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) [26]. Similarly, the HSV scale was −3 very humid, −2 humid, −1 slightly humid, 0 just right (neutral), 1 slightly dry, 2 dry, and 3 very dry. The scale of the airflow sensation vote was −3 very stuffy, −2 stuffy, −1 slightly stuffy, 0 comfortable breezeless, 1 acceptable breeziness, 2 draft, and 3 strong draft. Meanwhile, the status of window opening (opened/closed), fan use (used/not used), and mode of AC operation (on/off) was recorded during the survey period. The reasons for opening windows and turning ACs off were determined via interview.

The indoor and outdoor environmental parameters including air temperature, relative humidity (RH), and air velocity were measured during the survey. Table 1 shows the instruments used and their

accuracy. All the instruments whose measurement range and accuracy are shown in Table 1, were calibrated prior to use. Measurements were recorded simultaneously as the subjects filled the questionnaire. The room's air measurement point was located in the vicinity of the abdomen of the subject, i.e., 0.6 m from the floor when seated and 1.1 m from the floor when standing. Outdoor measurement points were chosen in an open area near the buildings where there was no direct solar radiation at a height of 0.6 m from the ground. The instruments for outdoor environment measurement were the same as those used for indoor measurement, which are shown in Table 1.

Table 1. The instruments used for environmental measurement.

Description	Trade name	Parameters measured	Range	Accuracy
Digital temperature-humidity instrument	dwyer485	Air temperature	−30 to 85 ℃	±0.5 ℃
		Relative humidity	0–100%	±2%
Hot-wire anemometer	Testo425	Air velocity	0–20 m/s	±(0.03 m/s +5% measured value)

2.2 Physiological measurement in a climate chamber

2.2.1 Experimental setup

Experiments were conducted in a climate chamber (1.4 m × 3 m × 2.7 m (H)) where the room air temperature (Ta) was adjustable within the range of −5 °C to 40 °C with an accuracy of ±0.30 °C. The RH was controlled between 10 %–90 % with an accuracy of ± 5 %.
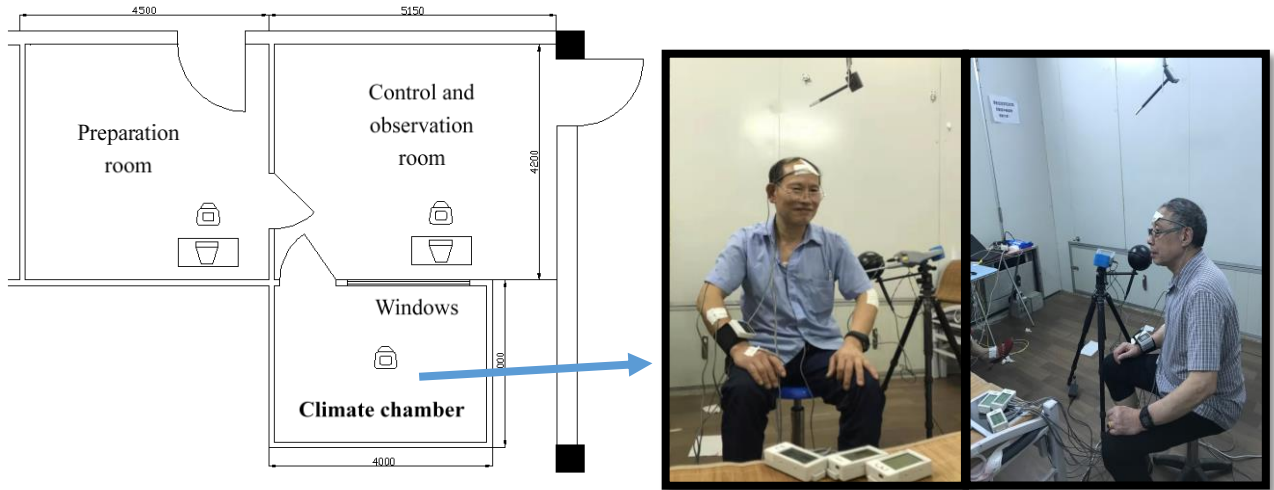
Figure 2. The layout (units: mm) and pictures of the climate chamber

The Thermal Comfort Monitoring Station equipment (LSI) was used to measure environmental parameters such as the indoor air temperature, RH, air velocity, and black-bulb temperature in the vicinity of the subjects. This station was capable of recording measurements and storing the data in a data logger.

Thermocouples with an accuracy of ±0.15 °C, connected to a four-channel data logger (HOBE, UX120-006M), were used to measure the local skin temperature of the subjects. The skin temperature information was automatically recorded by the data logger every 2 s. This parameter was measured at 4 points for the young and middle-aged persons, including the chest, upper arm, calf, and thigh, while measurements from the elderly were taken at 10 points, including the chest, upper arm, calf, thigh, forehead, back, abdomen, lower arm, hand, and foot. Prior to measuring, all the thermocouples were calibrated. On the basis of reliability and sensitivity, a four-point formula proposed in the literature was used to calculate the mean skin temperature (T_{skin}), expressed as [62]:

$$T_{skin} = 0.3T_{chest} + 0.3T_{upperarm} + 0.2T_{thigh} + 0.2T_{calf} \tag{1}$$

An electronic sphygmomanometer (HEM-6021) was used to measure the blood pressure of subjects. The sphygmomanometer was tied to the wrist and lifted to the same height as the heart during measurements. The readings of this instrument were recorded during the questionnaire survey. The heart rate was measured and recorded every 15 s using a heart rate telemeter (Polar RS400). Table 2 represents a summary of the measurement instruments that were used.

Table 2. Ranges and precision of instruments in climate chamber study

Brand/model	Equipment	Parameters	Range	Accuracy
LSI	Thermal Comfort Monitoring Station	Air temperature	−25 to 150 °C	± 0.1 °C
		Relative humidity	0–100% RH	±2% (15–40%) RH
				±1% (40–70%) RH
				±0.5% (70–98%) RH
		Air velocity	0.01–20 m/s	±0.05 m/s (0–0.5 m/s)
				±0.1 m/s (0.5–1.5 m/s)
				4% (> 1.5 m/s)
		Black-bulb temperature	−10 to 100 °C	±0.15 °C
TMC6-HD	Thermocouple temperature sensor	Skin temperature	−40 to 100 °C	±0.15 °C
HEM-6021	Electronic sphygmomanometer	Blood pressure	0–299 mmHg	±3 mmHg
Polar RS400	Heart rate telemeter	Heart rate	15–240 bpm	1 time/min

2.2.2 Subject characteristics

Power analysis, which was introduced by Lan and Lian [63], was helpful in determining the required sample size as well as the interpretation of the research results. Thus, the minimum sample size was obtained using the prior power analyses in G*Power 3.1 [64, 65], with the same parameter settings as found in previous studies [66] except the power $(1-\beta$ error) was set to 0.95. For the statistical test (ANOVA: repeated measures, within factors), the minimum sample size was determined based on effect size d; the minimum sample sizes were 6, 8, and 10 when d = 1, 0.8, and 0.5, respectively. In this study, the physiological responses were assumed to be relatively stable; thus, a minimum sample size of 8 subjects as a group (d = 0.8) was adopted and is verified in the Results Section 4.1.

