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The effect of indoor thermal history on human thermal responses in cold environments of early winter

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ABSTRACT

Human thermal adaptation is an important factor of indoor thermal comfort and energy conservation. To study the effect of indoor thermal history on cold adaptation in the early winter, climate chamber tests were conducted in cold environments at 16 °C with two different thermal experience groups. The groups are divided as follows: the natural ventilation (NV) group consisted of subjects living in naturally ventilated buildings (approximately 11.8 ± 3.4 °C in winter (Liu, H., Wu, Y., Li, B., Cheng, Y., Yao, R., 2017. Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China. Energy and Buildings 140, 9–18)) and the air conditioning (AC) group consisted of subjects living in air-conditioned buildings for at least one year before the climate chamber experiments. The experiments on the NV and AC groups were conducted between December 1–13 and December 15–25, respectively. Each group consisted of 20 subjects wearing winter clothes (1.15 ± 0.05 clo). The thermal sensation votes (TSVs) and thermal comfort votes (TCVs) in both groups were investigated and the subjects' skin temperatures were monitored during the experiments. The results showed that the mean TCV and TSV of both groups were not significantly different in the early winter. However, differences were observed in the subjects' localized body parts. The skin temperatures of the chest and arms of subjects in the NV group were higher than those in the AC group after exposure for 60 min at 16 °C, while calves skin temperatures of subjects in the NV group were lower. In addition, subjects in the AC group were found to feel colder compared to those in the NV group in cold environments at the same skin temperature. Thus, this study provides information about thermal comfort based on thermal experience in early winter.

1. Introduction

The concept of human thermal adaptation has been widely adopted in the evaluation of indoor thermal environments in "real world" buildings (Brager and de Dear, 1998). The concept argues that building occupants respond dynamically to the outdoor climate (Yao et al., 2010). Because of thermal adaptation, there are differences in thermal sensations perceived in different seasons (Cena and de Dear, 2001; Indraganti et al., 2014; Li et al., 2011; Liang et al., 2012; MA., 1994; Moujalled et al., 2008; Nicol et al., 1999; Yun et al., 2012), building models (Mishra and Ramgopal, 2013; Rupp et al., 2015; van Hoof, 2008), climates and cultures worldwide (Frontczak and Wargocki, 2011; Mishra and Ramgopal, 2013; Rupp et al., 2015). In the interest of energy conservation, this adaptive model (de Dear and Brager, 2002; Nicol and Humphreys, 2002) was also incorporated into the ASHRAE Standard 55–2013 and other existing standards.

China's hot summer and cold winter (HSCW) climate zone possesses unique climatic characteristics that include hot long summers, cold wet winters, and monsoon conditions, as described in reference (CMA, 2005). The residents of this area possess diverse adaptations to both cold winters and hot summers to ensure thermal comfort in naturally ventilated indoor environments (Li et al., 2010, 2011; Liu et al., 2012b, 2012c, 2017). However, to date, the adaptive thermal comfort of different body parts of the residents has not been well studied. If a better understanding of the effect of indoor thermal experience on the adaptive

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Nomenclature

ASHRAE	American Society of Heating Refrigerating and Air conditioning Engineer
AC	air conditioning
HSCW	hot summer and cold winter
I_{cl}	clothing insulation, clo
NV	natural ventilation
PMV	predicted mean vote
RH	relative humidity, %
R^2	determination coefficient
TSV	thermal sensation vote
TCV	thermal comfort vote
Ta	room air temperature, °C
Tout	outside air temperature, °C
T_{skin}	skin temperature, °C
T_{chest}	skin temperature of chest, °C
$T_{upperarm}$	skin temperature of upper arm, °C
T_{thigh}	skin temperature of thigh, °C
T_{calf}	skin temperature of calf, °C
NS	No significant difference

thermal comfort of various body parts is gained, there may exist potential to develop a system that incorporates an efficient cooling and heating method, which could contribute to personal comfort and energy conservation.

