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Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability?

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HIGHLIGHTS

- Warm and cool heating environments were investigated in winter.
- Human thermal adaptation can be impacted by different heating experiences.
- A higher thermal comfort zone was formed in warm exposure environment.
- Neutral temperature was still 1.9 °C higher in warm exposure after clothing standardization.
- The study has implication for rational heating temperature set in winter.

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ABSTRACT

Harbin is located in China's severe cold area with a long and cold winter. Currently, some buildings are overheated in winter, which not only waste energy, but also may weaken human adaptability to the cold climate. A long-term field tracking study was carried out from 2013 to 2015 covering two space heating periods in Harbin. Two types of residential heating environments, respectively warm exposure and cool exposure environments were investigated to discover relation between different indoor heating temperatures and human thermal responses. Totally, 36 residents volunteered as participants. The subjective survey and environmental parameters monitoring were simultaneously conducted. The results show that all participants could adapt to their thermal environments well. But the participants' thermal adaptation was evidently discrepant in different exposures. The neutral temperature was 1.9 °C higher in warm exposure than cool exposure sample after clothing insulation standardization, which suggests the possible effects of physiological and psychological adaptation. The discrepancy between AMV and PMV was greater in cool versus warm exposure. The results indicate that a higher thermal comfort zone might be formed for the residents exposing to a high indoor heating temperature for a long period in winter. Furthermore, a broader acceptable temperature range was presented in this climate area than ASHRAE steady-state comfort zone in winter. These findings have far-reaching implication for reasonable energy use.

1. Introduction

A fundamental and conceptual reorientation has taken place in thermal comfort study over the last 20 years. Namely, the adaptive thermal comfort has become the mainstream study instead of the physical determinism of Fanger's comfort model [1]. And the adaptive thermal comfort model has been presented in existing thermal comfort standards, such as EN15251-2007 [2] and ASHRAE 55-2013 [3]. The only thermal environmental parameter in the adaptive model is outdoor mean monthly temperature or some sort of running mean outdoor temperature. And some studies have underpinned the adaptive model in the standards and developed its application [4–9]. Meanwhile, a great amount of worldwide field surveys have carried out about adaptive thermal comfort. Generally, the studies indicate that people have a wider thermal comfort range in naturally ventilated environment than that in air-conditioned environment. And people's thermal comfort range is commonly beyond the limits of steady-state thermal comfort range [10,11]. Moreover, most relevant field studies also report that human neutral temperatures are evidently discrepant in different seasons in the same area [12–17] and the neutral temperatures are significantly different in different climates [18–23]. These results verify that people have thermal adaptability to the climates.

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However, most adaptive models ascribe the effect of the comfort temperature to the outdoor climate, ignoring the importance of indoor thermal experiences. As a matter of fact, the indoor thermal environments can also influence human thermal comfort and adaptation. Currently, some researches have begun to focus on this point. For instance, Yu et al. pointed that a long-term exposure to stable air-conditioned environment might weaken people's thermal adaptability to hotness [24]. Cândido et al. [25] found that occupants who were constantly exposed to air conditioned or free running buildings tended to prefer such buildings. These results suggest an "addiction" to static indoor thermal environments. Luo et al. [26] pointed that building occupants could adapt to the thermally neutral lifestyle more easily and long-term comfortable indoor thermal history could raise occupants' thermal expectation. Clearly, most previous studies about the effects of indoor thermal experiences to human thermal comfort and adaptation mainly focus on the air-conditioned or naturally ventilated buildings. Or some researches about heated buildings concentrate on adaptive differences in different seasons or climate zones [27–30] or different occupants' background [26]. But, how the thermal experience based on different heating temperatures in winter affects occupants' comfort and adaptive performance has not been subject to much research. Meanwhile, the adaptive factors are difficult to confirm separately.

Undoubtedly, China today is a large energy-consuming and carbon-emitting country although its per capita index is relatively lower compared with other major economies around the world. It has become the largest energy consuming and CO_2 emission country in 2009 [31]. The building sector is a dominating energy consumption field in many countries. Kwok and Rajkovich [32] reported that the building sector accounted for 38.9% of the total primary energy requirement in America, of which 34.8% was for HVAC system (heating, ventilation and air conditioning). In China, the annual building energy consumption has soared from 243 million tce (tons of standard coal equivalents) to 687 million tce over the last 15 years [33]. In 2020, about 35% of total national energy use is projected for the building sector and HVAC system inevitably account for a high proportion [34,35]. Currently, most researches on energy conservation of HVAC system mainly aim at systematic optimization, renewable energy utilization and passive building design. Nevertheless, occupants' thermal behaviors and adaptation to thermal environment can also considerably influence building energy consumptions. Wan et al. pointed that given the growing awareness and recognition of adaptive thermal comfort, raising the summer air-conditioning set point temperature by 1–2 °C could have great energy saving and hence mitigation potential [36].