A gender-balanced total of 24 subjects participated in the experiments, with 8 elderly persons, 8 college students, and 8 middle-aged persons. The basic information of each subject (e.g., age, height, weight) is summarized in Table 3. All the subjects lived in Chongqing for at least one year and could be considered to be thermally acclimated to the hot weather. The elderly participants were recruited from the local residents, whose age were more than 60 and had lived in Chongqing for an average of 40.0 ± 17.5 years. None of the subjects were under prescription medication during the study, and there was no history of cardiovascular disease among them. Subjects were asked to avoid caffeine, alcohol, and intense physical activity for at least 12 h prior to the tests.

2.2.3 Experimental condition and procedure

Because the physiological responses of human beings may not be significantly different in a comfortable temperature range, a cold environment at 18 °C and hot environment at 34 °C, which are possible air temperature values in summer in naturally ventilated buildings in Chongqing, China, used

in our study and in others [27], were used to conduct the test (maximum indoor air temperature is 36.2 °C during the survey).

The experiment lasted for one hour. First, subjects were placed in a preparation room and rested there for approximately 30 min at 26 °C to alleviate the thermal experience effect. Meanwhile, their height, weight, and body fat rate were measured using a height and weight scale (SUHONG) and body fat meter (TANITA BC-601), and their personal information such as age, gender, and length of residence were recorded via interview. This data are presented in Table 3. They were also instructed on the use of the physiological monitors and the process of completing the questionnaires. Subsequently, they entered the climate chamber where the room air temperature was set to either 18 °C or 34 °C for 30 min. In this chamber, measurements were performed at 10- to 15-min intervals for the elderly and at the end of the experiment period for the young and middle-aged subjects. During the experiments, the subject wore typical summer clothing, including short-sleeved T-shirts, trousers, and socks with an insulation level of approximately 0.5 clo (1 clo = 0.155 $m^2 \cdot K/W$) according to the ASHRAE Standard 55 [26].

Table 3. Summary of information on human subjects in the climate chamber study.

	Sample No.	Age	Height (cm)	Weight (kg)	Body fat rate (%)	Length of residence (y)
Young	8	22 ± 1	166 ± 6	56.8 ± 8.7	18.0 ± 4.8	7.9 ± 9.5
Middle-aged	8	50 ± 5	161 ± 8	59.8 ± 10.0	21.3 ± 9.4	25.1 ± 15.9
The elderly	8	65 ± 3	161 ± 8	66.5 ± 8.9	30.3 ± 6.4	40.0 ± 17.5

3 Results of the field study

3.1 Thermal environment and information of the elderly

A summary of the thermal environmental parameters and the information for the participants recorded during the survey is listed in Table 4. During the study, the thermal environment in the residential buildings and nursing homes were similar. The clothing insulation (I_{cl}) was calculated using the clo-checklist method [26]. The outdoor air temperature during the survey in both locations was very hot, with mean values of 30.0 °C and 29.2 °C, respectively. The average indoor air temperature was also approximately 28–29 °C. Throughout the experiment, the average RH of the room space was also high, in the range of 60%–70%. The mean indoor air velocity was as low as 0.14 m/s, and for 90% of the time, the velocity was less than 0.3 m/s. The average age of elderly persons in the residential buildings was 70.05 y with a clothing insulation of 0.30 clo. In nursing homes, the average age was 77.36 y with a clothing insulation of 0.36 clo.

Table 4. Summary of the thermal environmental parameters and occupant information during the survey

Locations		Age	I_{cl}	T_a	RH_{in}	v_{in}	T_{out}	RH_{out}	v_{out}
(No.)		(y)	clo	°C	%	(m/s)	°C	%	(m/s)
Residential	Mean	70.05	0.30	28.97	66.22	0.13	30.02	65.85	0.46
buildings	SD	8.57	0.15	3.00	10.83	0.19	4.58	12.38	0.46
(333)	Min.	60	0.11	22.00	43.40	0.00	19.80	41.90	0.00
	Max.	94	0.88	36.20	91.30	2.22	38.50	98.40	3.57
Nursing	Mean	77.36	0.36	28.31	67.09	0.14	29.21	62.32	0.22
homes	SD	9.22	0.11	2.21	11.10	0.18	2.27	13.08	0.12

(119)	Min.	60	0.11	25.20	52.80	0.03	25.70	45.20	0.04
	Max.	100	0.57	32.90	94.50	1.37	33.00	91.50	0.50

3.2 Psychological responses of the elderly in a hot environment

3.2.1 Overall thermal satisfaction

Overall, the dissatisfaction rates (the sum of dissatisfied and slightly dissatisfied) were 16.3% in residential buildings and 6.8% in nursing homes, as Figure 3 showed. This was very low given that approximately 50% of the questionnaire was conducted when the indoor air temperature was higher than 28 °C. The main reasons for dissatisfaction were hot (50%) and stuffy (25%). Approximately 15% of the elderly respondents experienced a humid environment, with very few reporting a dry, draft, or cold environment, as shown in Figure 4.
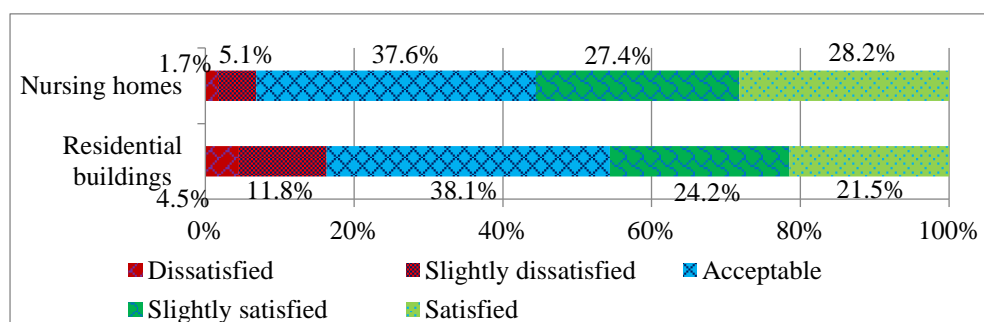

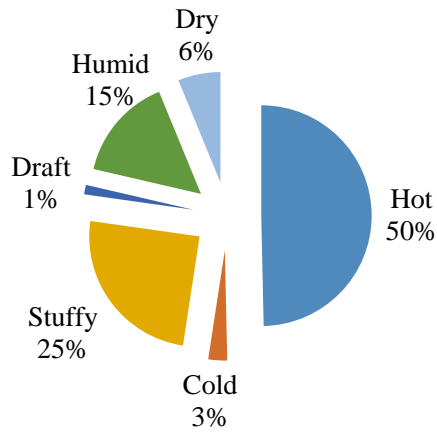**Figure 3.** The overall satisfaction vote for thermal environment

Figure 4. The reasons for dissatisfaction in the indoor thermal environment

The Spearman's test was applied to determine if there is a relationship between the thermal environmental parameters (or other sensations) and the thermal satisfaction vote, as shown in the first line of Table 5. Generally, a strong positive or negative relationship exists when $r_s > 0.3$ or $r_s < −0.3$. Thus, TSV, HSV, and ASV exhibited a significant correlation with the overall thermal satisfaction vote. Among all the thermal environmental parameters, only the indoor and outdoor air temperatures exhibited a significant relationship with the overall thermal satisfaction vote.