To add another dimension to comfort considerations in dynamic environments, thermal experience (Luo et al., 2016b; Zhang et al., 2016) and exposure time (Rohles, 1978) could well become the seventh comfort variable for human thermal sensation. Unfortunately, no studies have explicitly quantified thermal experience for the thermal adaptation model. To predict an individual's overall thermal sensations, researchers (Fang et al., 2018) have developed a thermal comfort model based on known local thermal sensations. Other models have used skin temperature (Jin et al., 2012). The adaptive comfort theory (Brager and de Dear, 1998; Liu et al., 2012a; Yao et al., 2009) argues that the occupants' physiological acclimatization can make them more tolerant of local, non-neutral climates. A laboratory study carried out in the HSCW climate zone (Yang et al., 2015) showed that psychological adaptation can neutralize the occupants' thermal sensations by moderating the thermal sensitivity of the skin. However, it is still unclear whether the skin uniformly adapted to thermal environments or in relation to the localized sensitivity of different body parts.

Therefore, experiments were conducted to investigate the effects of indoor thermal experience on human thermal adaptation of different body parts in a cold environment within the HSCW climate zone, including the psychological and physiological responses. The relationship between the localized TSV and skin temperatures of localized body parts was compared between two groups of subjects: those predisposed to AC and those predisposed to NV indoor thermal experiences. This study can serve as a basis for the application of a suitable heating system, which can heat localized body parts of different thermally adapted subjects, exhibiting potential for energy conservation.

2. Composition and definition of AC and NV groups

The prevalence of installed AC units is increasing dramatically in China due to economic development. However, there are still many residents living in NV buildings in rural China, as shown in Fig. 1 (Luo et al., 2016a). For NV buildings in the HSCW climate zone, the average indoor air temperature in winter is 11.8 ± 3.4 °C, which is similar to the outdoor air temperature (Liu et al., 2017). For AC buildings, the indoor air temperature ranged from 18 to 24 °C in winter (GB50176, 2016). To

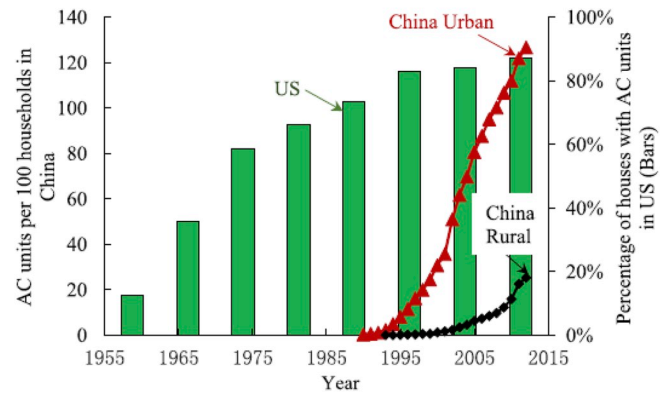

Fig. 1. Increasing trend in the use of air conditioning units in the US and China (Luo et al., 2016a).

study the effects of different indoor thermal experiences on human thermal adaptation in this area, two series of experimental investigations were conducted in the climate chamber.

First, the subjects who intended to participate in the experiment were asked to answer a survey in the form of a questionnaire that required information such as name, gender, birthplace, whether the individual lived in an NV or AC building, their duration of stay, average time spent in a heated space per day this winter, and contact information. Second, the subjects in the NV group were selected based on two criteria: those who had lived in an NV building for at least one year, as Fig. 2 I shows, and those who spent an average of less than 2 h/day in a heated space this winter before and during the experiment. The NV group only stayed in temporarily heated spaces in daily life during the winter such as shopping centers, libraries and stations. The subjects in the AC group were selected based on two criteria: those who had lived in an AC building for at least one year, as Fig. 2 II shows, and those who spent an average of more than 12 h/day in a heated space this winter before and during the experiment.

