Building and Environment 64 (2013) 213–224

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal comfort in buildings with split air-conditioners in hot-humid area of China

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ARTICLE INFO

Article history:
Received 17 July 2012
Received in revised form
14 September 2012
Accepted 14 September 2012

Keywords:
Thermal comfort
Buildings with split air-conditioners
Hot-humid area
Thermal adaptation

ABSTRACT

Occupants' thermal sensations, perceptions and behaviors in buildings with split air-conditioners in hot-humid area of China were systematically investigated for a whole year with longitudinal design. Thirty college students, naturally acclimatized to local climate and well experienced with the indoor environments of buildings, participated in the present study. They reported their thermal sensations, perceptions and behaviors in questionnaires while their ambient environmental variables were measured. A close match of indoor and outdoor climate was found. Thermal sensation was found to be a linear function of ET* or SET and thermal neutrality was 25.6 °C in ET* or 24.9 °C in SET. The central five categories of the ASHRAE 9-point thermal sensation scale were found to be acceptable and the 90% (80%) acceptable range of thermal environment was found to be 20.6–30.5 °C (16.9–34.2 °C) in ET*. The adaptive behaviors of clothing adjustment, opening windows and using fans were found to be closely correlated with indoor ET*. The split air-conditioners were used from May to October and turned on most often at midnight with indoor air temperature of 30.1 °C and setting temperature of 26.1 °C. Compared with those from naturally ventilated buildings, the occupants from buildings with split air-conditioners kept indoor climates much cooler, used adaptive opportunities much earlier and perceived their ambient environments more sensitively and rigidly.

1. Introduction

Literature reviews on thermal comfort studies in built environment reveal that not only indoor environments, but also outdoor climates and building controls may have significant impacts on human thermal comfort through behavioral or psychological approaches [1,2]. Along with this finding, a lot of field studies on thermal comfort have been conducted in a great many real buildings throughout the world, which are rich in adaptive opportunities and human interactions with environment and provide strong evidences for human thermal adaptation.

Located in South China, the hot-humid area of China has a large population, a fast-developed economy and a huge number of buildings. The summer is hot and humid and nearly half a year and thermal comfort study is very important in this area especially for building designers and engineers. As only few studies have been carried out before, a thermal comfort field study had been conducted in this area by the authors and their colleagues (refer to [3]). As its continuing part, the present study is focused as well on human thermal comfort in real buildings in hot-humid area of China.

The greatest difference between the two mentioned studies is on buildings. Naturally ventilated buildings were investigated in the previous one and buildings installed with split air-conditioners were studied in the present one. Compared with naturally ventilated (NV) or centrally air-conditioned (AC) buildings, buildings with split air-conditioners (referred to as SAC buildings for convenience) are much more common and widely distributed in South China. SAC buildings are very often encountered in residential, office and commercial buildings due to their reasonable prices, great conveniences and good balances between investment and environmental quality. Taking a fast-developed province in hot-humid area of China as an example, the ownership of air-conditioners has reached to 2 units per household for the urban residents of Guangdong Province at the end of 2010, and most of the household air-conditioners are split type. To conduct thermal comfort study in SAC buildings can provide valuable information and guidance for design of buildings and air-conditioners in hot-humid area of China.

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0360-1323/$ – see front matter
http://dx.doi.org/10.1016/j.buildenv.2012.09.009

On the other side, human thermal comfort and adaptation in SAC buildings could be different with NV or AC buildings. SAC buildings on one hand provide occupants with adaptive opportunities of operable windows, electrical fans and clothing adjustments as NV buildings do, and on the other hand, SAC buildings are yet similar with AC buildings on aspects of cool and constant indoor thermal environments. Human thermal adaptation in SAC buildings might be a mixture of that in NV and AC buildings and the thermal comfort study in SAC building is believed to provide important evidences for understanding human thermal adaptation to built environments.

The present study is aimed to investigate occupants' thermal sensations, perceptions and behaviors in buildings with split air-conditioners in hot-humid area of China and make comparisons between buildings with split air-conditioners and naturally ventilated buildings. The present study is believed to be potentially valuable for both the knowledge on human thermal comfort and adaptation and the practical applications for design of such buildings.

2. Survey methods

2.1. City and buildings

Guangzhou, located at latitude 23°08'N and longitude 113°19'E, is a typical city in hot-humid area of China. Summer is hot and humid and winter is warm. The mean outdoor air temperature is 28.4 °C in July and 13.3 °C in January. The relative humidity is around 83% in summer and 70% in winter. The mean daily temperature variation is only 7.5 °C.

The dormitory and teaching buildings in a college in Guangzhou were selected to be investigated in the present study, which provide occupants with split air-conditioners, operable windows and electrical fans (see Fig. 1). Each air-conditioner in the dormitory buildings was shared and controlled by three or four persons living together in a room, just like the normal situation in residential buildings. More than 15 students shared one classroom in the teaching buildings and air-conditioners were mainly controlled by managers or teachers, which is similar with that in small offices in the area.

2.2. Subjects

Table 1
Anthropometric data of the subjects.

Gender	Number	Age	Height (cm)	Weight (kg)	BMI[a] (kg/m^2)
Male	15	20±1[b]	173.7 ± 7.0	64.9 ± 6.6	21.5 ± 1.7
Female	15	20 ± 1	159.5 ± 5.5	48.8 ± 5.6	19.1 ± 1.2
Male + Female	30	20 ± 1	166.6 ± 9.5	56.8 ± 10.1	20.3 ± 1.9

[a] Body mass index, BMI = weight/height^2, normally between 18 and 25 kg/m^2.
[b] Standard deviation.

Thirty healthy Chinese college students, half males and half females, with a normal range of age, height and weight (see Table 1 for details), participated in the study. The subjects have been studying or living in the investigated buildings for more than one year and they were all born in and grew up in the Pearl River Delta region (a typical hot-humid area of China), which guarantees their long experiences with the investigated buildings and natural acclimatization to local climate.

2.3. Conduct of the survey

Longitudinal design was adopted in the present study that the group of subjects was surveyed repeatedly for a whole year. Each subject was surveyed twice a week, one in the teaching buildings and the other in the dormitory buildings. During each survey, the subjects completed a subjective questionnaire, and meanwhile their ambient environments were measured by the investigators. The total time taken by each survey is about 15 min.

Measurements of air temperature, relative humidity, globe temperature and air velocity were conducted by using lab-grade instruments as shown in Table 2 and Fig. 2a. The measuring positions were chosen to be close to the subjects within a distance of 0.3 m, and at three heights (0.1, 0.6 and 1.1 m) above floor (see Fig. 2b).