China is a geographically vast country with different climate zones. According to Chinese code [37], five climate zones are totally defined. They are respectively termed as severe cold, cold, hot summer and cold winter, hot summer and warm winter, and temperate zones shown in Fig. 1. Among Chinese climate zones, the centralized heating was required for urban buildings in winter in severe cold and cold zones. And these two climatic zones account for a vast area in Chinese mainland including 19 provinces and 134 major cities. For the past few years, the centralized heating area presents a tendency of sharp increasing year by year. Since 2005, there is a growth rate of 200–300 million m^2 by average per year. The centralized heating area is 4.36 billion m^2 in 2010 and soars to 6.11 billion m^2 in 2014. So far, the centralized heating consumes nearly 25% of total energy cost annually in China [33]. Therefore, a suitable indoor design temperature for space heating is very important to save energy and reduce carbon emission.

Harbin (45°41′N 126°37′E) is a large capital city in the severe cold area of China. There is a severe cold and long winter in this metropolis. The mean daily highest/lowest outdoor temperatures in January are −13 °C/−25 °C [30]. The centralized heating is applied in winter and its operating time usually lasts nearly half a year. Previous studies revealed that the occupants had adaptability to the local cold climate and thermal neutral temperature was lower compared with the occupants at low latitudes [38]. Meanwhile, the neutral temperature was close to the indoor air temperature [39]. However, the local occupants often expose themselves to the indoor heating environment in winter to avoid the freezing coldness outside. Additionally, the indoor heating space is relatively enclosed in winter. Therefore, does the long-term indoor heating experience impact human thermal comfort and adaptability? And what are the possible differences of thermal responses if the occupants expose them to different heating temperatures during the winter? To answer these questions, a long-term field investigation was conducted during space heating periods in Harbin. Two groups of participants respectively exposed to warm and cool heating environments were surveyed to discover the interaction between indoor heating experiences and thermal adaptation. Meanwhile, the energy-saving potential is analyzed and the practical implication is elaborated according to the study.

This study aims:

1. To investigate residents' thermal perception and performance under different heating experiences in winter.
2. To discover the differences of residents' adaptive responses between warm and cool exposure groups.

2. Research methods

2.1. Research time and samples

The field study was carried out in two types of residential thermal environments, respectively "slightly warm to neutral" exposure and "slightly cool to neutral" exposure environments during two heating periods in Harbin. To make them concise, the terms of "warm exposure" and "cool exposure" were correspondingly used in the paper. The warm exposure sample was surveyed from October 20 to April 20, 2013–2014 and the cool exposure sample was surveyed from October 20 to April 20, 2014–2015. Most of participants' apartments were heated by the centralized heating system with radiator heating terminal. Only one participant's home was heated with floor heating terminal. According to the Chinese standard [40], the residential indoor air temperature should be required within 18–24 °C in winter in the severe cold zone. However, to reduce the residents' complaints, the upper limit 24 °C even higher heating temperature is usually applied as the actual indoor heating temperature in winter. Therefore, the upper limit temperature 24 °C is considered as an index for warm exposure sample recruitment. The mean indoor air temperatures in warm exposure samples were close to or over 24 °C. Notwithstanding, some residential apartments are heated close to the lower limit of indoor air temperature during winter in Harbin. So, some apartments with lower indoor air temperature were investigated to compare the adaptive differences. And the mean indoor air temperatures in cool exposure samples were around 20–22 °C. 36 residents (age ranges from 26 to 72, gender ratio is nearly 1:1) volunteered as the participants in this study. Among them, 20 occupants lived in warm apartments and 16 participants lived in cool apartments. All the participants have been living in Harbin for more than 20 years and they have fully adapted to the local climate. The samples' information is shown in Table 1.

The BMI (Body Mass Index) links to the fat layer that can influence heat transfer between the inner body and its ambient thermal condition [41]. Therefore, the index may become a factor to affect human thermal sensation. Meanwhile, some studies also found that BMI affected people's sensitivity to thermal history [42,43]. According to WHO (World Health Organization), BMI can be cate-

