Behavioral Adaptation of Different Set Point Temperature Modes in Office Buildings with Split Air Conditioners

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Abstract. It was divided into different modes according to the level of set point temperature (SPT): SPT ≥ 26 ℃ and SPT < 26 ℃. To study behavioral adaptation of different set point temperature modes in office buildings with split air conditioners, a summer field survey was conducted in Zhengzhou and Jiaozuo, China. The results showed that the clothing insulation in high SPT mode was primarily affected by age, whereas the clothing insulation in low SPT mode was influenced by age and indoor temperature. The clothing insulation in high SPT mode was significantly lower than that in low SPT mode, and the air velocity and air movement sensation of subjects in H mode were significantly higher than those in L mode. 1 ℃ rise in Top could lead to 0.026 m/s increase in air velocity in high SPT mode, but the air velocity in low SPT mode had no relationship with indoor temperature. People’s behavioral adaptation enthusiasm in high SPT mode was greater than that in low SPT mode. The energy consumption can be saved by about 14.8% after considering the adjustment of people's clothing.

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1 Introduction

To balance the relationship between comfort and energy consumption, studies on thermal adaptation in building environments have sprung up. People's perceived thermal discomfort can be weakened to a certain extent through the feedback loop of three ways of thermal adaptation (physiological adaptation, behavioral adaptation and psychological adaptation), in which behavioral adaptation is the key to people's having higher acceptability and comfort in the case of thermal discomfort[1]. de Dear and Brager [2] presented that occupants of naturally ventilated buildings were more inclined to behaviorally regulate their heat balance than their counterparts within centrally air-conditioned buildings. Ning et al. [3] conducted a field study and found that the clothing insulation was obviously greater in common heating intensity buildings than high heating intensity buildings. Zhang et al. [4] proved that the adaptive behaviors in split air-conditioned (SAC) buildings are much more sensitive to thermal environment than those in naturally ventilated buildings. Ning et al. [3] indicated that when behavioral adaptation was considered, 2.3% of heating energy would be saved in winter. In conclusion， previous studies on the behavioral adaptation did not consider the influence of set point temperature (SPT). In SAC buildings, people can control air conditioners according to their wishes, so SPT is widely distributed. Therefore, the difference in behavioral adaptation under different SPT in SAC buildings is still unknown. In addition, the energy saving potential of considering behavioral adaptation in summer is also unclear.

To solve the above problems, the authors conducted a thermal comfort field study in 21 SAC office buildings in the cold zone of China. The research results can provide a theoretical foundation in SAC office buildings for government energy conservation policies and enrich the theory of thermal adaptation.

2 Methods

The field study was conducted from June 9th to September 14th, 2019 in Zhengzhou and Jiaozuo, which are typical cities in the cold climate zone in China. A total of 21 split air-conditioned office buildings were involved in this study. Office buildings have operable windows, fans and split air conditioners. All selected respondents were healthy, lived in the area for at least 1 a, and adapted to the local climate. Taking the set point temperature of public buildings stipulated by the Chinese government as the limit, it was divided into two SPT modes: high (H) set point temperature mode (SPT≥26 ℃) and low (L) set point temperature mode (SPT<26 ℃). A total of 529 valid questionnaires and corresponding objective parameters were collected, in which H mode: 291 sets, L mode: 238 sets.

The field survey included two parts: the subjective feeling of thermal comfort and the measurement of objective parameters, both of which were conducted simultaneously. The scales of the subjective response voting used in the survey are shown in Table 1. Indoor thermal environmental parameters were measured by the class II method in literature [5], such as air velocity (v_a), globe temperature (T_g), air temperature (T_a) and relative humidity (RH). Table 2 gives the information about the instrument.

Table 1. Index scales of subjective evaluations.

Voting scale	Thermal sensation	Air movement sensation
-3	Cold	Very stuffy
-2	Cool	Stuffy
-1	Slightly cool	Slightly stuffy
0	Neutral	Neutral
+1	Slightly warm	Slightly windy
+2	Warm	Windy
+3	Hot	Very windy

Table 2. Measured range and accuracy of instruments.

Instrument	Test content	Valid range	Accuracy
JT-IAQ Indoor thermal comfort tester	T_a	1~60 ℃	±0.2 ℃
	RH_{in}	10~98%	±1.5%
	V_a	0.05~5 m/s	±(0.03 m/s+2% reading)
	T_g	1~60 ℃	±0.3 ℃

The standard effective temperature (SET*) considers the comprehensive effects of various environmental parameters (air temperature, radiation temperature, relative humidity and air velocity) and human parameters (metabolic rate, clothing insulation), and the calculation of heat balance is more accurate. SET* was calculated based on all measured physical quantities and personal factors by the two-node model [5]. All statistical analyses were performed using SPSS v 26.0 software, and the P-value was used to describe the level of significant difference between the two sets of data: $P < 0.05$ means the difference is significant, thus $P > 0.05$ means no significant difference.