The subjective questionnaire started with activity report and clothing checklist, followed by a section on behaviors of opening windows and using fans, and concluded with ratings on thermal

Table 2
Detailed information of instruments.

Physical quantity	Instrument	Range	Accuracy
Air temperature	RHLOG temperature and humidity recorder	−20–75 °C	±0.3 °C
Relative humidity	WBGT-103 WBGT meter	10–90%	±5%
Globe temperature	WBGT-103 WBGT meter	0–80 °C	±2 °C
Air velocity	HD 2303.0 Omni-directional anemometer	0–5 m/s	±0.02 m/s (0–0.99 m/s) ±0.1 m/s (1–5 m/s)

Dormitory buildings

Teaching buildings

Fig. 1. Buildings to be investigated.

Instruments

Physical measurements

Fig. 2. Instruments and physical measurements.

sensation, comfort and acceptability scales (see Appendix and Fig. 3). Considering the hot and humid conditions probably encountered in the survey, the ASHRAE 9-point thermal sensation scale was adopted in the questionnaire. The questionnaire was written in Chinese, and some English captions were reserved as well to ensure a correct understanding.

The field survey were lasted for a whole year long, from January of 2009 to January of 2010, and interrupted for several weeks intermediately for summer and winter holidays. Some data were missing due to the absence of subjects and finally 1395 sets of raw data in 33 weeks were obtained. The collected data were categorized as data set of spring (1st–11th week), summer (12th–21st week), autumn (22nd–32nd week) and winter (33rd week) according to the season division of Guangzhou [3] (see Table 3).

Besides the above survey, 10 recorders were placed in 10 rooms of the dormitory buildings to get the information of using split air-conditioners. The recorders continuously measured indoor air temperature (accuracy ±0.3 °C) and relative humidity (accuracy ±3%) and recorded them at a 10-min interval for a whole year. There is no recorder placed in the teaching buildings for the practical reasons of safety and management difficulties.

3. Results and discussions

3.1. Thermal environments

3.1.1. Air temperature and relative humidity

Mean value was calculated for each week and the weekly changes of air temperature and relative humidity are shown in Fig. 4. Air temperature increased in spring from 18.0 °C to 28.3 °C, varied slightly in summer with a range of 28.3–31.7 °C and an average of 29.6 °C, decreased rapidly in autumn from 27.9 °C to 16.2 °C, and then reached the winter value of 16.1 °C. Mean values of relative humidity were 60% in spring, 66% in summer, 52% in autumn and 54% in winter.

Compared with the typical meteorological year of Guangzhou (Fig. 5), it can be seen that the indoor climate of the investigated buildings closely tracks the variations of outdoor climate in aspects of both air temperature and humidity.

3.1.2. Air velocity and mean radiant temperature

The weekly changes of air velocity and mean radiant temperature are shown in Fig. 6. Mean radiant temperature (MRT) was calculated based on air temperature, velocity and globe temperature according to ISO 7726 [5].

The subjects kept their ambient air velocity at a lower level of 0.11 m/s in spring, increased rapidly in summer with an average of 0.41 m/s, decreased rapidly in autumn and then kept at a lower level again. The weekly change of MRT is similar with that of air temperature. MRT was greater than air temperature in most of the time by an average of 1 °C, which indicates a significant radiant impact that can not be ignored in the investigated buildings.

3.1.3. Non-uniformity

The maximum difference among the values measured at three heights was calculated as non-uniformity and the non-uniformities of indoor environment are shown in Table 4. Compared to the absolute value, air velocity was found to be the most non-uniformly

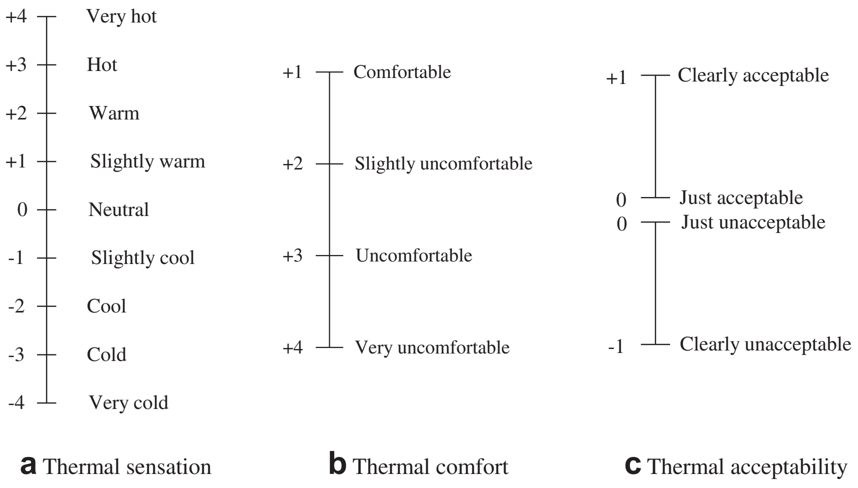


Fig. 3. Rating scales of thermal sensation and perceptions.

Table 3
Weeks, months and seasons.

Week	Month	Season	Week	Month	Season	Week	Month	Season
1–5	Mar	Spring	14–18	Jun	Summer	24–27	Nov	Autumn
6–9	Apr	Spring	19–20	Sep	Summer	28–32	Dec	Autumn
10–11	Early May	Spring	21	Early Oct	Summer	33	Jan	Winter
12–13	Late May	Summer	22–23	Late Oct	Autumn	–	–	–

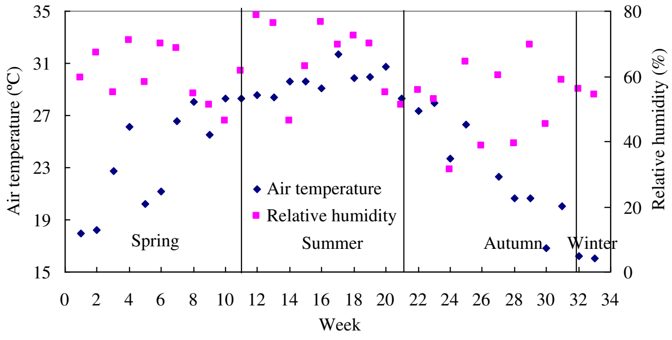


Fig. 4. Weekly changes of air temperature and relative humidity.