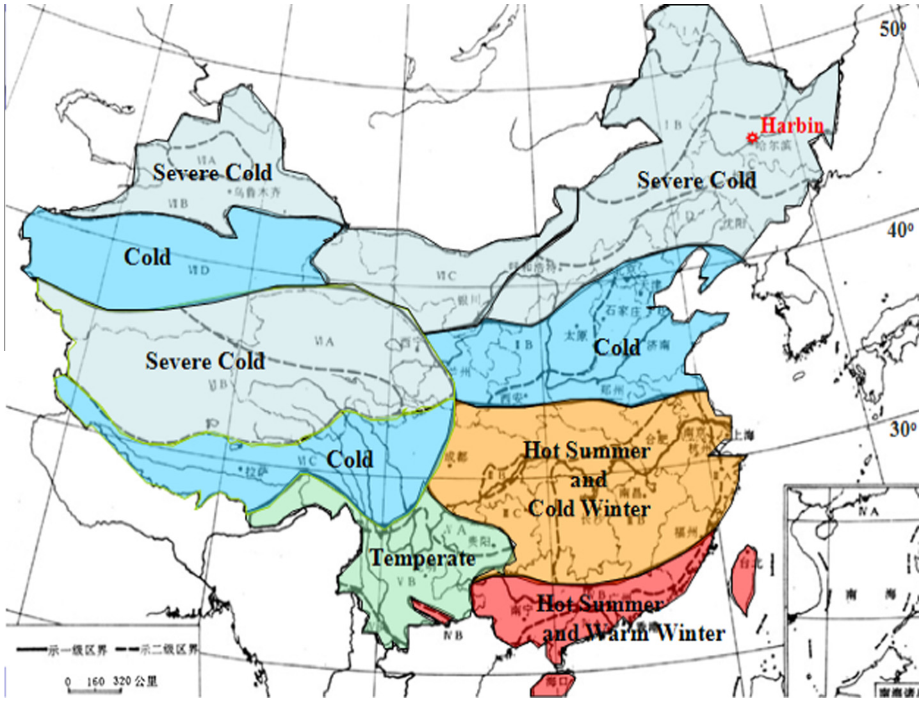

Fig. 1. Division of five climate zones in China.

Table 1
Investigated sample information.

	Community amount	Building amount	Home amount	Participants amount	Gender ratio	Average age	Years in Harbin	Questionnaires
Cool exposure	8	8	8	16	1:1	46.7 ± 9.6	37.1 ± 8.3	304
Warm exposure	5	9	10	20	9:11	48.5 ± 13.2	39.7 ± 19.5	321

gorized at 4 levels. The BMI categories and the participants' BMI in this field study are shown in Table 2. It shows that majority of participants' BMI was in the normal zone to avoid the errors of thermal sensation. The calculation of BMI can be referred to the literature [30].

2.2. Physical measurement

This field study consists of indoor physical measurement and participants' subjective survey, which were simultaneously conducted. Indoor air temperature, relative humidity, globe temperature and air speed were incorporated in the indoor physical measurement. The indoor air temperature and relative humidity were monitored per 5 min using self-recording loggers which were placed at about 1.0 m high above the floor in the investigated rooms. The test instruments and accuracy are shown in Table 3.

2.3. Subjective survey

The participants were reminded to answer the subjective online questionnaires at weekends. The "right-here-right-now" research design was used in the survey. Namely, the physical parameters were recorded at the same point in time and space as the questionnaires were filled in. The questionnaire recorded the information including respondents' thermal sensation, thermal comfort, preferred temperature, thermal acceptance and behavioural adjustments. ASHRAE's seven-point scale was used for participants to rate their thermal sensation. The subjective vote scales are presented in Table 4.

Participants' clothing insulation was estimated and calculated referring to the garment insulation table of ASHRAE Standard 55-2013 [3]. The clothing insulation included the value 0.15clo of the chair the respondents sat on. And the following PMV calculation also included the incremental value of the chair insulation. Their metabolic rate was estimated to be 1.1 met in this survey, which corresponds to light activities according to ASHRAE Standard 55-2013 [3].

Table 2
Participants' BMI information.

Category	Index range	Amount	
		Cool exposure	Warm exposure
Thin	<18.5	0	2
Normal	18.5–24.9	12	14
Slightly fat	25.0–29.9	4	4
Fat	30.0–34.9	0	0

3. Results

3.1. Indoor thermal environment

The mean indoor air temperatures in warm exposure and cool exposure environments were respectively 24.3 °C and 20.7 °C. The indoor air speed was much lower than 0.2 m/s and ranged within 0.01–0.05 m/s in the investigated apartments which met ASHRAE Standard 55-2013 [3]. The distribution of average indoor air temperature and humidity each day during space heating in two thermal exposure environments is shown in Fig. 2. It could be seen that most indoor air temperature in cool exposure environment was close to the lower limit of ASHRAE steady-state comfort zone in winter and 20.1% was beyond the lower limit. On the con-

Table 3
Test instruments and accuracy.

Name	Type	Parameter	Range	Accuracy
Thermo-hygrometer	WSZY-1A	Air temperature Relative humidity	−40 to 100 °C 0–100%	±0.5 °C ±3%
Globe thermometer	HWZY-1	Globe temperature	−50 to 100 °C	±0.5 °C
Hot wire anemometer	Testo425	Air speed	0–20 m/s	±0.03 m/s

Table 4
Subjective vote scales used in the survey.

	Scale
Thermal sensation	−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot
Preferred temperature	−1 cooler, 0 no change, +1 warmer
Thermal comfort	0 comfortable, 1 slightly uncomfortable, 2 uncomfortable, 3 very uncomfortable, 4 unbearable
Thermal acceptability	Acceptable, unacceptable

trary, most indoor air temperature in warm exposure environment was close to the upper limit of ASHRAE steady-state comfort zone and 27.9% was beyond the upper limit. Generally, the humidity in cool exposure environment was slightly higher than warm exposure environment. Through calculation, the discrepancy between indoor radiant temperature and air temperature was ±0.5 °C in all residential environments, which fell within the precision of measuring instruments. Therefore the indoor air temperature could be used as an evaluation index of indoor thermal environment.

3.2. Clothing insulation

The variations of clothing insulation with indoor air temperature are illustrated in Fig. 3. It shows that the participants could adjust their clothing insulation well according to the indoor temperature variation. The mean clothing insulation was 0.97clo and 0.74clo respectively in cool and warm exposure environments.