The relationships between the thermal environmental parameters and TSV/HSV/ASV are also shown in Table 5. TSV exhibited a stronger correlation with outdoor air temperature ($r_s = 0.440$**) than with indoor air temperature ($r_s = 0.241$**). This means that TSV of the elderly was not only affected by indoor air temperature; it was also affected by outdoor air temperature. The HSV had a strong correlation with the outdoor RH ($r_s = −0.223$**) and indoor RH ($r_s = −0.276$**). This implies that the elderly was able to sense the RH of the air. The ASV was not significantly correlated to any single thermal environmental parameter. However, the ASV was significantly correlated to the overall satisfaction vote, TSV, and HSV, which means that understanding the demand for air movement may depend on the comprehensive assessment of these sensations, in which the air velocity could be actively controlled by elderly persons when the air temperature or RH changes.

Table 5. Spearman's rank correlation coefficient (r_s)

	T_{out} (°C)	T_a (°C)	RH_{out} (%)	RH_a (%)	V_{out} (m/s)	V_a (m/s)	TSV	HSV	ASV
Overall	**−0.221****	**−0.206****	0.045	0.031	0.079	−0.070	−0.411**	0.297**	0.332**
TSV	**0.440****	**0.241****	−0.131*	−0.140*	0.101	0.068	/	−0.155**	−0.331**
HSV	−0.094	−0.025	**−0.223****	**−0.276****	−0.100	−0.009	−0.155**	/	0.257**
ASV	−0.044	−0.022	−0.047	−0.052	0.037	0.031	−0.331**	0.257**	/

**p < 0.001, *p < 0.05
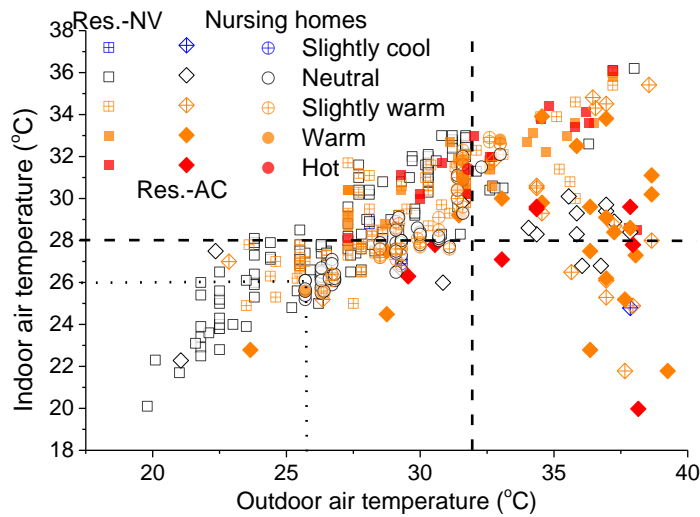
3.2.2 Thermal sensation vote (TSV)

Figure 5 The distribution of the thermal sensation vote with indoor and outdoor air temperature

The distribution of the thermal sensation vote with indoor and outdoor air temperature is shown

in Figure 5, which shows that for approximately half of the time, the outdoor temperature was higher

than 32 °C, or the indoor air temperature was higher than 28 °C. To investigate the contribution of the

outdoor thermal experience on TSV, a comprehensive temperature was used, which was defined as

$T_e = (1 − e)*T_a + e*T_{out}$, where e is the weight associated with the outdoor air temperature. Then, T_e is

linearly fitted with TSV, with the correlation r of the fit for different values of e shown in Table 6.

Results show that TSV was affected by both the indoor and outdoor air temperature. Meanwhile, the outdoor air temperature had a stronger relationship with the indoor TSV under hot climate conditions in residential buildings.

Table 6. Correlation coefficient (r) of linear fitting for thermal sensation vote with comprehensive temperature

e =	0 (T_a)	0.2	0.5	0.8	1 (T_{out})
Res.-NV	0.361	0.396	0.432	0.452	0.458
Res.-AC	0.001	0.068	0.059	0.091	0.101
Nursing homes	0.355	0.356	0.259	0.296	0.258
All	0.265	0.338	0.408	0.433	0.435

Thus, the relationship between the mean thermal sensation vote (each 0.5 °C interval) and the air temperature is shown in Figure 6. Compared with the PMV model, TSV in both nursing homes and residential buildings is less sensitive to the thermal environment. The TSV of the elderly in nursing homes was slightly lower than that in residential buildings, which may be because of the difference in the mean age and health status of the participants. As a result of the low correlation coefficient (r/R^2) of the linear fitting (Table 6 and Figure 6), the PMV or adaptive PMV method based on the indoor air temperature might not be a good index for assessing the thermal environment criterion of the elderly in the AC environment in homes.
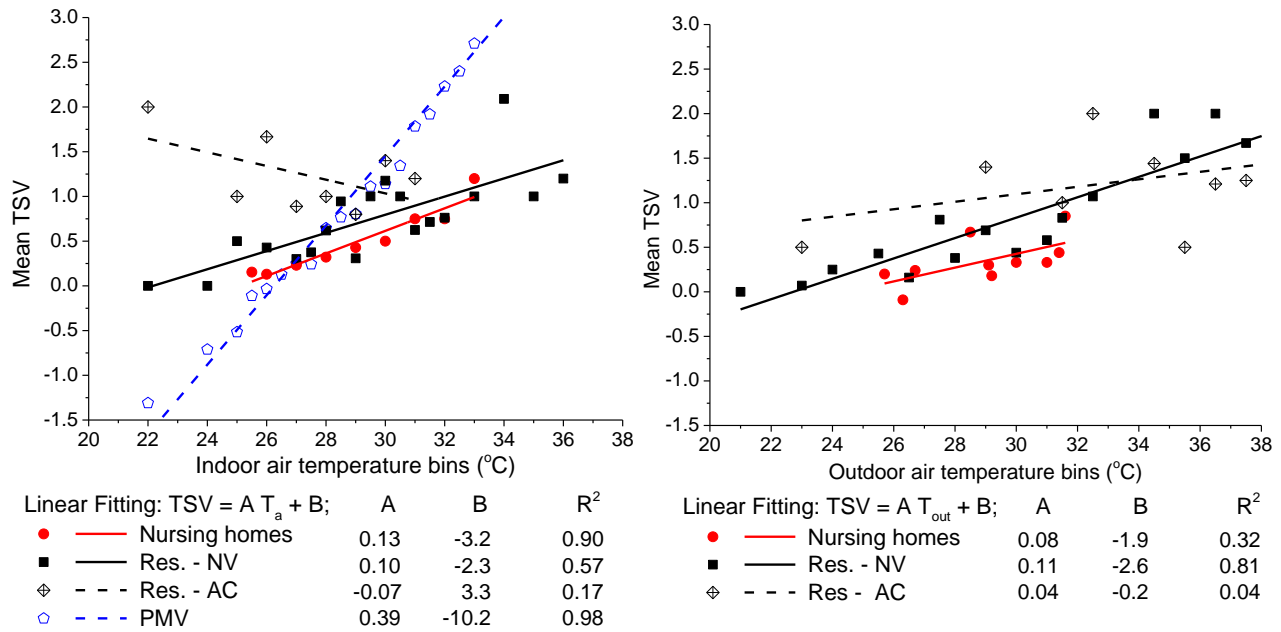
Linear Fitting: TSV = A Ta + B;	A	B	R²
● —— Nursing homes	0.13	-3.2	0.90
■ —— Res. - NV	0.10	-2.3	0.57
⊕ - - - Res. - AC	-0.07	3.3	0.17
⬠ - - - PMV	0.39	-10.2	0.98