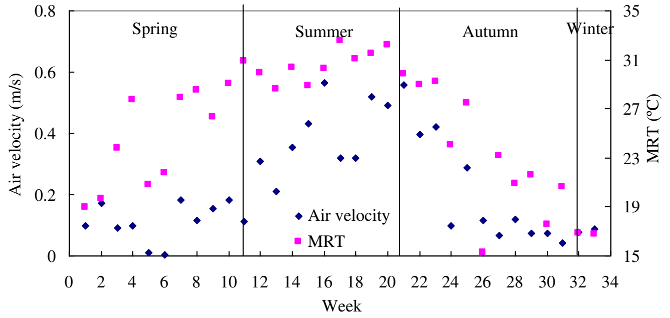


Fig. 6. Weekly changes of air velocity and mean radiant temperature.

distributed quantity, which may be caused by the natural ventilation from windows and local airflow from fans.

3.2. *Personal factors*

More than 80% of the subjects reported to be sedentary in the preceding 20 min before survey, and all the subjects were kept seated quietly for 15 min during survey, which can to a large extent ensure that the metabolic rate is 1.0 met.

The individual articles were first converted into their respective thermal insulation values as tabulated in ASHARE standard 55 [6], and then summed together with that of a normal chair (0.1 clo) to achieve the overall clo value for an entire clothing ensemble. The weekly change of clothing insulation is shown in Fig. 7. The subjects changed their clothing from heavy ones to light ones gradually in spring, dressed lightly in summer with an average insulation of 0.43 clo, and then dressed more and more in autumn and winter.

As an important approach to adapt to thermal environment, clothing adjustment has been viewed as an adaptive behavior by many studies [7–11] and the clothing insulation has been accordingly related to indoor and outdoor climate. In the present study, correlations between clothing insulation and indoor air temperature, operative temperature, globe temperature and effective temperature (ET*) were analyzed respectively, and the results show that their correlation coefficients are almost the same. Considering the high humidity level and strong radiant impact found in the investigated buildings (see Figs. 4 and 6), ET*, which integrates air temperature, humidity and radiation together, was decided to be the proper factor correlated with clothing insulation (Clo). Their relationship is obtained as follows and shown in Fig. 8.

$$\text{Clo} = -0.039\ \text{ET}^* + 1.625 \quad \left(R^2 = 0.296\right) \tag{1}$$

Hwang R et al. [9] obtained the linear relationships between clothing insulation and indoor ET* for both NV and AC buildings in Taiwan as follows (obtained by the figure provided in the original paper and the insulation of a normal chair was included):

$$\text{Clo} = -0.0275\ \text{ET}^* + 1.3267 \quad (\text{NV buildings in Taiwan}) \tag{2}$$

$$\text{Clo} = -0.02\ \text{ET}^* + 1.18 \quad (\text{AC buildings in Taiwan}) \tag{3}$$

Compared with those results by Hwang R et al, it can be found that the clothing adjustment function obtained in SAC building of the present study is very similar with that of NV buildings, which is more sensitive than that of AC buildings in Taiwan (see Fig. 8).

3.3. *Thermal sensation*

The weekly change of thermal sensation is shown in Fig. 9. The sensations of subjects changed from ‘slightly cool’ to ‘slightly warm’

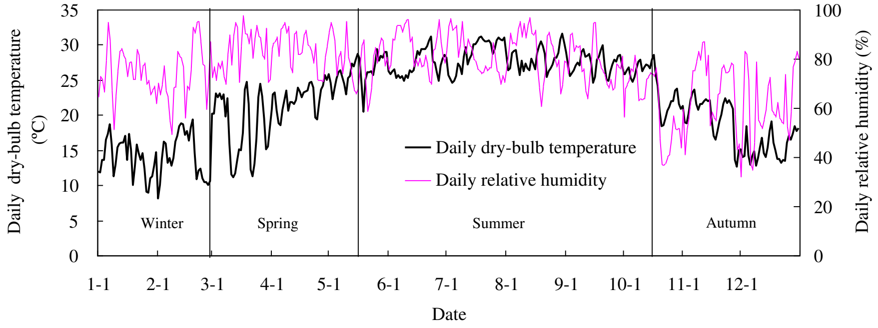


Fig. 5. Daily changes of dry-bulb temperature and relative humidity in the typical meteorological year of Guangzhou (revised based on the figures from [4]).

Table 4
Non-uniformities of physical quantities.

Physical quantity	Non-uniformity		
	Spring	Summer	Autumn
Air temperature (°C)	0.3	0.3	0.6
Relative humidity (%)	2.4	0.8	3.1
Globe temperature (°C)	0.3	0.2	0.5
Air velocity (m/s)	0.06	0.23	0.09

in spring, varied slightly between ‘slightly warm’ and ‘warm’ in summer except the hottest week, and then dropped down quickly in autumn and maintained between ‘cool’ and ‘cold’ in winter.

Thermal sensation has been analyzed in previous studies as the function of various indoor environmental factors, such as air temperature, operative temperature, globe temperature and ET* [12–19]. In the present study, correlations between thermal sensation and those factors were analyzed and the results show that the correlation coefficient is highest for ET*, which might because the humid and radiant impacts mentioned before. Therefore, thermal sensation (TS) as a function of ET* is established and shown in Fig. 10a:

$$\mathrm{TS} = 0.243\mathrm{ET}^* - 6.211 \quad \left(\mathrm{R}^2 = 0.472\right) \tag{4}$$

Thermal neutrality is 25.6 °C, and the 90% (80%) acceptable range is 23.5–27.6 °C (22.1–29.1 °C) in ET* along with the assumption that the votes within the central three categories of the scale are acceptable.

The traditional thermal sensation indices such as PMV [20] and SET [21,22] are established mainly based on climate chamber experiments, and their applicability to real buildings, especially those with various adaptive opportunities, still remains unknown. SET was selected to be correlated with thermal sensation in the present study due to its wider applicable range.

SET was calculated based on all measured physical quantities and personal factors by the two-node model [21,22], and a linear relation was found between thermal sensation and SET as shown in Fig. 10b.

$$\mathrm{TS} = 0.271\mathrm{SET} - 6.760 \quad \left(\mathrm{R}^2 = 0.336\right) \tag{5}$$

Thermal neutrality is 24.9 °C in SET and the sensitivity of sensation to SET is 0.271. Compared with those results obtained in the previous studies in climate chambers [23], it can be seen that the subjects in the real buildings in the present study have a higher neutral SET and greater sensory sensitivity.