The clothing insulation was obviously greater in cool exposure than warm exposure environment. And the clothing insulation in cool exposure environment was close to 1.0clo, the value prescribed by ASHRAE Standard 55-2013 [3] indoors in winter. Through independent samples *t*-test, participants' clothing insulation was significantly different ($p < 0.01$) between two exposure samples. Furthermore, the slopes of fitted lines were similar, which indicates the trends of clothing insulation adjustment with indoor air temperature variation were similar in two groups. The participants' clothing insulation decreased 0.15clo and 0.11clo respectively in cool and warm exposures as the indoor air temperature increased every 2 °C.

3.3. Thermal perceptions

The distributions of actual mean thermal sensation votes (AMV), thermal comfort votes (TCV), thermal acceptability and preferred temperature are illustrated in Fig. 4. The percentage of voting for neutrality was the highest and over 60% in both environments as shown in Fig. 4(a). Over 70% participants felt "comfortable" in both environments shown in Fig. 4(b). The proportion of voting for comfort was slightly higher in warm exposure than cool exposure environment. Fig. 4(c) illustrates that there was a high thermal acceptability and over 80% votes for acceptance were presented in both environments. It demonstrates that the percentage of preferring warmer was slightly higher in cool exposure and vice versa in warm exposure shown in Fig. 4(d). However, the proportion of expecting no change was over 70% in both environments. The above results indicate that all respondents could adapt to their occupied environments. The occupants in both thermal exposures generally felt comfortable, acceptable and preferred maintaining the current indoor temperatures.

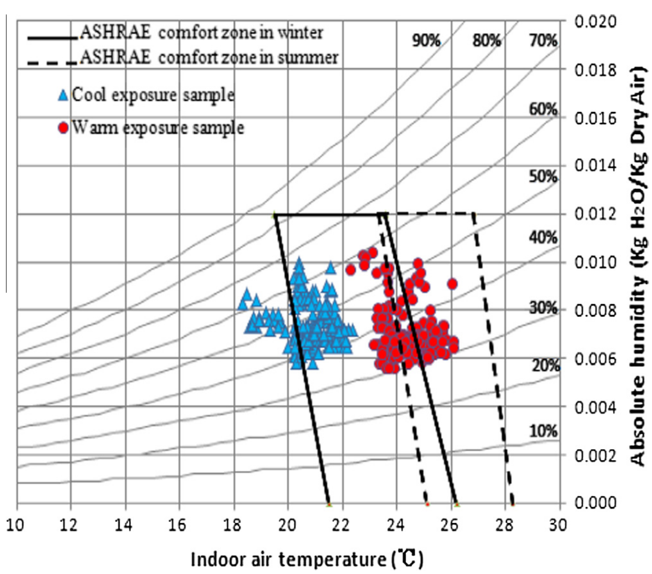

Fig. 2. Distribution of indoor thermal parameters in two environments.

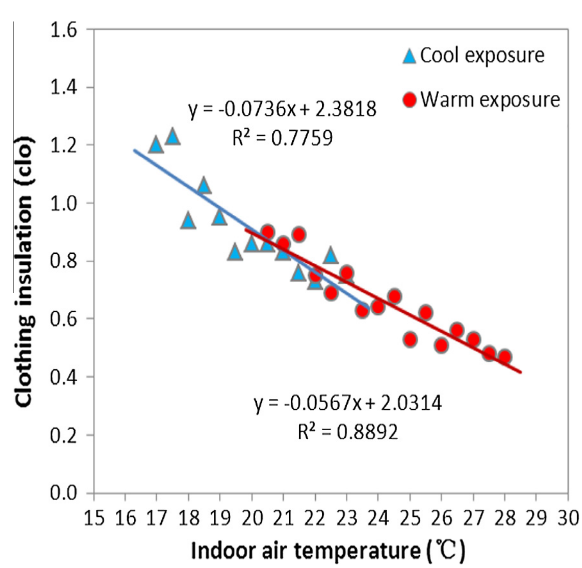

Fig. 3. Variations of clothing insulation with indoor air temperature.