Linear Fitting: TSV = A Tout + B;	A	B	R²
● —— Nursing homes	0.08	-1.9	0.32
■ —— Res. - NV	0.11	-2.6	0.81
⊕ - - - Res - AC	0.04	-0.2	0.04

Figure 6 Mean thermal sensation vote with indoor and outdoor air temperature

3.3 Behavioral responses of the elderly

3.3.1 Brief overview

The main cooling measures in the residential buildings were NV, i.e., opened windows (53.1%), fans (19.5%), AC (11.11%), and none (15.2%), as shown in Figure 7. However, elderly persons in nursing homes notably did not turn on the AC unit during the survey, even though the indoor air temperature was as high as 30 °C. Approximately 30.3% of elderly persons in nursing homes opened windows and switched on fans when the weather was hot; others took no action, which may have been influenced by the nurses.
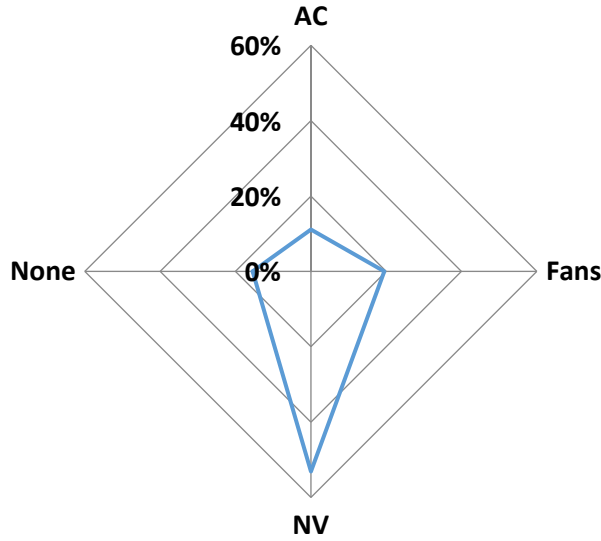
Figure 7. The proportions of the different cooling measures in residential buildings during the survey

To analyze the relationship between behaviors and the thermal environment, the room air temperature bins were divided for each 0.5 °C interval. The proportion of fan usage (PFU) is defined as the ratio of the number of fans being used to the total number surveyed in one environmental parameter bin. Similarly, the proportion of windows opened (PWO) and air-conditioned (PAC) are defined as the ratio of the number of rooms with open windows and those that are air-conditioned to the total surveyed number of rooms in one environmental parameter bin.

Logistic regression is a useful method for the analysis of binary response variables with only two outcomes, such that the probability varies with a stimulus [38, 39]. Thus, logistic regression is used when the correlation between environmental parameter bins and PFU (PWO or PAC) is analyzed and can be expressed as:

$$\mathrm{P} = \frac{e^{b*x+c}}{1+e^{e^{b*x+c}}} \tag{2}$$

where P is the probability that the adaptive behavior appeared, e.g., PFU (PWO or PAC), x is the environmental stimulus, e.g., the indoor and outdoor temperature, b is the regression coefficient, and c is the constant in the regression equation. Efron's pseudo R^2 is applied to evaluate the goodness-of-

fit of the logistic model in this study, and the level of the significance is set to < 0.05.

3.3.2 Proportion of air-conditioned (PAC) with outdoor air temperature

Air conditioners were not turned on during the survey in the welfare facility. Thus, PAC was analyzed in the residential buildings, as shown in Figure 8. PAC increased when the outdoor air temperature was higher: 20% of the elderly at 32.5 °C, 50% at 35 °C, and 80% at 38.5 °C. This indicates that the elderly threshold for unacceptable thermal discomfort was approximately 32.5 °C, which was slightly higher than the value obtained in another study in a similar climatic zone in Nanjing, China [67]. Logistic regression was used to fit PAC with the outdoor air temperature, as shown in Figure 8 and Table 5. The pseudo R^2 is 0.89, which means that the degree of fit is good.
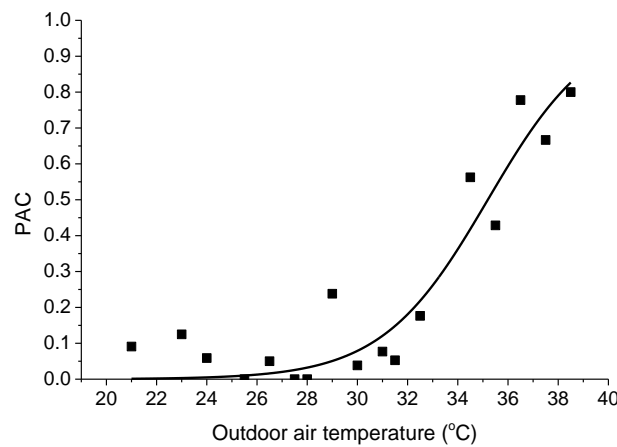

Figure 8. Proportion of air-conditioned rooms as a function of outdoor air temperature in residential buildings

Although air conditioners were installed in approximately 87.5% of the rooms, the ACs were used in only 11.1% of the rooms during the survey in the residential buildings. The reasons for the low usage of ACs was investigated in the field study. From Figure 9, the indicated reasons are: 1) save money (29%)—some of the elderly lived frugally and were not willing to use AC all the time; 2) no need for AC (23%)—some of the elderly were not used to an AC environment and preferred to use other methods, such as fans or reduce clothing, in the current indoor thermal environment; 3) avoiding the onset of sickness (draft 19% and stuffy air 15%)—the cool air from the AC vent and the

temperature difference between indoor and outdoor might cause the elderly to be more susceptible to the common cold. Moreover, sick building syndrome increased owing to the stuffy environment, as 87.8% of the elderly closed the windows when the ACs were turned on to save money; 4) no ACs installed (14%).
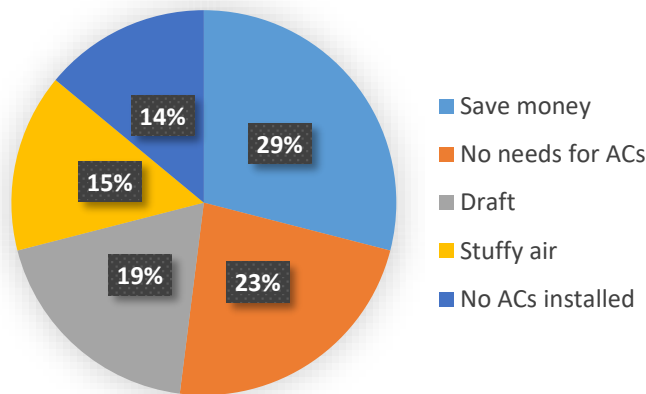

Figure 9. The reasons that elderly participants did not use AC

Table 7. The prevalence of sick building syndrome symptoms between AC and non-AC environments from the survey in residential buildings

	Fatigue	Dizzy	Eye irritation	Respiratory tract discomfort	Nose obstruction	Tinnitus	Skin problem
AC	9.76%	7.32%	6.10%	3.66%	10.98%	2.44%	4.88%
Non-AC	5.48%	3.08%	3.77%	2.40%	2.05%	2.40%	3.42%

As Table 7 shows, the most prevalent symptoms of sick building syndrome were nose obstruction (11.0%), fatigue (9.8%) and dizziness (7.3%), followed by eye irritation (6.1%) and skin problem (4.9%), in an AC environment. All the reported symptoms were reduced in a non-AC environment. The prevalence of nose obstruction was significantly less in a non-AC environment (only 2.1%). This

result also supports the findings from the field study by the Chinese Center for Disease Control and Prevention (also known as CCDC) [68].