Finally, each group contained 20 participants (10 males and 10 females), who were in good health and had resided in Chongqing for a period of more than one year. The subjects' basic information was recorded prior to the tests, as summarized in Table 1. None of the subjects were taking prescription medication at that time or had a history of cardiovascular disease. From Table 1, it can be seen that the ages, weights, and heights of the subjects between the AC and NV groups were not significantly different.

3. Experiment methods in climate chamber

3.1. Experimental platform and equipment

All the experiments were conducted in a climate chamber (A room of dimensions 1, 4 m × 3 m × 2.7 m in height) as Fig. 3 shows, located in Chongqing, within the HSCW climate zone, China (Li et al., 2011). In the climate chamber, the room air temperature (Ta) was adjustable within the range −5 °C–40 °C with an accuracy of ±0.30 °C. The relative humidity (RH) was controlled in the range between 10% and 90% with an accuracy of ±5%.

Thermal Comfort Monitoring Station equipment (LSI, Italy, Fig. 3), the precision of which can been seen in Table 2, was used to measure environmental parameters such as ambient indoor air temperature, relative humidity, air velocity, and black-bulb temperature around the test subjects. The station (LSI) was placed in the middle of the climate chamber with one subject on either side of it, and the height of the sensors in the station was set to approximately 0.6 m, considering that the subjects was seated during the experiment. Thermocouples with an accuracy of ±0.15 °C were used to test the test subjects' localized skin temperatures. These were connected to a four-channel data logger

I II

Fig. 2. Illustrations of the apartments I) NV lifestyle (no AC unit), and II) AC lifestyle (with AC unit).

Table 1
Test subject information.

Groups	No.	Age (y)	Weight (kg)	Height (m)	Time in heated space (h/d)
NV	20	23.6 ± 1.0	53.9 ± 8.7	166.3 ± 8.0	<2
AC	20	22.5 ± 0.9	57.3 ± 9.5	167.2 ± 8.5	>12

Heating time: Time in heated space per day (h/d).

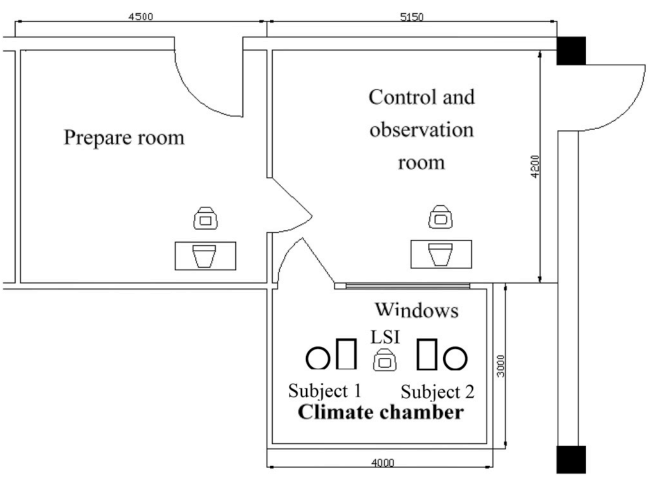

Fig. 3. Experimental platform (Unit: mm).

Table 2
Range and precision of climate chamber and the LSI instruments.

Brand/ model	Equipment	Parameters	Range	Precision
LSI	Thermal Comfort Monitoring Station	Air temperature	−25–150 °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

(HOBE, UX120-006 M). The skin temperatures were automatically recorded on the data logger every 2 s during the experiment. The subjects' localized skin temperatures were measured at 4 points, including the chest, upper arm, calf, and thigh. Before the measurement, all thermocouples were calibrated. On the basis of reliability and sensitivity, a four-point formula was used to calculate the mean skin temperature (*Tskin*), which can be expressed as (Choi et al., 1997)

$$Tskin = 0.3T_{chest} + 0.3T_{upperarm} + 0.2T_{thigh} + 0.20T_{calf} \quad (1)$$

3.2. Experimental conditions and procedures

During the experiment, the air temperature was set to 16 °C, RH was set to approximately 50% ± 5%, and the air velocities were all less than 0.15 m/s. The daily mean outdoor air temperatures (T_{out}) during the experiment were obtained from the nearest meteorological station (Shapingba, No. 57516) of the China Meteorological Administration (China Meteorological Administration, 2019), as presented in Table 3.