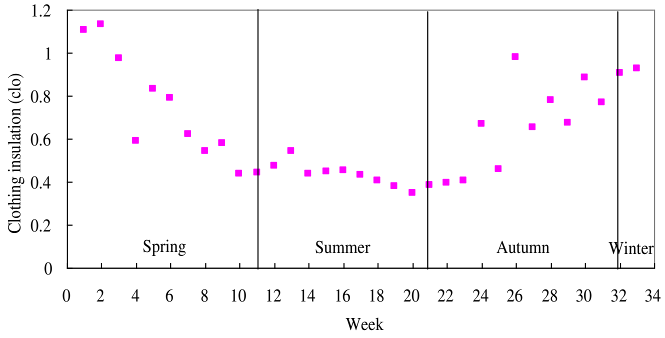


Fig. 7. Weekly change of clothing insulation.

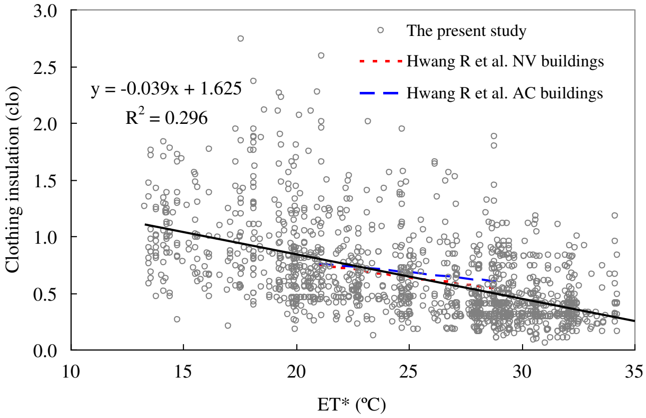


Fig. 8. Clothing insulation as a function of ET* values. (The same below.)

3.4. *Thermal comfort and acceptability*

3.4.1. *Thermal comfort*

A quick observation on the weekly change of thermal comfort shows that thermal comfort follows with thermal sensation in a relatively fixed tendency, which is that the subjects feel comfortable while their sensations near to ‘neutral’ and feel uncomfortable while sensations far from ‘neutral’. The relationship between thermal sensation and comfort was previously studied in climate chambers by Gagge et al. [24] and Zhang and Zhao [25,26], and they found that reports between ‘warm’ and ‘hot’ and ‘cool’ and ‘cold’ were always associated with reports of ‘slightly uncomfortable’ or ‘uncomfortable’ under uniform and steady conditions.

The relationship between thermal comfort (TC) and thermal sensation was analyzed in the present study and a second-order polynomial function was obtained as follows (also see Fig. 11a):

$$\mathrm{TC} = 0.063\mathrm{TS}^2 + 0.021\mathrm{TS} + 1.716 \quad \left(\mathrm{R}^2 = 0.213\right) \tag{6}$$

Sensation of ‘neutral’ corresponds to the most comfortable vote. As thermal sensation departs from ‘neutral’, more and more discomforts are reported. Sensation of ‘warm’ or ‘cool’ is associated with reports of ‘slightly uncomfortable’. These findings found in

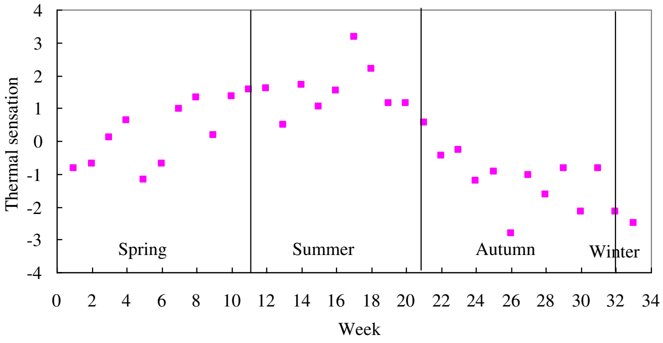
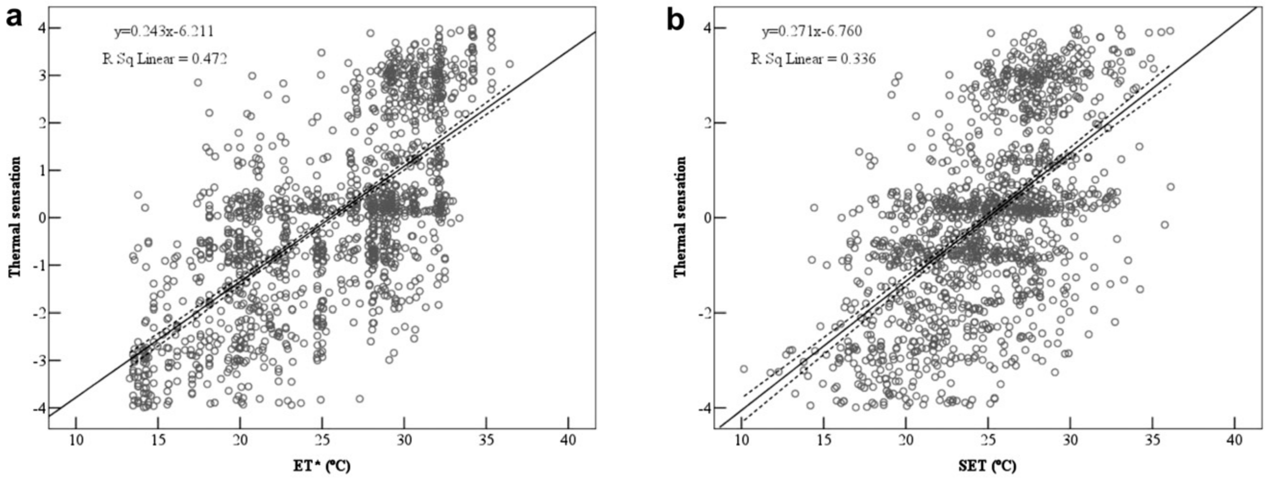


Fig. 9. Weekly change of thermal sensation.



Thermal sensation as a function of ET*

Thermal sensation as a function of SET

(Note: solid lines are regression curves and dotted lines are 95% confidence intervals for mean values. The same below.)

Fig. 10. Thermal sensation as functions of ET* and SET.

real buildings in the present study are in good agreements with those found before in climate chambers.