3.3.3 Proportion of windows opened (PWO) and proportion of fans used (PFU) with air temperature

The relationship between PWO (or PFU) and air temperature measured at the moment of the survey is shown in Figure 10 and Table 6. Logistic regression was used to fit PWO/PFU with the indoor and outdoor air temperature, which can be expressed as shown in Table 8. In nursing homes, the windows were opened when the indoor air temperature was higher than 29 °C (or outdoor 31 °C), which was at the same level as that for PFU. The pseudo R^2 is 0.99 for the nursing homes, which means that the degree of fit is good. In the residential buildings, PWO slowly increased when the indoor air temperature increased. However, it decreased with outdoor air temperature in the range of 0.2–1.0 over the entire summer season. The pseudo R^2 of the logistic regression between PWO with indoor and outdoor air temperature bins are 0.32 and 0.51, respectively, as shown in Table 8, which means that the indoor and outdoor air temperature have weak relationships with PWO in residential buildings.
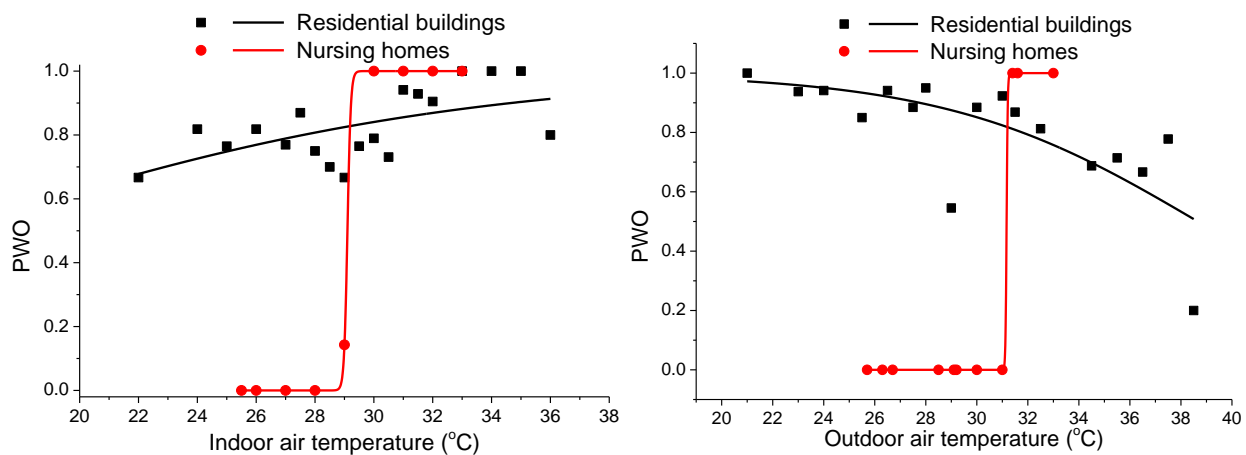

Figure 10. Proportion of windows open with air temperature bins

PFU also has a strong relationship with the indoor air temperature in this study (Figure 11). In nursing homes, fans were allowed to run when the indoor air temperature was higher than 29 °C (31 °C

for outdoors), which was the same condition as that for PWO. In residential buildings, the pseudo R^2

for PFU with indoor air temperature bins is 0.74, which is higher than that for outdoor air temperature

bins (0.59). PFU generally increased with the indoor and outdoor air temperature and reached a value

of approximately 20% at 30 °C, and 40% and 80% at indoor air temperatures of 33 °C and 36 °C,
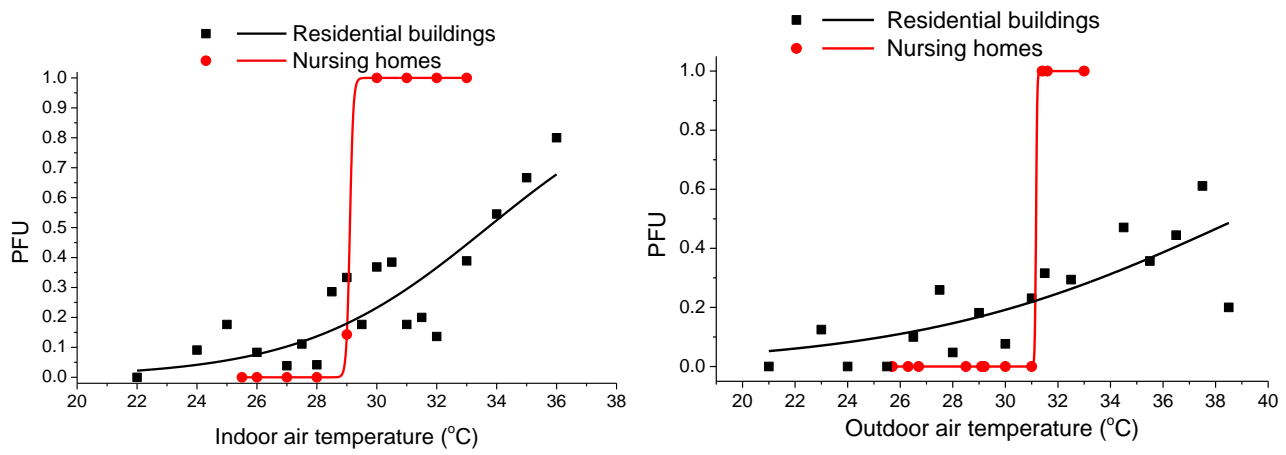
respectively.

Figure 11. Proportion of fans used with indoor air temperature bins

Table 8. Logistic regression for the relationship between the usage proportion of each control and air temperature

Types	P	x	b	c	R^2	P
Residential buildings	PAC	T_{out}	0.473	−16.64	0.89	< 0.001
	PWO	T_a	0.115	−1.783	0.32	0.005
	PWO	T_{out}	-0.201	7.788	0.51	0.002
	PFU	T_a	0.323	−10.89	0.74	< 0.001
	PFU	T_{out}	0.162	−6.312	0.59	< 0.001
Nursing homes	PWO/PFU	T_a	−17.66	513.8	0.99	0.001
	PWO/PFU	T_{out}	46.05	−1435.2	0.99	0.011

Note: The parameters are used in Equation (2)