Subjects were asked to avoid caffeine, alcohol, and intense physical activity for at least 12 h prior to participating in the tests. During the experiment, the test subjects wore winter clothing that was typical for this area. This included underwear with long sleeves and legs, trousers, sweater, light jacket, socks, and shoes with an insulation level of approximately 1.15 clo (1 clo = 0.155 m^2 K/W) referenced from garment checklists provided in the ASHRAE Standard 55 (ASHRAE, 2013).

As Fig. 4 shows, prior to the test, the subjects arrived at the preparation room and rested for approximately 30 min at an ambient temperature of 20 °C, during which they changed clothes, and recorded their personal information. During this time, they were also instructed in how to put on the physiological monitors and were allowed to become familiar with the experimental requirements and the questionnaires. Informed consent was also obtained at this time for experimentation with human subjects. Two subjects participated in each session.

Once the test began, both the AC and NV groups answered a questionnaire every 10 min for the first 30 min of the experiment. Then, the NV group voted every 10 min and the AC group voted every 15 min. The duration of each session was 70 min for the NV group and 90 min for the AC group. In this study, only the first 60 min of the experiments were considered for the analysis. The work described was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and all experiment protocols were approved by the university's ethics committee. During this time, the subjects were seated in the climate chamber and allowed to read or use mobile phones; however, no discussion

Table 3
Experimental condition settings.

Conditions	Experiment date	I_{cl} (clo)	Ta (°C)	RH (%)	T_{out} (°C)
NV - Winter	12.1–12.13	1.15	16	52% ± 7%	9.4 ± 1.3
AC - Winter	12.15–12.25	1.15	16	50% ± 5%	11.0 ± 2.1

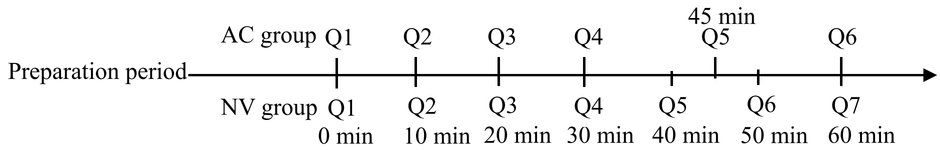

Fig. 4. Experimental procedures.

related to the experiment was allowed.

3.3. Questionnaire and data processing

During the experiments, the subjects were asked to evaluate their environment on a scale representing their perceptions using questionnaires that covered the overall TSV and TCV, as well as those of the localized body parts, including the head, chest, upper arm, lower arm, calf, and thigh. A seven-point scale was used for the TSV: 3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot (ASHRAE, 2013). The TCV made use of a four-point scale: 0 comfort, −1 slight discomfort, −2 discomfort, −3 severe discomfort.

A statistical analysis was conducted using mean values calculated on the basis of data collected from the 20 subjects in each group. The Statistical Package for Social Science (SPSS) 22 was used for this purpose. Linear and non-linear regression analyses were used to investigate the relationship between TSV and skin temperature. The results were considered to be statistically significant at $P < 0.05$.

4. Results and discussion

4.1. TCV

The overall TCV with respect to time, as shown in Fig. 5, revealed that the overall TCVs were not significantly different between the NV and AC groups within the first 60 min. The TCV was stable after 30 min at an ambient air temperature of 16 °C. In addition, the standard deviation (SD) of TCV was higher in the AC group.

The TCV for localized body parts at 0, 30, and 60 min are shown in Fig. 6. The TCV for localized body parts was not significantly different at the beginning of the experiment between the NV and AC groups. However, as time progressed, the TCV for the upper arm, thigh and calf were lower in the AC group than in the NV group within an environment containing an ambient temperature of 16 °C. The TCV for localized body parts also decreased with respect to time in the AC group, especially for the calf, which was −1.05 (slight discomfort) after 30 min of exposure and −1.3 (between slight discomfort and discomfort) after 60 min within a 16 °C ambient temperature environment.