3.4.2. Thermal acceptability

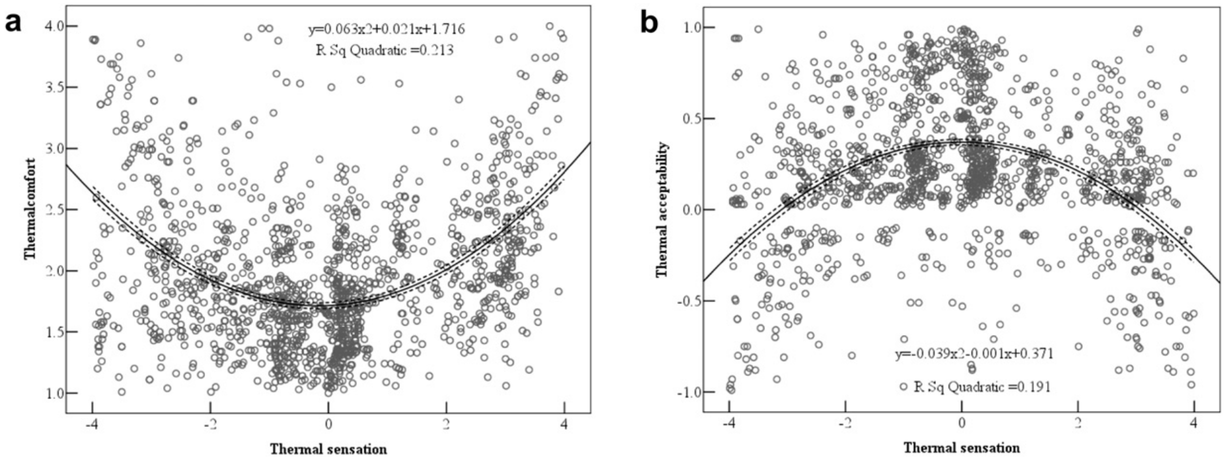
To achieve 80% occupant acceptability has been the objective of ASHRAE standard 55 [6] for more than 30 years, which is mainly based on the assumption that the sensation votes falling within the central three categories of the ASHRAE scale are viewed as satisfied or acceptable. This assumption was proposed by Gagge et al. [24] and Fanger [20] based on the experimental results from climate chambers and confirmed by Berglund [27] and Zhang and Zhao [25,26] in climate chambers as well.

This assumption was testified in real buildings in the present study. Thermal acceptability (TA) was found to be a second-order polynomial function of thermal sensation (see Fig. 11b):

$$\mathrm{TA} = -0.039\mathrm{TS}^2 - 0.001\mathrm{TS} + 0.371 \quad \left(\mathrm{R}^2 = 0.91\right) \tag{7}$$

The most acceptable state is close to ‘neutral’ sensation as the previous studies show. However, the acceptable range becomes much wider and covers sensory domains from ‘cool’ to ‘warm’, indicating that it is the central five instead of three categories of the sensation scale that should be considered as acceptable.

There are two possible reasons for the difference. One is the effect caused by the 9-point sensation scale adopted in the present study. Compared with the 7-point scale used in the previous studies, the 9-point scale might extend the limits of sensory range and potentially enhance the unacceptable sensory levels of subjects. The other one is related to the past experiences of subjects. The subjects participated in the present study have fully acclimated to local climate and well experienced hot and humid



Relationship between thermal comfort and sensation

Relationship between thermal acceptability and sensation

Fig. 11. Relationships between thermal comfort, acceptability and sensation.

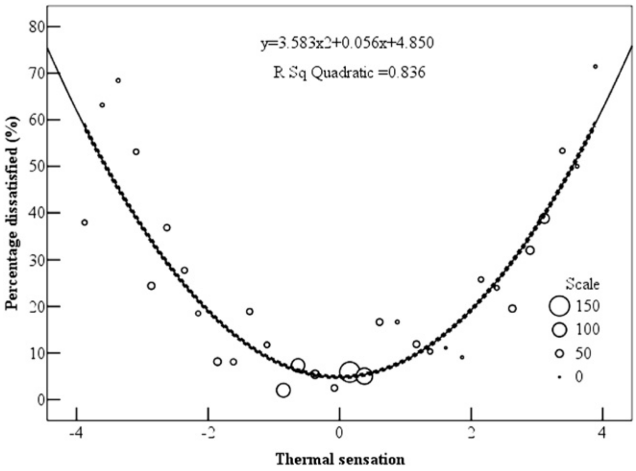


Fig. 12. Percentage dissatisfied as a function of thermal sensation.

environments in summer. Such acclimatization and experiences might not vary their understandings of the basic sensory categories, but instead, might vary their interpretations of acceptable sensory range from a narrow one to a broad one. To fully explain the difference needs further studies, and a suggestion can be drawn here is that more studies should be done to validate the traditional assumption in real buildings as McIntyre mentioned before [28].

3.4.3. Percentage dissatisfied

The relationship between percentage dissatisfied and thermal sensation was established by Fanger [20], cited by ISO 7730 [29] and ASHRAE 55 [6] and have served in many studies and engineering projects. As the acceptable range of thermal sensation was found to be very different in the present study, the relationship between percentage dissatisfied and thermal sensation needs to be re-established.

The raw data were first divided into 32 bins according to thermal sensation votes with an increment of 0.25, and then the percentage dissatisfied was counted for each data bin as the percentage of thermal acceptability votes that less than zero. The relationship between percentage dissatisfied and thermal sensation was then analyzed by regression. As the sample sizes of data bins vary greatly from 9 to 152, the regression was therefore performed under weighting of sample size.

A good polynomial relationship was established between percentage dissatisfied (PD) and thermal sensation (see Fig. 12):

$$\mathrm{PD} = 3.583\mathrm{TS}^2 + 0.056\mathrm{TS} + 4.850 \quad \left(\mathrm{R}^2 = 0.836\right) \tag{8}$$

Sensation of 'neutral' corresponds to a minimum percentage dissatisfied of 5%, which is in good agreement of that found by Fanger. The 10% and 20% dissatisfied ranges of thermal sensation are (−0.5, +0.5) and (−0.85, +0.85) according to the PMV-PPD curve proposed by Fanger, however, the ranges obtained in the present study are (−1.2, +1.2) for 10% dissatisfied and (−2.1, +2.1) for 20% dissatisfied, which are much wider than those by Fanger. Based on the new function of percentage dissatisfied, the 90% (80%) acceptable range of thermal environment change accordingly to 20.6–30.5 °C (16.9–34.2 °C) in ET*. These ranges are much wider than those calculated along with the traditional assumption that the votes within the central three categories of the scale are acceptable, which confirms again the findings found in the section of thermal acceptability.