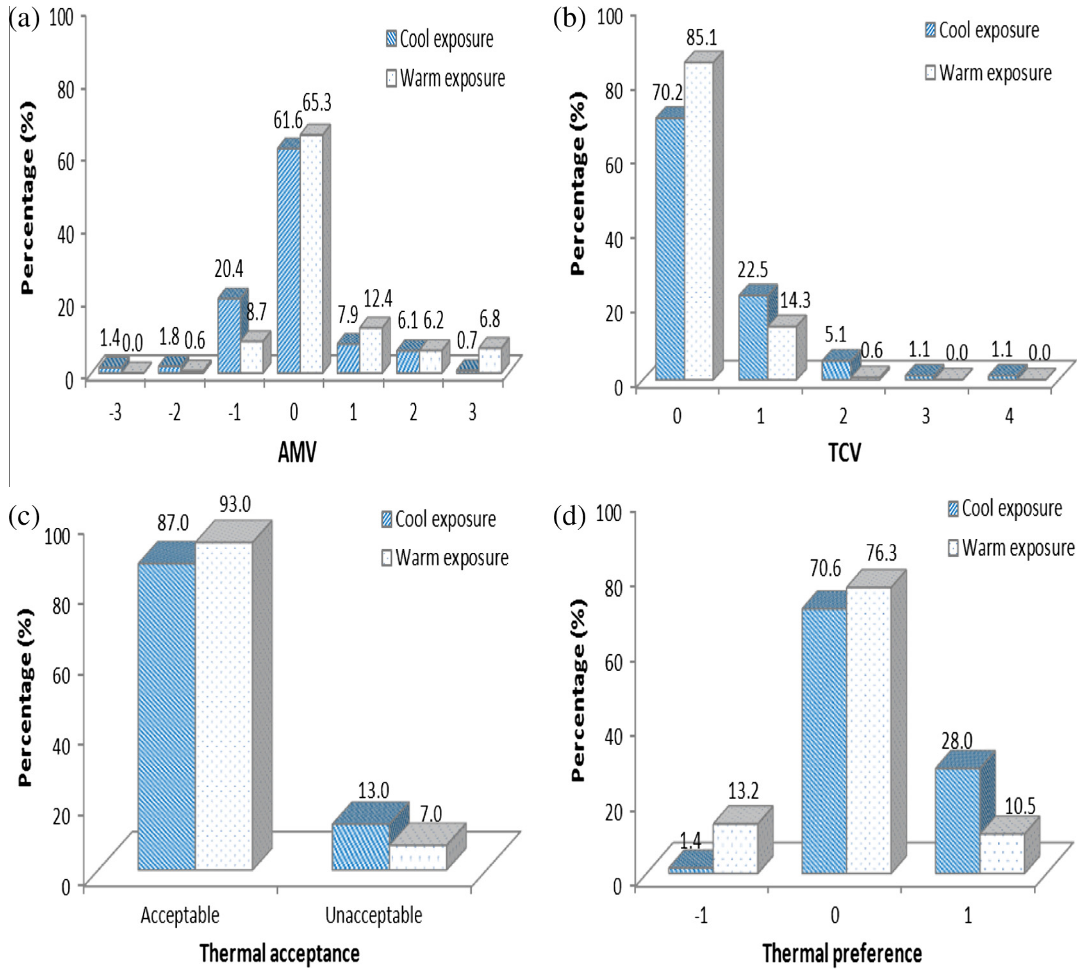

Fig. 4. Distributions of participants' thermal perception votes. (a) AMV distribution, (b) TCV distribution, (c) thermal acceptance distribution and (d) preferred temperature distribution.

The distributions of indoor air temperature corresponding to AMV and TCV are illustrated in Fig. 5. It shows that most participants perceived thermal neutrality and comfort when indoor air temperature distributed around the mean indoor air temperature in each thermal environment. And participants correspondingly perceived cool or warm to indoor temperature fluctuation. When the temperature distributed over the mean value, participants felt warm and vice vasa. As shown in Fig. 5(a), it is interesting to

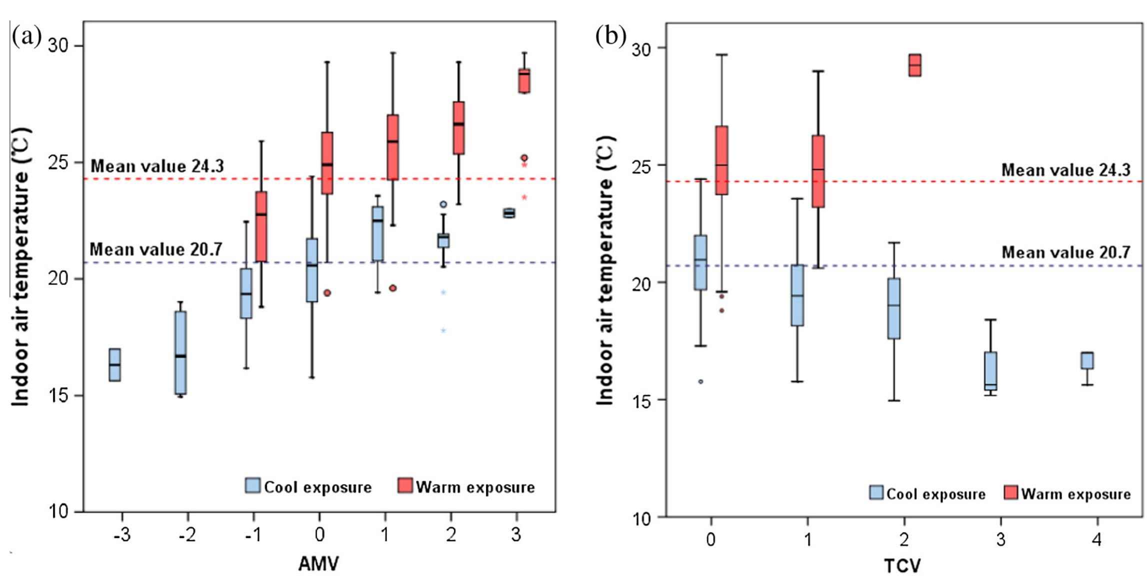

Fig. 5. Distributions of indoor air temperature with AMV and TCV. (a) Indoor air temperature distribution with AMV and (b) indoor air temperature distribution with TCV.