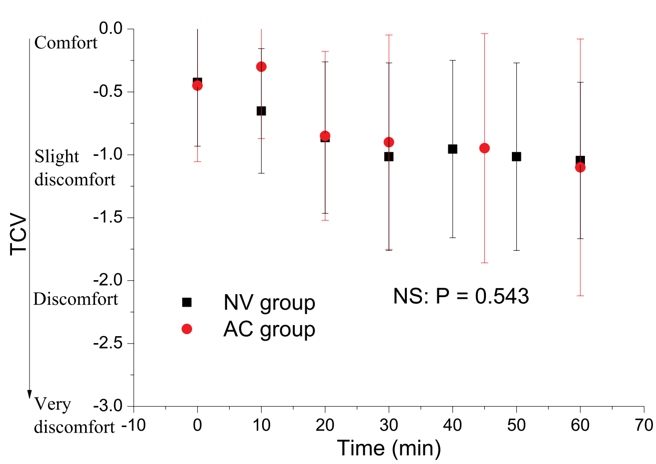

Fig. 5. Overall TCV with respect to time (mean ± SD).

4.2. TSV

The overall TSV with respect to time is shown in Fig. 7. The TSVs for localized body parts at 0, 30, and 60 min are shown in Fig. 8. The overall TSV was lower in the NV group within the first 30 min. In addition, the TSV in the NV group remained stable at a value of approximately −1.1 after 30 min in a 16 °C ambient air temperature environment but increased towards the end of the experiment. Although there was no significant difference in the mean TSV between the AC and NV groups, the SD of the TSV was higher in the AC group, which implied that the TSV in the AC group was less stable in cold environments.

The TSV for the chest and thigh were higher in the AC group at the beginning of the experiment. However, over time, all of the TSVs for localized body parts decreased in the AC group. The TSVs for the chest, arm, thigh and calf were significantly lower in the AC group than in the NV group after 60 min in a an environment with an ambient temperature of 16 °C, with values of −0.60, −1.15, −1.05 and −1.35 at 60 min, respectively. The TSVs for localized body parts were less sensitive with respect to time in the NV group, except for the hand and calf with values of −1.00 and −1.11 at 60 min, respectively.

4.3. Skin temperature

Overall and localized skin temperatures with respect to time are shown in Fig. 9. The overall skin temperature was lower in the NV group ($P = 0.022$). The localized skin temperatures demonstrated different trends, the skin temperature of the chest and arm were higher in the NV group than in the AC group at the start of the experiment, which did not change significantly with respect to time for both groups during the experiment. However, calf skin temperature was lower and decreased faster in the NV group than in the AC group. Thigh skin temperature was near constant with respect to time in the NV group and decreased with respect to time in the AC group. Thus, the decrease in overall skin temperature was predominantly caused by the decreased skin temperature of the calf in the NV group and the thigh in the AC group. The differences in the starting localized skin temperatures of the subjects may be due to differences in the indoor thermal experiences prior to the experiment, as the outdoor air temperatures were low (approximately 8–13 °C) during the experiment for both groups, and the AC groups spent significantly more time in heating spaces.

4.4. The relationship between TSV and skin temperature

During the experiment performed at an ambient air temperature of 16 °C, the overall TSV and skin temperature measurements were predominantly below −0.5 and 32.0 °C for both groups, respectively. Generally, the overall TSV decreased with a decrease in overall skin temperature, especially in the AC group, as seen in Fig. 10. However, the TSV for the NV group was higher than in the AC group for the same overall skin temperature. As can be seen in Figs. 8 and 9, the TSV for the chest decreased as the skin temperature of the chest increased with respect to time in the AC group. This implied that a TSV for one localized body part might be affected by the overall TSV, or by other body parts. From Fig. 11 it can be seen that the TSV for the calf and thigh was lower in the AC group than in the NV group for the same skin temperature. In addition, the skin temperatures of the head and arm were lower in the AC group than in the NV group for the same TSV. This implied that the