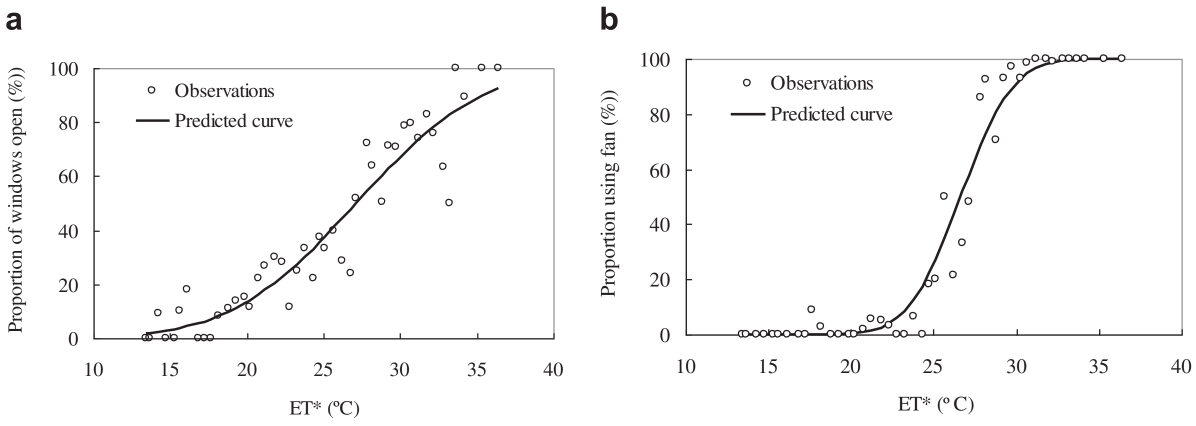
3.5. Adaptive behaviors

3.5.1. Open windows and use fans

The proportions of windows open and using fans have been studied as adaptive behaviors and related to indoor or outdoor climate previously [30–35]. The behaviors were studied as well in the present study. As mentioned in the analysis of clothing adjusting, ET* that considers humidity and radiant impacts was adopted as the indoor climate index to build relationship with adaptive behaviors.

The raw data were first divided into 45 bins according to ET* with an increment of 0.5 °C, and then the proportions of windows open and using fans were counted for each data bin as the percentage of all operable windows open and all electrical fans running. The relationships between proportions of windows open (Pwin), using fans (Pfan) and ET* were then obtained by probit regression weighted by sample size (see Fig. 13):

$$\mathrm{Pwin} = 100\,\Phi(0.155\mathrm{ET}^* - 4.208) \tag{9}$$



Windows open

Using fans

Fig. 13. Proportions of windows open and using fans as functions of ET*.

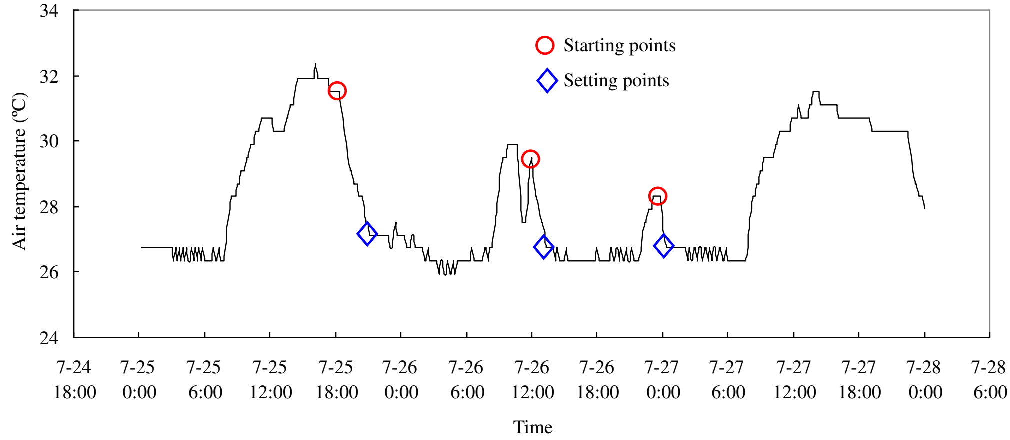


Fig. 14. Starting and setting points for air-conditioners.

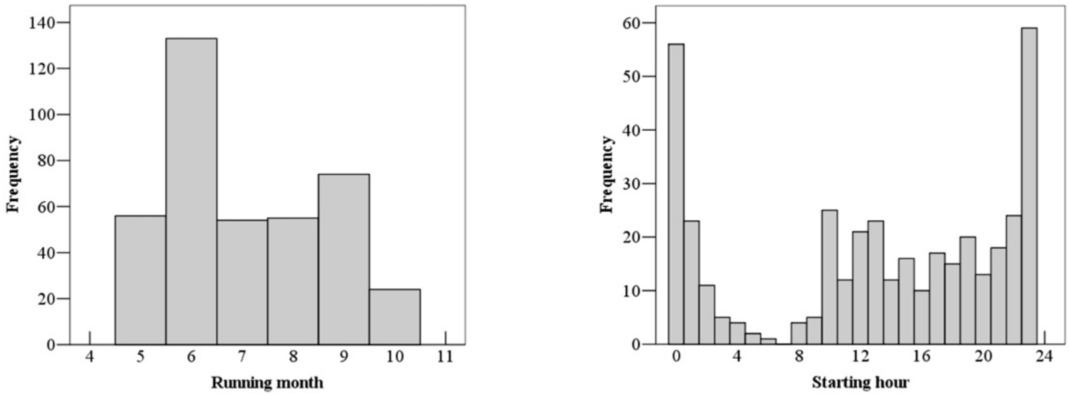
$$\mathrm{Pfan} = 100\,\Phi(0.403\mathrm{ET}^* - 10.739) \tag{10}$$

where $\Phi(x)$ is standard normal distribution function.

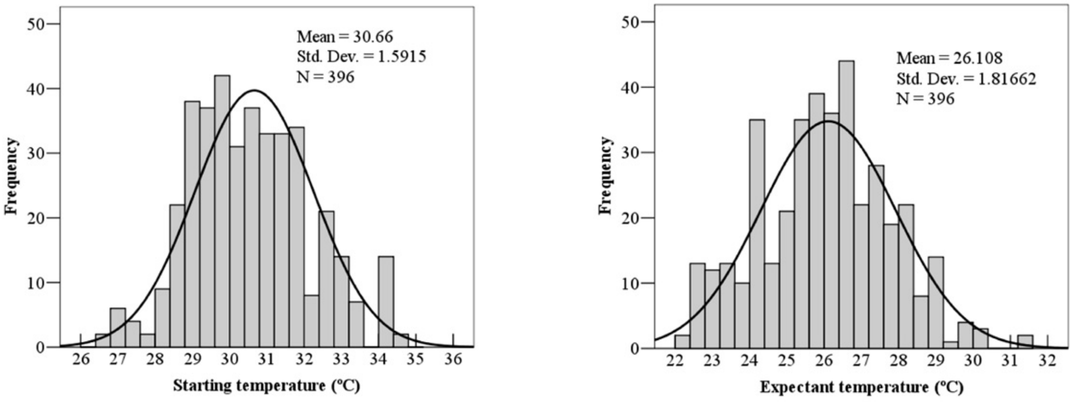
The proportion of windows open started to change while ET* was 14 °C, increased rapidly and linearly as ET* rose from 18 °C to 32 °C, and reached its maximum of 90% while ET* was 36 °C. The proportion of using fans started to increase at a higher ET* of 21 °C, went up much faster as ET* changed from 21 °C to 30 °C, and reached its maximum of 100% while ET* was 32 °C. The sensitivity of behavior to thermal environment is much greater for using fans.