observe that participants in cool exposure felt warm when indoor air temperature was between the mean values. However, the participants in warm exposure felt slightly cool between the mean values. Fig. 5(b) illustrates that the participants' comfortable temperature distributed much higher in warm exposure than cool exposure environment. However, most participants' thermal comfort maintained at "comfortable" and "slightly uncomfortable" levels in warm exposure. And 85.1% votes in warm exposure distributed at "comfortable" level as shown in Fig. 4(b). Through independent samples t-test, the indoor air temperatures between two exposures were significantly different ($p < 0.01$) when participants felt thermally neutral and comfortable.

3.4. Thermal neutrality and acceptable range

The indoor air temperature distributions and thermal neutral temperatures in two environments are shown in Fig. 6. As shown in the figure, there was a concentrated distribution of indoor air temperature in each environment. The mean indoor air temperatures were 24.3 ± 1.6 °C and 20.7 ± 0.9 °C respectively in warm and cool exposures. Based on the regression analysis, the neutral temperatures were obtained respectively 22.8 °C and 20.2 °C in two environments. It is clear that the neutral temperature was much higher in warm exposure than cool exposure environment. And the neutral temperature was close to the mean indoor air temperature in each environment. However, the clothing insulation was much lower in warm exposure environment compared with the recommended value 1.0clo indoors in winter in ASHRAE Standard 55-2013 [3]. It was only 0.74clo by average in warm exposure group. In order to compare the neutral temperatures' difference between two exposures with the same participants' clothing insulation, the participants' clothing insulation in two groups was standardized by 1.0clo. And the neutral temperatures were recalculated as shown in Fig. 6. The standardization process is illustrated from Eqs. (1)–(4).

$$PMV = f(t_a, t_r, \varphi, v, I_{clo}, M) \tag{1}$$

$$PMV' = f(t_a, t_r, \varphi, v, \bar{I}_{clo}, M) \tag{2}$$

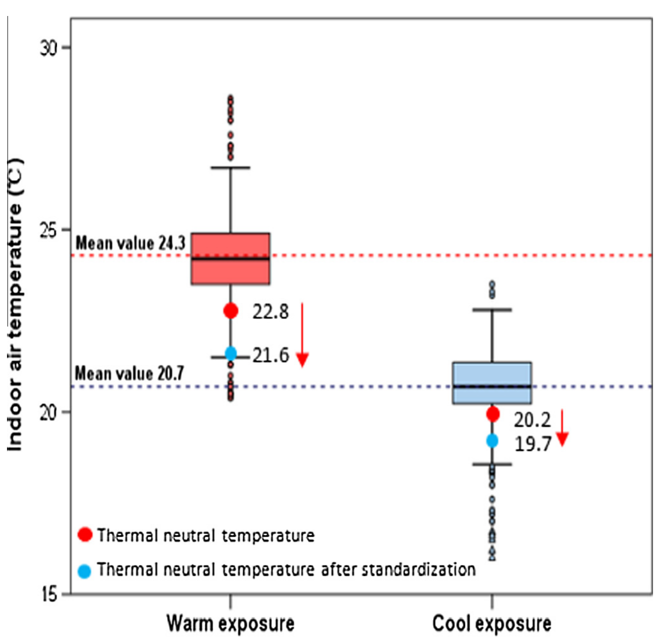

Fig. 6. Relationship between indoor air temperature and neutral temperature in two exposures.

$$\Delta PMV = PMV - PMV' \tag{3}$$

$$AMV' = AMV - \Delta PMV \tag{4}$$

where t_a represents the mean air temperature, °C. t_r represents the mean radiant temperature, °C. φ represents the mean relative humidity, %. v represents the mean air speed, m/s. I_{clo} represents the mean clothing insulation, clo. $\bar{I}_{clo}$ represents the standardized clothing insulation, 1clo. M represents the metabolic rate, met. PMV' represents the PMV value after standardization. AMV' represents the actual mean thermal sensation after standardization.

After clothing insulation standardization, the neutral temperatures decreased to 21.6 °C and 19.7 °C respectively in warm and cool exposures. However, the neutral temperature was still 1.9 °C higher in warm exposure versus cool exposure environment.

Through regression of AMV votes, the acceptable temperature ranges for both groups were obtained as shown in Fig. 7. The 90% acceptable temperature ranges were 17.6–22.9 °C and 19.1–26.4 °C respectively in cool and warm exposure groups, which were all beyond the steady-state comfort zone of ASHRAE Standard 55-2013 [3] indoors in winter. Besides, it shows that AMV was higher in cool exposure than warm exposure environment at the overlapped temperature range and the difference became bigger as temperature moved to the warm/hot side. Furthermore, the 90% acceptable temperature range after clothing standardization was 18.4–24.7 °C and 18.1–21.4 °C respectively in warm and cool exposures. The regression equations of AMV and AMV′ with indoor air temperature are shown in Table 5. It can be seen that the participants' thermal sensation varied 0.3 and 0.16 units respectively in cool and warm exposures as the indoor air temperature increased 1 °C under the same clothing insulation.