4. Results of the experimental study in the climate chamber

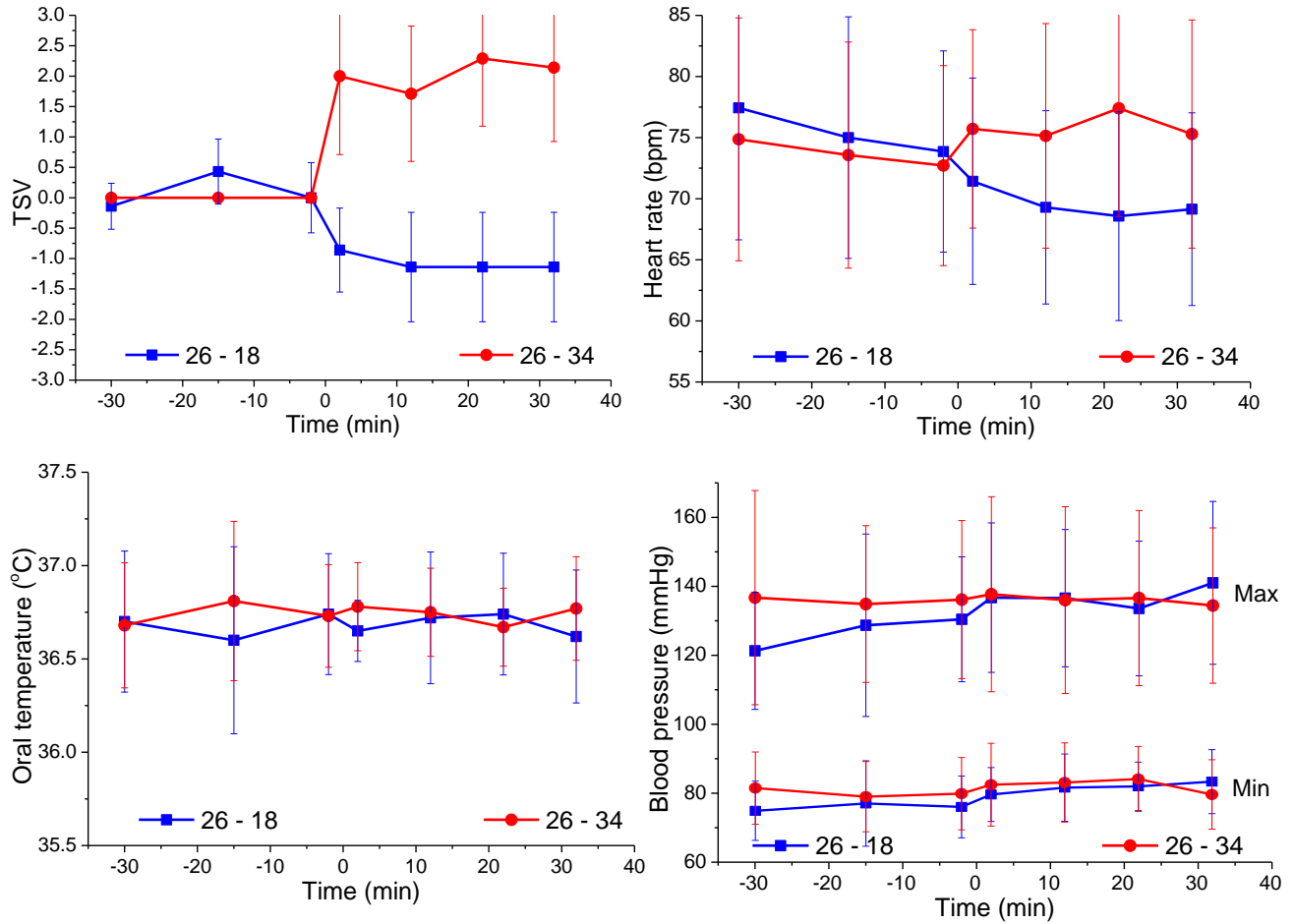## 4.1 Thermal responses of the elderly to cold/hot exposure

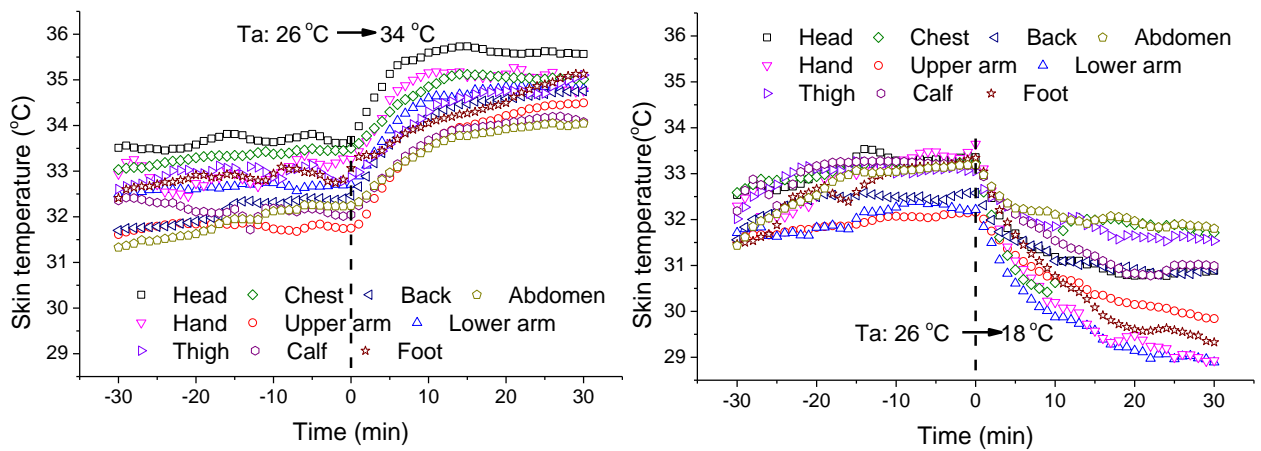**Figure 12.** Thermal sensation vote and physiological responses with time

Figure 13. Local skin temperature of the elderly with time

TSV of the elderly exposed to 18/34 °C with time is shown in Figure 12. Theoretically, the skin temperature could be an index for human body heat balance to the thermal environment, the oral temperature could be used to represent the core temperature of the human body, the heart rate could reflect the metabolism of the human body and blood output, and the blood pressure was relative to angiectasis and vasoconstriction in human skin. Vasoconstriction of the skin occurs to reduce blood flow volume in the skin to minimize heat loss in cold environments, which results in higher blood pressure. Thus, generally, blood pressure might be negatively correlated to air temperature. However, no significant difference in the oral temperature and blood pressure was demonstrated when the elderly were exposed to a cold/hot environment. Meanwhile, TSV and local skin temperature all responded to the change in air temperature, as shown in Figure 13.