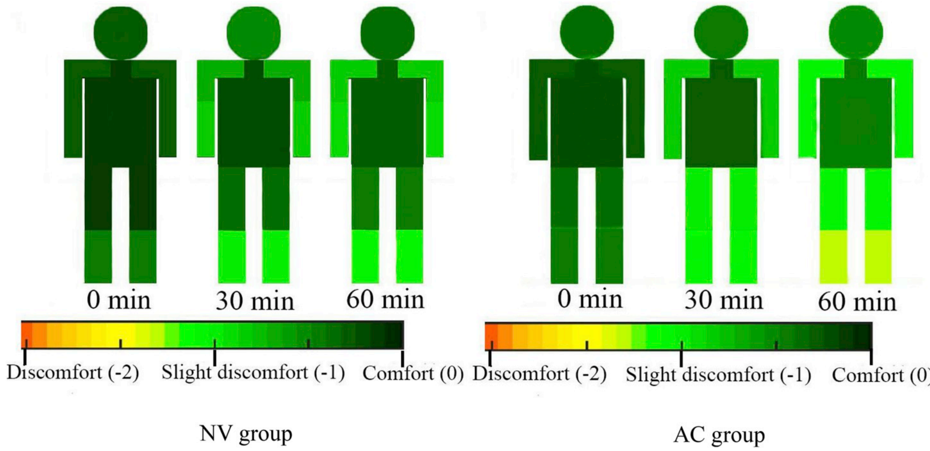

Fig. 6. TCV for localized body parts at 0, 30, and 60 min.

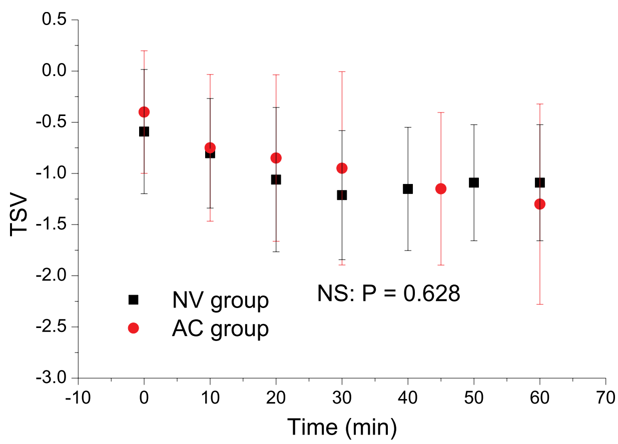

Fig. 7. Overall TSV with respect to time (mean ± SD).

subjects in the NV group were accustomed to a body skin temperature distribution that was higher at the chest and arms and lower at the thigh and the calves, which they identified as a neutral condition. The subjects in the NV group felt neutral with more uniform localized skin temperature, implying the existence of a thermal adaptation strategy for cold environments that incorporated the reduction of heat loss through the extremities with a lower localized skin temperature.

5. Conclusions

In this study, experiments were conducted to investigate the effects of indoor thermal experience on human thermal responses in cold environments in HSCW climate zone. The following conclusions could be drawn:

1) The results revealed that the mean TCV and TSV were not significantly different between the AC and NV groups. However, some localized TCVs and TSVs were lower for the AC group after 60 min of exposure to cold environment, although they were higher than or equal to those of the NV group at the beginning of the experiment.
2) The chest and arm skin temperatures were higher in the NV group than in the AC group after 60 min of exposure to cold environment, while the calf skin temperature was lower in the NV group than in the AC group. The decreased overall skin temperature was predominantly caused by the decreased calf skin temperature in the NV group and decreased thigh skin temperature in the AC group. This also implies that the presence of thermal adaptation in the NV group to cold environments incorporated the reduction of heat loss through the extremities.
3) The subjects who were used to living in an air conditioned environment (heating in winter) typically felt colder at the same skin temperature than those in the NV group already living within a cool/cold environment.