3.5. AMV and PMV

The relationship between AMV and PMV predictions is presented in Fig. 8. As shown in the figure, the AMV in cool exposure was always greater than PMV predictions. Namely, participants in cool exposure actually felt warmer than PMV predictions. However, the AMV in warm exposure approximate to the PMV predictions. Even when PMV predicted a warmer state than neutrality, the AMV was closer to the neutrality. Moreover, the participants'

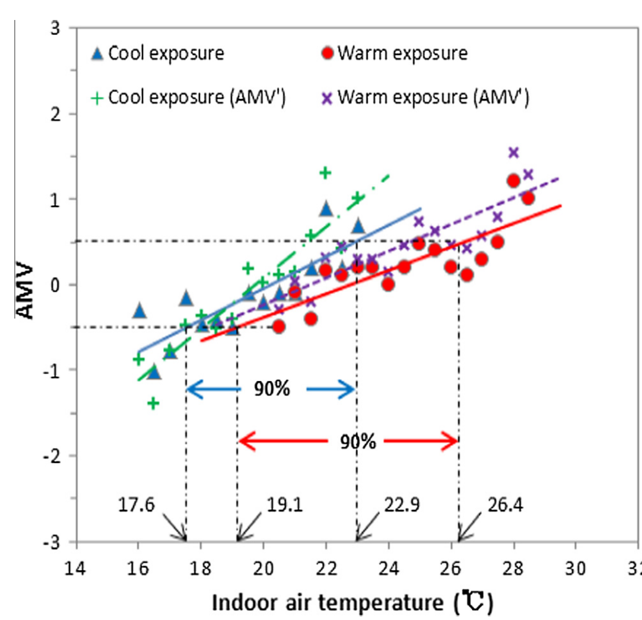

Fig. 7. 90% acceptable temperature ranges in two environments.

Table 5
Regression equations of AMV and AMV′ with indoor air temperature.

	Equation	R^2
Cool exposure (AMV)	$y = 0.1848t_a - 3.7411$	0.6865
Warm exposure (AMV)	$y = 0.1374t_a - 3.1281$	0.6794
Cool exposure (AMV′)	$y = 0.2981t_a - 5.8843$	0.8558
Warm exposure (AMV′)	$y = 0.1569t_a - 3.3807$	0.7338

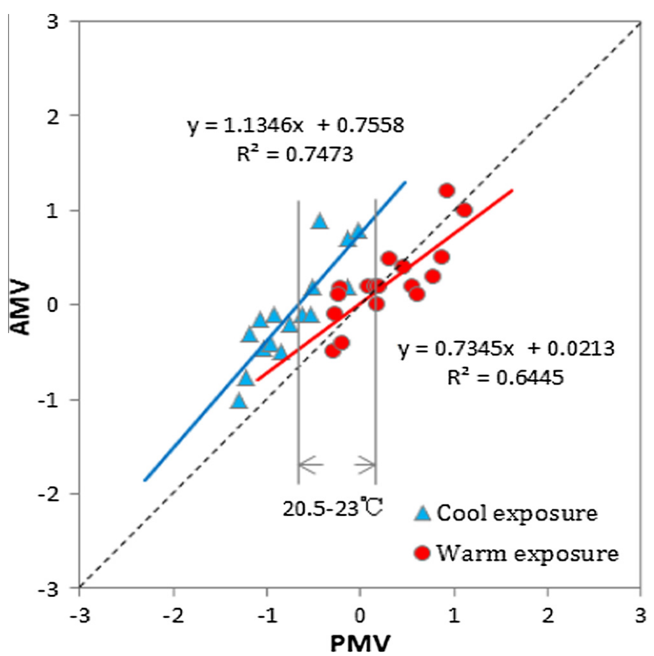

Fig. 8. Relationship between AMV and PMV predictions.

AMV was evidently higher in cool exposure versus warm exposure environment at the overlapped temperature range 20.5–23 °C. And the difference became larger as the PMV prediction moved to warm side.

4. Discussion

Occupants' wellbeing was maintained and improved through physiological, psychological and behavioural adjustments to environmental stimuli [44]. In this study, the occupants' clothing insulation and thermal responses between cool and warm exposure environments were evidently different. The mean indoor air temperatures in warm and cool exposure environments were respectively 24.3 °C and 20.7 °C. The indoor air temperature was close to and partially beyond the lower and upper limits of steady-state comfort zone in ASHRAE Standard 55-2013 [3]. However, majority of occupants achieved thermal neutral, felt thermally comfortable and their environments were thermally acceptable in both exposures. It can be ascribed to the effective behavioural, physiological and psychological adaptation like previous studies. The difference of behavioural adaptation is clear due to the apparent difference of clothing insulation in two exposures. However, does the physiological and psychological adaptation contribute to this discrepancy? To verify this proposition, the clothing insulation was standardized according to the prescribed value 1.0clo in ASHRAE Standard 55-2013 [3]. It was found that the neutral temperature was still 1.9 °C higher in warm exposure versus cool exposure group. To some extent, this verified the effects of physiological and psychological adaptation by different indoor thermal histories. Although, most participants in two exposures could generally achieve thermal neutrality and comfortable state, however, their thermal sensation and comfort discriminatively corresponded to the indoor air temperatures. Through regression analysis, the neutral temperature was close to the mean indoor air temperature in each environment, which met the results by Wang [38,39]. These results suggest that occupants' thermal responses were significantly impacted by the different indoor heating experiences.