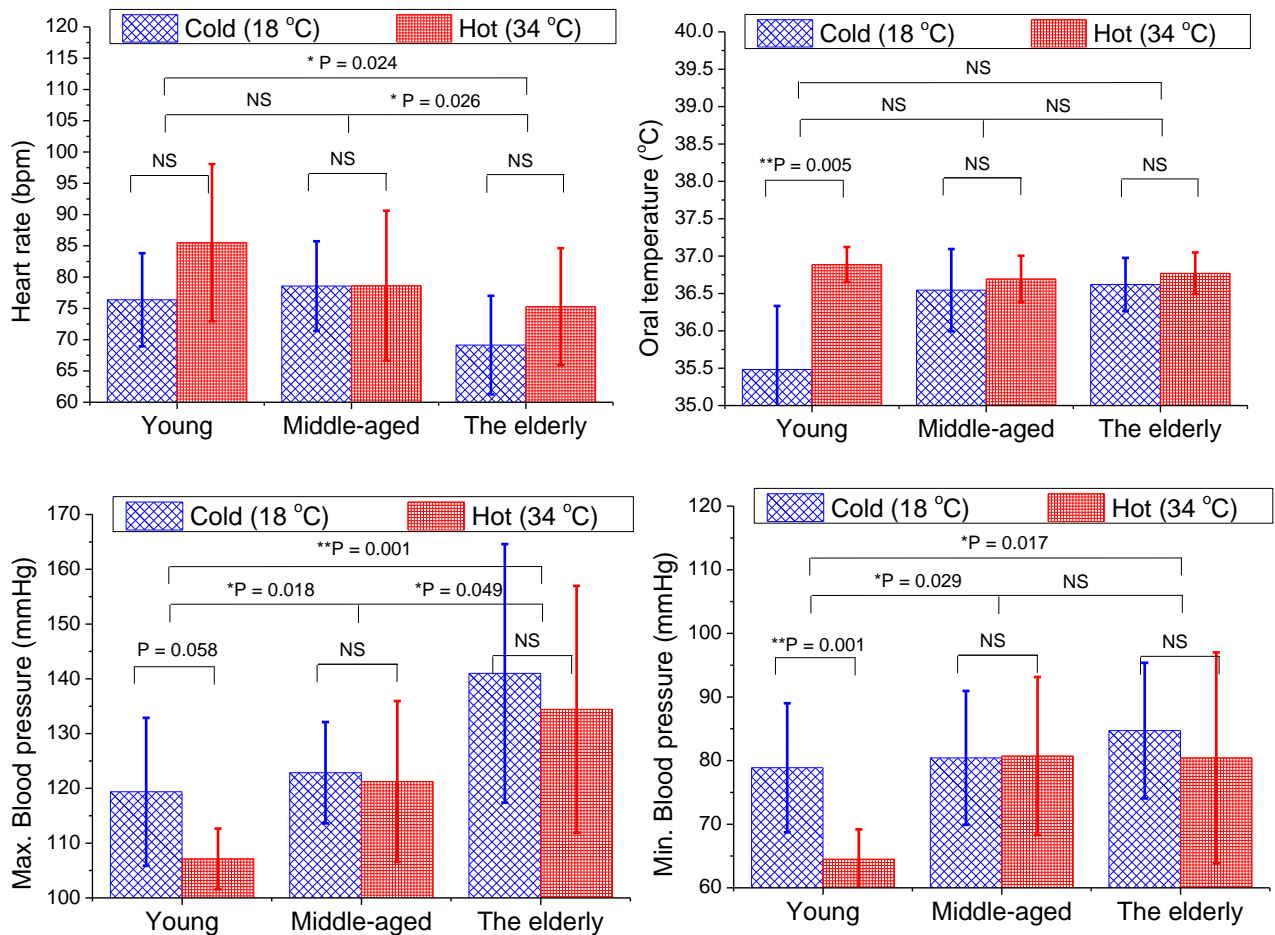## 4.2 Difference in physiological responses with aging
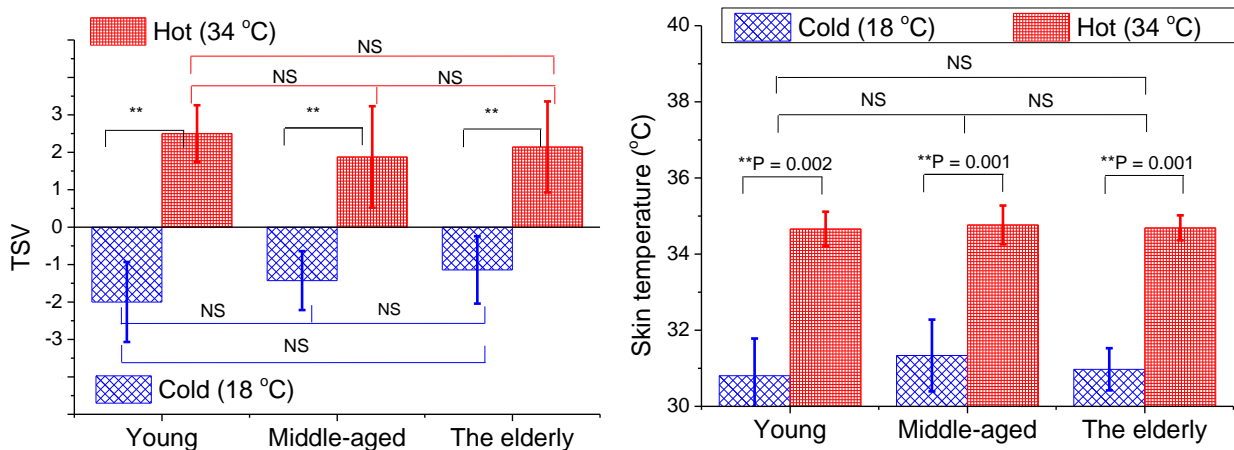
Figure 14. Physiological responses of subjects of different age groups in cool (18 °C) and hot (34 °C) environments (note: p – significant value, d – effect size)

To compare the results from younger subjects, the mean values and standard deviation of TSV and physiological responses are shown in Figure 14, and significance tests were conducted. Figure 14 shows that there were no differences in the responses for skin temperature between the young, middle-aged, and elderly groups. The oral temperature and blood pressure of the young subjects revealed significant differences in cold and hot exposure. However, the oral temperature and heart rate of the middle-aged and elderly groups did not increase in the hot environment, nor did the blood pressure of these groups. This is in contrast to the result for the group of young persons. As such, the skin temperature could be regarded as an optimal indicator to evaluate thermal sensation in the elderly,

demonstrating the need for more studies on this theme.