3.5.2. *Use split air-conditioners*

The behaviors of using split air-conditioners in dormitory buildings were obtained based on the records of indoor air temperature. The measured air temperatures were first plotted



a Running month **b** Starting hour



c Starting temperature **d** Setting temperature

Fig. 15. Frequency distributions of using split air-conditioners.

Table 5
Comparison between SAC and NV buildings in hot-humid area of China.

Items	SAC buildings (The present study)	NV buildings [3]
Mean indoor air temperature in summer (°C)	29.6	30.4
Mean indoor relative humidity in summer (%)	66	70
Mean indoor MRT in summer (°C)	30.5	31.0
Mean indoor air velocity in summer (m/s)	0.41	0.44
Mean clothing insulation in summer (clo)	0.43	0.43
Sensitivity of clothing insulation to ET* (clo/°C)	0.039	0.036
ET* range for modification of opening windows (°C)	14–36	18–36
ET* range for modification of using fans (°C)	21–32	22–35
Thermal neutrality in SET (°C)	24.9	25.4
Sensitivity of thermal sensation to SET (/°C)	0.271	0.256

against time, and then the starting and setting points for air-conditioners were determined by direct observations (see Fig. 14), which are the points that temperatures start to fall down in a steep tendency and the points for the stop of falling. Totally 396 pairs of starting and setting points were obtained based on the whole-year-long records from 10 recorders.

The running month, starting hour, starting and setting temperatures were accordingly obtained based on the starting and setting points and their frequency distributions are shown in Fig. 15.

The subjects started to use air-conditioners in May and ended in October. The month for the subjects to most frequently use air-conditioners is June instead of July and August, which is mainly due to the summer holiday. The subjects turned on air-conditioners at midnight most often, indicating that the main usage of cooling is for sleep.

There are subjects start to use air-conditioners while their indoor air temperatures are 26.5 °C and the most often temperature for the subjects to turn on air-conditioners is 30.1 °C. The setting temperatures of the air-conditioners vary from 22 °C to 30 °C with the mean value of 26.1 °C. The mean values of indoor relative humidity are 68% and 57% for the starting and setting conditions.

3.6. Comparison with NV buildings

The SAC buildings investigated in the present study, which provide split air-conditioners to occupants, were systematically compared in Table 5 with the NV buildings surveyed in the previous study by the authors and their colleagues [3] in hot-humid area of China.

The indoor climate in summer was compared since the long and hot-humid summer is the focus of both the studies. It can be seen that the indoor climates in SAC buildings are cooler than those of NV buildings with lower air and radiant temperatures and humidity, and accordingly, the occupants in Split AC buildings maintain their ambient airflow at a slightly lower level of air velocity.

The adaptive behaviors in SAC buildings are much more sensitive to thermal environment than those in NV buildings, with a greater sensitivity of clothing insulation to ET* and a lower starting ET* for modifications of opening windows and using fans. Another response in SAC buildings that is much more sensitive to thermal environment is occupants' thermal sensation, where neutral temperature is lower and thermal sensitivity of sensation is higher.

The following implications can be accordingly drawn from above comparisons. Compared with those from NV buildings, occupants from SAC buildings keep indoor climates much cooler, use adaptive opportunities much earlier and perceive their ambient environments more sensitively and rigidly. The early and quick use of adaptive opportunities and the sensitive and rigid requirements that produced by using air-conditioners in turn increase the dependences on air-conditioners and result in more and more energy consumptions. NV buildings, in which people adjust their expectations with outdoor climate and make full use of adaptive opportunities, are much more environment-friendly and sustainable design solutions.

4. Conclusions

Human responses of sensations, perceptions and behaviors to thermal environments in buildings with split air-conditioners in hot-humid area of China were systematically investigated for a whole year with longitudinal design, and the following conclusions can be drawn:

The indoor climate closely tracked the variations of outdoor climate. The mean values of indoor climate in summer were 29.6 °C in air temperature, 66% in relative humidity, 30.5 °C in mean radiant temperature and 0.41 m/s in air velocity.

Thermal sensation was found to be a linear function of ET* or SET and thermal neutrality was 25.6 °C in ET* or 24.9 °C in SET.

The central five categories of the ASHRAE 9-point thermal sensation scale were found to be acceptable and the 90% (80%) acceptable range of thermal environment was determined as 20.6–30.5 °C (16.9–34.2 °C) in ET*.

The adaptive behaviors of clothing adjustment, opening windows and using fans were found to be closely correlated with indoor ET*. The split air-conditioners were used from May to October and turned on most often at midnight with indoor air temperature of 30.1 °C and setting temperature of 26.1 °C.