The participants' thermal sensation varied 0.3 and 0.16 units respectively in cool and warm exposures as the indoor air temperature increased 1 °C under the same clothing insulation. This indicates that the residents in warm exposure didn't respond sensitively as the cool exposure residents did to the indoor air temperature increase. According to this result, it suggests that a higher thermal comfort zone might be formed for the residents exposing to a high indoor heating temperature for a long period in winter.

Comparing AMV with PMV predictions, it shows that the AMV was higher than PMV predictions in cool exposure but they were close in warm exposure. It suggests that a long-term indoor thermal exposure to the high heating temperature undermined human's adaptability to the cold climate at a large extent in this climate zone.

The winter is very long and cold in Harbin where people spend more time indoors during space heating. Therefore, it is very important to set a reasonable indoor design temperature based on human adaptability to climate to save heating energy. The above analysis has fully demonstrated that the different heating exposures had great impact on human thermal adaptability during long space heating period in this area. Occupants can be generally accustomed to their environment well in different heating temperatures. But, the high neutral temperature indirectly increases the heating energy consumption and carbon footprint in winter.

Wang et al. pointed that the energy consumption was huge in winter in the severe cold zone and the lower limit heating temperature was recommended [13]. According to the results, the occupants can adapt to the warm or cool heating temperatures and accordingly reach their thermal comfort. However, the energy consumption is completely different in two types of thermal environments. According to the Chinese code [40], the outdoor design temperature is −24.2 °C in Harbin. If the mean indoor air temperature in cool environment was used instead of the mean value in warm environment, 8% heating energy would be saved in winter, as determined by the following equation. If taking the factor of occupants' rational clothing insulation into account, the further 2.3% (from 20.7 °C to 19.7 °C) energy can be saved in this climate zone.

$$\Delta N = \frac{t_{n1} - t_{n2}}{t_{n2} - t_w} = \frac{24.3 - 20.7}{20.7 - (-24.2)} \times 100\% = 8\% \tag{5}$$

where ΔN represents the percentage of energy saving, %. t_{n1} represents the average indoor air temperature in warm exposure, °C. t_{n2} represents the average indoor air temperature in cool exposure, °C. t_w represents the outdoor design temperature, °C.

In conclusions, occupants' thermal behaviour and adaptation to the environment as a non-negligible source of building performance uncertainty should be well recognized and attached more importance in the future. As the energy policy plays a more and more momentous role in sustainable development. This study presents a practical reference for future built environment design and energy policymaking in the severe cold climate. An adaptive viewpoint should be fully regarded to the heating temperature set in winter. Human thermal adaptation to outdoor climate should be given more consideration and an irrational high indoor thermal comfort zone should be avoided during space heating period. Along this way, a both comfortable and energy-efficiency heating environment would be established in winter in this climate.

5. Conclusions

The long-term indoor thermal exposure during space heating period can impact human thermal adaptability according to the results.

Occupants could actively adapt to their indoor heating environments. The occupants' thermal comfort and acceptance levels were generally high in both exposures. Occupants' thermal neutrality was always distributed around their mean indoor air temperature. And there are evidently different temperature distributions with AMV and TCV in two exposures. A higher thermal comfort zone was formed in the warm exposure group.

Occupants' neutral temperatures were different in two groups. The neutral temperature was still 1.9 °C higher in warm exposure versus cool exposure based on clothing standardization, which verified the physiological and psychological adaptation to some extent.

The AMV was always higher than PMV predictions in cool exposure group but they were closer in warm exposure group. The participants' AMV was much higher in cool exposure than that in warm exposure environment at the overlapped temperature range. And the difference became larger as the PMV prediction moved to the warm side. It indicates that the long-term indoor thermal exposure undermined human's adaptability to cold climate at different degrees. The occupants' acclimatization to coldness was better in cool exposure than warm exposure environment.

This study presents a practical reference for future built environment design and energy policymaking in the severe cold area. An adaptive viewpoint should be fully regarded to the heating temperature set in winter. The potential mitigation for carbon footprint and heating energy consumption in winter would be substantial and considerable through the adaptive comfort recognition. According to the study, at least 8% heating energy could be conserved during space heating in Harbin. If considering residents' behavioural adaptation and rational clothing insulation, 2.3% energy can be saved further in this climatic zone. As an important implication, human thermal adaptation to outdoor climate should be cognized and an irrational high indoor thermal comfort zone should be avoided during space heating. Consequently, a both comfortable and energy-efficiency heating environment would be built in winter in this climate.

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