3 Results

3.1 Thermal environments

The indoor environmental variables of different SPT modes during the study period are shown in Table 3. During this survey, the indoor air temperature, operative temperature, relative humidity and air velocity in H mode were significantly higher than those in L mode ($P < 0.001$). However, there was no significant difference in standard effective temperature (SET*) between the two modes ($P = 0.277$).

The correlation analysis of indoor air temperature and SPT revealed that there was no association ($P = 0.247$). This was because, during the measurement, the time the air conditioner was turned on, the power of the air conditioner, personnel position, and other factors

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caused the air temperature and SPT mismatch, so the air conditioner SPT could not be used to describe the indoor thermal environment.

Table 3. Distribution of outdoor and indoor thermal environment parameters.

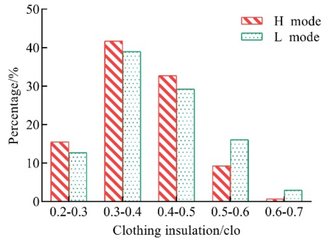
SPT modes		T_{in}/°C	T_{op}/°C	RH/%	V_a/(m/s)	SET*/°C
H mode	Mean	27.6	27.7	52.2	0.18	26.0
	Max	31.0	31.1	71.2	1.35	29.6
	Min	24.7	24.8	35.2	0.00	21.5
	Std	±0.97	±0.94	±7.0	±0.16	±1.41
L mode	Mean	27.2	27.3	49.4	0.14	25.7
	Max	29.8	29.9	65.3	0.81	29.4
	Min	24.3	24.4	32.0	0.00	22.0
	Std	±1.23	±1.24	±6.7	±0.13	±1.54

3.2 Clothing insulation

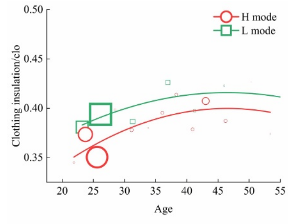
The mean clothing insulation values of respondents in H and L modes were 0.38 and 0.40 clo, respectively, which were lower than the assumed value (0.5 clo) of building energy consumption simulation and laboratory research in summer. Theremore, it is suggested to adopt 0.4 clo as the clothing insulation assumed value. Fig. 1(a) shows the distribution frequency of clothing insulation variations. The clothing insulation in H mode was significantly lower than that in L mode (P = 0.015), indicating that subjects in H mode were more active in reducing clothing insulation to improve their thermal discomfort. It can be seen from Fig. 1(b) that age had a significant impact on the clothing insulation, and the clothing insulation increased with age (P < 0.001), and at the same age, the clothing insulation in L mode was significantly higher than that in H mode. As can be seen from Fig. 1(c), only the clothing insulation of L mode decreased with indoor operative temperature (P = 0.000). It can thus be concluded that the clothing insulation in H mode was primarily affected by age, whereas the clothing insulation in L mode was influenced not only by age but also by indoor temperature. This could be because the indoor temperature was relatively high in H mode, causing the clothing adjustment to reach the threshold. As a result, the clothing insulation difference of subjects mainly came from age in H mode. With the increase of age, the human metabolic rate will decrease, so a higher temperature is needed to maintain comfort [6]. In L mode, the indoor temperature was low, and the respondents would be cold and uncomfortable. Therefore, clothing insulation would be affected not only by age but also by temperature. This also suggested that in office buildings, when people in L mode feel a little cold, they would make the behavior adjustment of adding clothes to improve their thermal comfort rather than raising the SPT, but this behavior is not conducive to the air conditioner energy saving.

3.3 Air velocity and air movement sensation

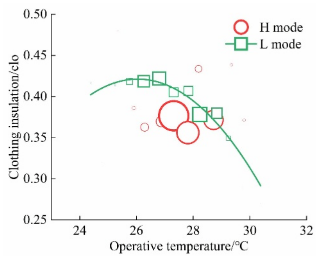
The relationship between air velocity and indoor



(a) Distribution frequency of clothing insulation.



(b) Relationship between clothing insulation and age.



(c) Relationship between clothing insulation and operative temperature.

Fig. 1. The differences in the clothing insulation.

operative temperature, as shown in Fig. 2. A linear relationship was determined between these two parameters in H mode, and Eq. (1) expresses the regression between air velocity and indoor operative temperature.

H mode: $V_a = 0.026T_{op} - 0.543$ （$R^2 = 0.024$， $P = 0.008$） (1)

Fig. 3 shows that the air velocity in H mode increased with the operative temperature, and 1 °C rise in T_{op} could lead to 0.026 m/s increase in air velocity. However, the air velocity in L mode had no relationship with indoor temperature (P > 0.05), and the air velocity and air movement sensation of subjects in H mode were significantly higher than those in L mode (P < 0.01). It can thus be inferred that compared with L mode, the respondents in H mode would actively improve their thermal discomfort by increasing indoor air velocity.