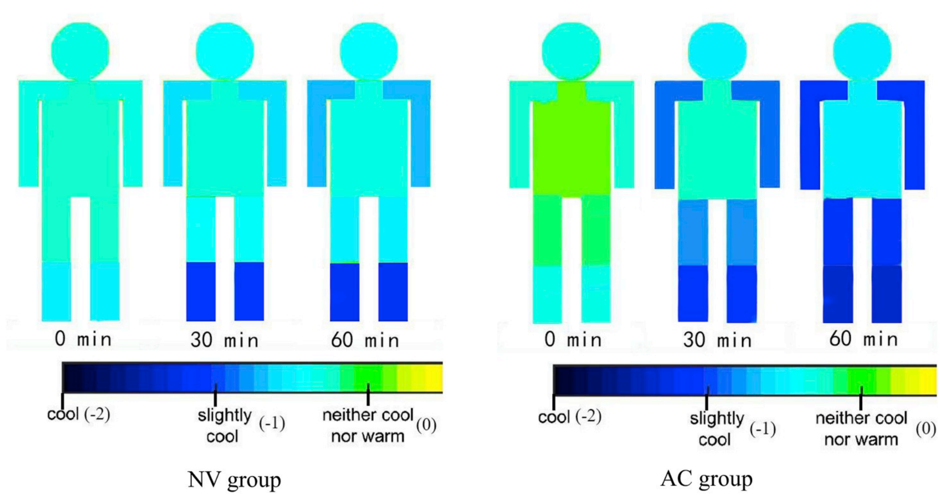

Fig. 8. TSV for localized body parts at 0, 30, and 60 min.

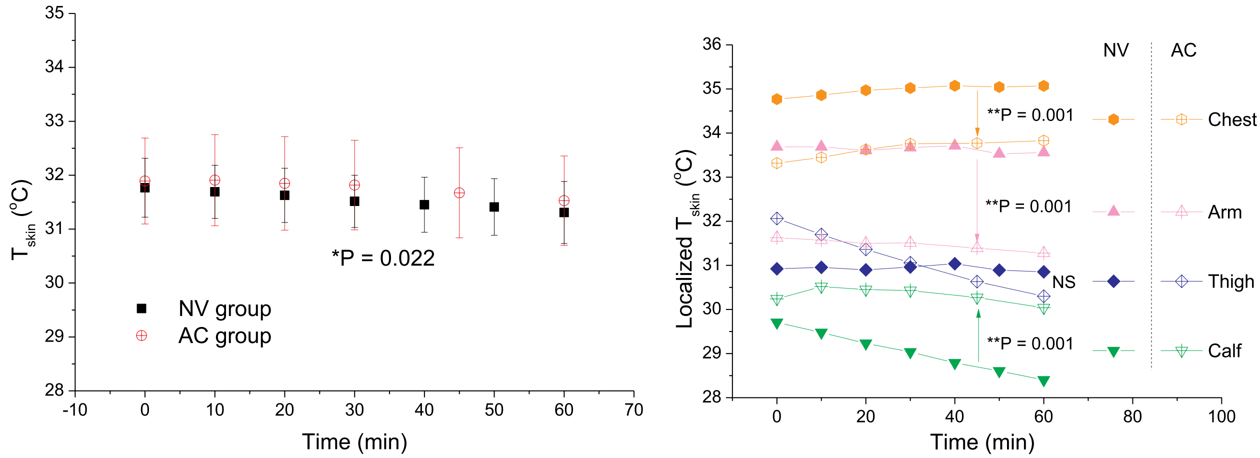

Fig. 9. Mean skin temperature (T_{skin}) with respect to time.