5 Discussion

5.1 Behavioral responses

Figure 15 shows that the elderly are passive users of air conditioners, as the PAC of the elderly was lower than that for working-aged persons in most cases of both office buildings [69] [70] and residential buildings [71] [72]. The PFU of the elderly in residential buildings was similar to that of the study of residential buildings in Sydney [72], and PFU in nursing homes was similar to that in office buildings [69] [70] but less flexible. The PWO of the elderly in residential buildings was higher than that of the study in residential buildings in Sydney, while PWO in these two studies decreased with outdoor air temperature owing to the usage of ACs in hot weather [72], which was different than the case for office buildings [69] [70]. It is noted that the PWO of study [57] from nursing homes in Shanghai was close to that in office buildings, which was similar to the situation of nursing homes in this study. The behavioral responses of the elderly subjects in a hot environment were unavoidably affected by other members who lived with the subjects or the nurses who cared for them. They also preferred natural ventilation because of the higher prevalence of sick building syndrome symptoms in an AC environment and avoided staying in an unacceptable cooling environment owing to insensitivity in both psychological and physiological ways.
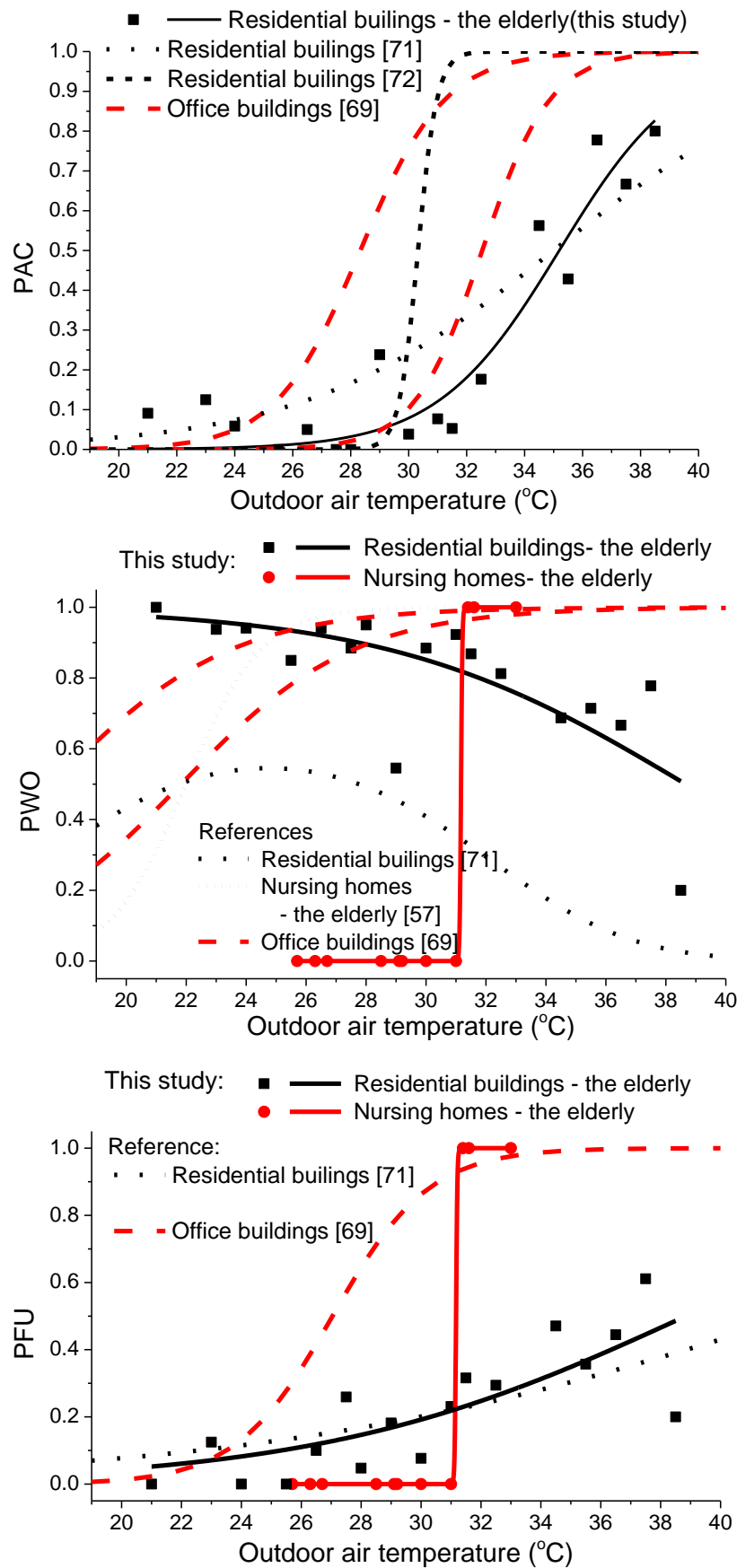
Figure 15. Comparison of behavioral responses of the elderly in this study with other studies in the literature

5.2 The psychological and physiological responses of the elderly in summer

In this study, the thermal satisfaction and thermal sensation of the elderly were significantly correlated to indoor and outdoor air temperature, according to the results of Spearman's rank correlation test. However, the mean thermal sensation vote of the elderly was not only lower than the estimates of the PMV model in a warm environment but also had a weak linear relationship with indoor air temperature bins in the field study. The results from the chamber study showed that elderly persons were able to perceive variations in the thermal environment, implying that their thermal sensation was highly affected by the outdoor thermal experience in a dynamic environment in real building setting [73].

This is due to several reasons: 1) Elderly undergo physiological debility with aging. Elderly persons are more insensitive to the change in the surrounding environment than young subjects are [74], i.e., they are unable to sense thermal stresses immediately and encounter more difficulty in restoration from a previous hot thermal stress. 2) Thermal expectation could also account for the observed effect on occupant thermal sensation and comfort, which was indicted by Fanger [75]. As such, the elderly might prefer a warm climate to a cool climate [55, 76] and have low thermal expectations for neutral climates in a warm environment owing to long thermal histories with the hot local climate. 3) Psychological dependency on other family members or nurses might also be a factor, with less willingness to express discomfort when interviewed by researchers.

Although the acceptable air temperature could be much wider than indicated by calculations from the TSV vote of ±0.5, this may not satisfy the long-term physical health requirements of the elderly [77]. Given that the skin temperature shows similar responses for the young and the elderly in this study and previous study [78], the relationship between TSV and skin temperature for college students

in the hot humid climate zone is recommended for the elderly in this climate area [66, 79-81]. Considering that the elderly experience higher health risks in cold environments, we suggest that the warmer end of the acceptable skin temperature range should be used to apply the results of this study.

6 Conclusions

This study examined the psychological, behavioral, and physiological responses of the elderly in a hot environment. The main results are as follows:

1) The main reasons for dissatisfaction of the elderly were hot (50%) and stuffy (25%) in the field study. Spearman's rank correlation test revealed that the indoor and outdoor air temperature significantly and strongly affected the overall thermal satisfaction and thermal sensation of the elderly. It also established that the elderly can perceive air RH.

2) The mean thermal sensation vote of the elderly was not only lower than the PMV model estimates for a warm environment but also had a weak linear relationship with indoor air temperature owing to the effect of the outdoor thermal experience.

3) The results show that elderly persons are passive users. Natural ventilation was the main cooling method used by the elderly. The behaviors of the elderly in nursing homes were closer to that found in office buildings.

4) The elderly and middle-aged persons were less sensitive to the thermal environment than college students in terms of physiological responses including oral temperature, blood pressure, and heart rate, all of which were almost constant when the air temperature changed. The elderly also had a lowest mean heart rate and higher maximum blood pressure than that of younger people, which served to jeopardize their thermal adaptation to a cold environment. As such, these parameters are not ideal thermal comfort indexes to represent the elderly without revision.

5) The skin temperature of the elderly changed significantly with air temperature, similar to that experienced by college students. As such, this parameter was noted as a potential thermal comfort index for the elderly.

Limitation of this study

To interpret the research results based on power analysis and verify the sample size, a post hoc power analysis was conducted in G*Power 3.1, and the power level $(1 − \beta$ error) was calculated to be higher than 0.96 and 0.99 when effect size d was larger than 0.8 and 1, respectively.

The effect size (d) in this study was calculated using the following equations:

$$d = \frac{\overline{x_1} - \overline{x_2}}{S} \tag{3}$$

$$S = \sqrt{\frac{(n_1-1)S_1^2 + (n_2-1)S_2^2}{n_1+n_1}} \tag{4}$$

where d = effect size, x = group mean, S = standard deviation, n = number of subjects, and subscripts 1 and 2 refer to the two groups. Effect size d was calculated for P values lower than 0.05, and the d values are all larger than 1 with a preset value of 0.8. 'Effect size' is a way of quantifying the size of the difference between two groups. This means that a sample size of 8 is sufficiently large for a significance test (when $P < 0.05$) of the physiological comparison in this study. However, for the comparison of TSV between different age groups in the climate chamber, no significant difference was founded, even when the max TSV difference was 0.86. A larger sample size may be needed for subjective evaluation.

The test period in the experimental study for the consideration of the health risk of subjects in a hot/cold environment only lasted for 30 min. Thus, the results from this study only reflect the ability and responsiveness of physiological thermal adaptation for short-time exposure, which may not represent the stable values of the physiological parameters of the subjects at 18 °C and 34 °C for longer

time exposure, e.g., 8 h/24 h. Further study into the clear mechanism of elderly physiological responses with thermal adaptation behaviors is necessary in the future.

Declarations of interest: none

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