Fig. 4 depicts the link between thermal sensation and air movement sensation. There were negative associations between thermal sensation and air movement sensation (P < 0.01), and no significant differences in gradient and intercept between the two modes (P > 0.05), showing that air movement sensation affected the thermal sensation of the respondents in both SPT modes to the same degree. As a result, people might improve their thermal sensation in the two SPT modes by raising indoor air velocity and enhancing air movement sensation.

3.4 Energy-saving potential

Using the Bin method, a weighted linear regression analysis was performed on the TSV of the two modes with T_{op} and SET*. Eqs. (2) ~ (5) express the regressions among TSV and T_{op}, SET*.

H mode: $TSV = 0.172T_{op} - 4.803$ （$R^2 = 0.728$， $P = 0.000$） （2）

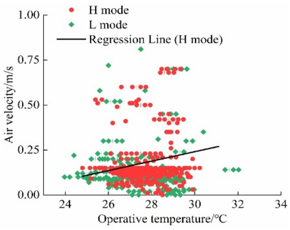


Fig. 2. Relationship between air velocity and operative temperature.

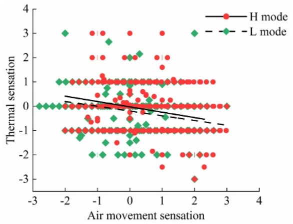


Fig. 3. Relationship between thermal sensation and air movement sensation.

L mode: $TSV = 0.238T_{op} - 6.700$ （$R^2 = 0.669$， $P = 0.000$） (3)

H mode: $TSV = 0.119SET^* - 3.180$ （$R^2 = 0.431$， $P = 0.006$） (4)

L mode: $TSV = 0.155SET^* - 4.151$ （$R^2 = 0.585$， $P = 0.000$） (5)

The temperature at which the TSV regression line crosses the line of TSV = 0 is regarded as the neutral temperature. With TSV = 0 in Eqs. (2) ~ (5), the neutral Top in H and L mode were 27.9 °C and 28.1 °C respectively, and the neutral SET* in H and L mode were 26.7 °C and 26.8 °C separately. It can be seen that the neutral temperature of the two modes was similar, and the mean neutral SET* (26.8 °C) of the two modes was 1.2 °C lower than the mean neutral Top (28.0 °C). Compared with Top, SET* considers more parameters, such as the influence of relative humidity, metabolic rate and clothing insulation. From section 3.1, the relative humidity was lower than 70%, the influence of relative humidity on thermal sensation was not obvious [7], and there was no significant difference in metabolic rate between the two modes (P = 0.743), that is, the difference between SET* and Top mainly comes from clothing insulation. This indicated that the neutral temperature can be increased by 1.2 °C only by adjusting the clothing in SAC office buildings.

According to the Chinese architecture standard [9], the outdoor design temperature is 34.9 °C in summer in Zhengzhou. the energy-saving value after clothing adjustment was calculated by Eq. (6).

$\Delta N = (t_1 - t_2)/(t_s - t_2) \times 100\%$ (6)

where ΔN represents the percentage of energy-saving, %. t_1 represents the neutral SET, °C. t_2 represents the neutral T_{op}, °C. t_s represents the outdoor design temperature, °C.

The calculation results showed that the energy consumption could be saved by about 14.8% considering the behavioral adaptation of clothing adjustment.

4 Discussion

In SAC office buildings, people have many opportunities besides using air conditioners to adopt behavioral adjustments, such as opening and closing doors and windows, using fans, adjusting clothing, etc. According to the results in Section 3.1, indoor air temperature, air velocity and other environmental parameters in H mode were significantly larger than those in L mode, while there was no significant difference in SET* between the two modes. This indicated that although the thermal environments of the two SPT modes were different, there was no discrepancy in indoor thermal environments perceived by people under different SPT modes after considering the behavioral adaptations such as increasing air velocity and adjusting clothing.

From sections 3.2 and 3.3, it can be seen that there were differences in the behavioral adjustments of subjects between different SPT modes. Compared with the H mode, subjects in L mode did not actively improve their thermal comfort by increasing air velocity or reducing clothing. This is because people do not have to consider economic factors in office buildings, so some people did not actively adopt low-energy behavior adjustments other than the use of air conditioners. This phenomenon may also have a lot to do with age. The ages of respondents in H mode were significantly older than those in L mode (P=0.000). The behavioral habits of the elderly and young people are different, and the elderly are more inclined to open windows or adjust clothing for their thermal comfort while young people who have been living in a low-temperature air-conditioned environment since childhood get used to using air conditioners when they feel hot, rather than using low-energy window opening, clothing adjustment or the use of fans, which have adapted psychologically and behaviorally [8].

5 Conclusions

(1) People’s behavioral adaptation enthusiasm in high SPT mode was greater than that in low SPT mode.

(2) The energy consumption can be saved by about 14.8% after considering the adjustment of people's clothing.

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