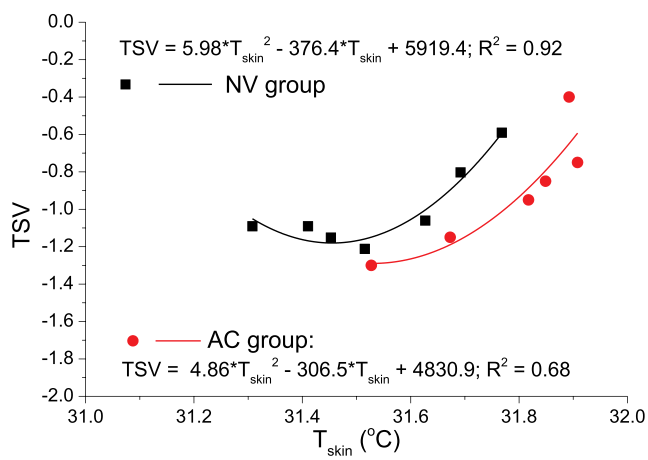

Fig. 10. The relationship between TSV and T_{skin}.

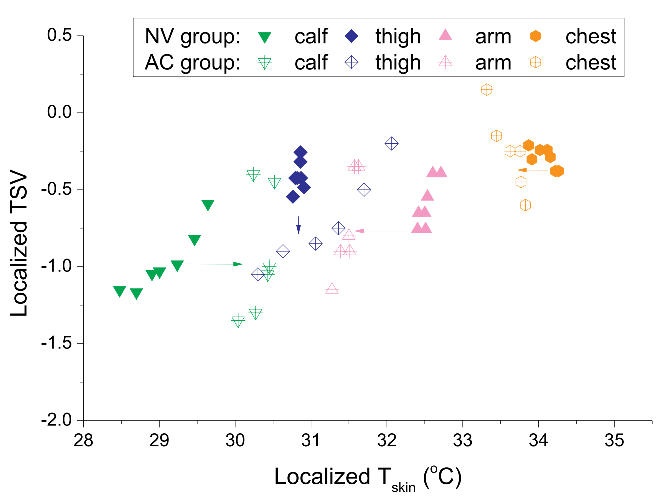

Fig. 11. The relationship between localized TSV and localized T_{skin}.

6. Limitations and future study

The effect of indoor thermal history on human thermal responses was investigated at 16 °C in this study. There are several factors that could affect the results of cold adaptation in this study that need further investigation. The results are specific to these conditions and might vary under different cold adaptation conditions, such as air temperature (i.e. 12 °C) and exposure time prior to and during the experiment, which could also be the comfort variable for human thermal sensation (Luo et al., 2016b; Zhang et al., 2016) (Rohles, 1978). Firstly, the tests of NV and AC groups were not conducted simultaneously. Although all the experiments were conducted in the early winter, the experiments for the NV group were conducted earlier than the AC group. Moreover, as these experiments were all conducted in December, the results may be different in the late stage of winter for a longer adaptation time to cold. Secondly, daily exposure conditions in one year long before the climate-chamber experiments were not controlled, and differentiation between the groups is only an approximation. The exposure time scales to cold environment might also affect the conclusions in this study. Thirdly, the departure localized skin temperatures were different in the test experiments. The phenomenon was caused by different thermal experiences prior to the experiment, and exposure for 30 min at 20 °C prior to the experiments might not be sufficient to eliminate this effect. Thus, the results may vary if there was no departure difference between NV and AC groups. Overall, the results on skin temperature in this study were not only determined by the test conditions, but also related to the status of cold exposure in their daily life. Besides that, some general factors, such as occupation, age, gender and culture (Wu et al., 2019), might affect the conclusions.

The differences in the localized skin temperature distributions between NV and AC groups has potential to help engineers improve heating systems. Thus, a heating system with localized heating at the thigh may benefit both the energy conservation and thermal comfort for the AC groups (Bae and Chun, 2009) based on the findings of this study. However, more localized body parts that are also sensitive to cold environments, including the head, fingers, and feet, were not considered in this study. The effect of inherent mechanisms of localized skin temperature distribution of the human body in the NV/AC groups is a point of future interest.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2019.102448.

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