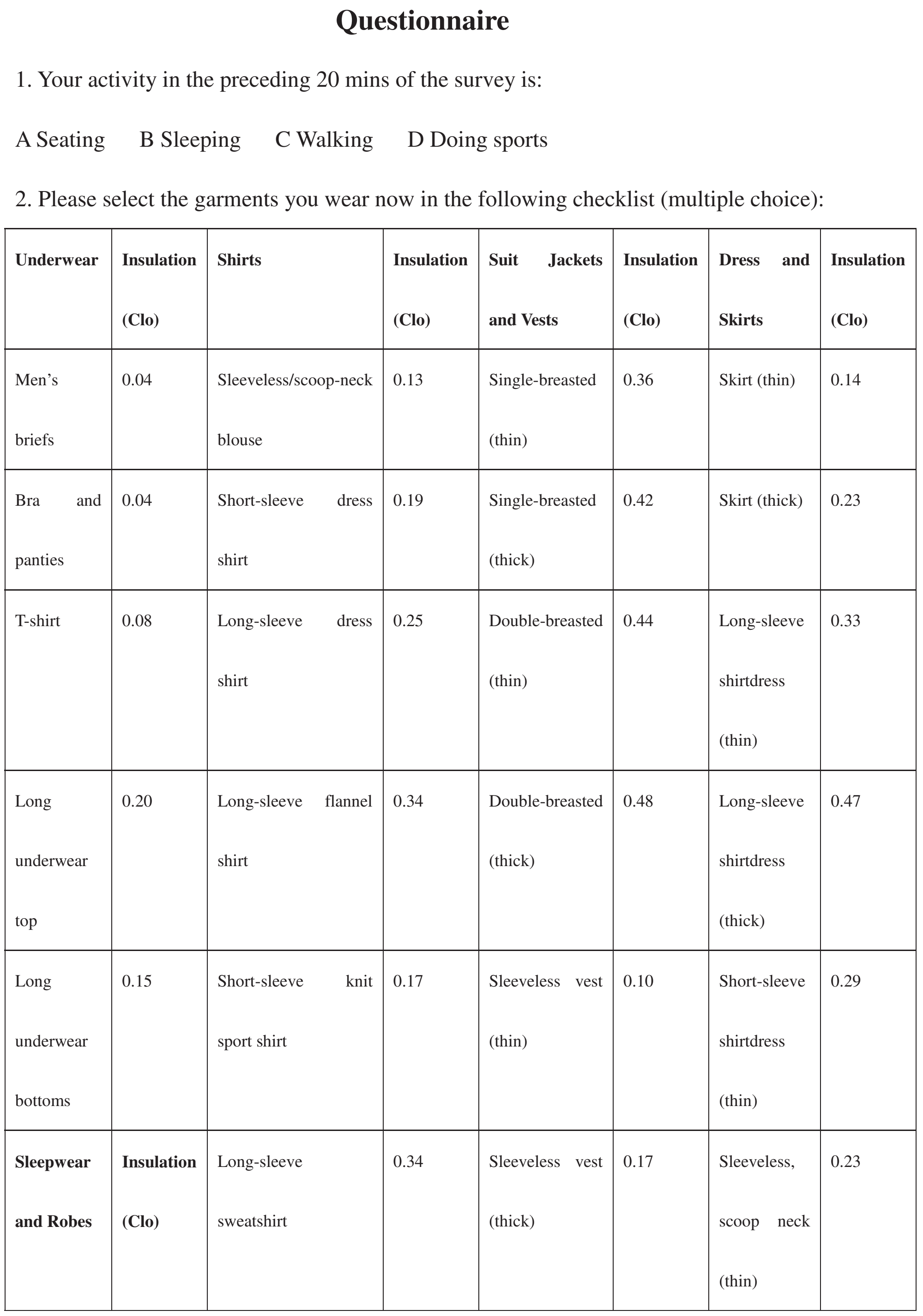
Compared with those from naturally ventilated buildings, the occupants from buildings with split air-conditioners kept indoor climates much cooler, used adaptive opportunities much earlier and perceived their ambient environments more sensitively and rigidly.

The present study can provide the following implications for practical applications. The functions of thermal sensation and perceptions can be used as important tools to predict occupants' thermal sensation, comfort and acceptability in buildings with split air-conditioners. The 90% and 80% acceptable range can be used to evaluate the indoor climates of existing or design buildings acceptable or not. The functions of various adaptive behaviors are important to building performance simulations as boundary or operating conditions. The information of using air-conditioners can benefit both the manufactures and users. What should be mentioned here is that the results of the present study can only be applied directly to the buildings with split air-conditioners in hot-humid area.

Acknowledgments

The work was supported by National Natural Science Foundation of China (Project No. 50708038, 50838003), Program for New Century Excellent Talents in University and the State Key Laboratory of Subtropical Building Science of China (Project No. 2011ZB09).

Appendix



Questionnaire

1. Your activity in the preceding 20 mins of the survey is:

A Seating B Sleeping C Walking D Doing sports

2. Please select the garments you wear now in the following checklist (multiple choice):

Underwear	**Insulation (Clo)**	**Shirts**	**Insulation (Clo)**	**Suit Jackets and Vests**	**Insulation (Clo)**	**Dress and Skirts**	**Insulation (Clo)**
Men's briefs	0.04	Sleeveless/scoop-neck blouse	0.13	Single-breasted (thin)	0.36	Skirt (thin)	0.14
Bra and panties	0.04	Short-sleeve dress shirt	0.19	Single-breasted (thick)	0.42	Skirt (thick)	0.23
T-shirt	0.08	Long-sleeve dress shirt	0.25	Double-breasted (thin)	0.44	Long-sleeve shirtdress (thin)	0.33
Long underwear top	0.20	Long-sleeve flannel shirt	0.34	Double-breasted (thick)	0.48	Long-sleeve shirtdress (thick)	0.47
Long underwear bottoms	0.15	Short-sleeve knit sport shirt	0.17	Sleeveless vest (thin)	0.10	Short-sleeve shirtdress (thin)	0.29
Sleepwear and Robes	**Insulation (Clo)**	Long-sleeve sweatshirt	0.34	Sleeveless vest (thick)	0.17	Sleeveless, scoop neck (thin)	0.23

Sleeveless short gown (thin)	0.18	**Trousers**	**Insulation (Clo)**	**Sweaters**	**Insulation (Clo)**	Sleeveless, scoop neck (thick)	0.27
Sleeveless long gown (thin)	0.20	Short shorts	0.06	Sleeveless vest (thin)	0.13	**Footwear**	**Insulation (Clo)**
Short-sleeve gown	0.31	Walking shorts	0.08	Sleeveless vest (thick)	0.22	Ankle-length athletic socks	0.02
Long-sleeve long gown (thick)	0.46	Straight trousers (thin)	0.15	Long-sleeve (thin)	0.25	Calf-length socks	0.03
Long-sleeve pajamas (thick)	0.57	Straight trousers (thick)	0.24	Long-sleeve (thick)	0.36	Knee socks (thick)	0.06
Short-sleeve pajamas (thin)	0.42	Sweatpants	0.28			Pantyhose /stockings	0.02
		Overalls	0.30			Sandals	0.02
						Slippers	0.03
						Boots	0.10

3. The operable windows in the room you stay now are:

A all opening B partly opening C all closed

4. The electrical fans in the room you stay now are:

A running at high speed B running at middle speed C running at low speed D not running

5. How you feel now?

Very hot	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold	Very cold
+4	+3	+2	+1	0	-1	-2	-3	-4

6. You feel the current thermal environment is:

Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable
+1	+2	+3	+4

7. How you rate the current thermal environment?

Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
+1	+0.01	-0.01	-1

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