Chinese older people's subjective and physiological responses to moderate cold and warm temperature steps

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Abstract

Older people are very likely to experience transitions among spaces with different temperatures in daily life. But little has been known about their thermal comfort and physiological responses to these temperature steps. This study investigated 18 healthy older people's thermal perceptions and physiological parameters under cold and warm exposures with 3/5/6°C temperature steps. The results showed that subjects' thermal sensation was sensitive to all moderate temperature steps, but their thermal comfort perception could only distinguish temperature changes greater than 5°C. Thermal unacceptability was only observed when subjects' tympanic temperature reached at 37.08°C. Also, we found older people need more than 50 minutes time to get their mean skin temperature steady after cold stimuli, while they only need < 24 minutes after warm ones. Cold stimuli could significantly boost subjects' blood pressure, respiratory rate, blood oxygen saturation, and depress heart rate. To predict older people's transient thermal sensation after temperature steps, we proposed two regression models for cold and warm exposures respectively. Based on the above observations, we suggest older people should try their best to avoid large step temperature changes, especially for cold side steps.

Keyword: older people; elderly people; thermal comfort; temperature step; thermal sensation; physiological response

Abbreviation

A/B	Coefficients of regression models
AV	Absolute value
BMI	Body mass index
DBP	Diastolic blood pressure
H	Height
HR	Heart rate
L	Length
mTSV	Mean thermal sensation vote

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PT	Physiological test
RH	Relative humidity
RMSE	Root mean square error
RR	Respiratory rate
RV	Relative value
SBP	Systolic blood pressure
SD	Standard deviation
SPO2	Blood oxygen saturation
t	Time after a temperature step
Ta	Air temperature
TA	Thermal acceptability
TC	Thermal comfort
TS	Thermal sensation
TAV	Thermal acceptability vote
TCV	Thermal comfort vote
TSV	Thermal sensation vote
Va	Air velocity
W	Weight
T_{skin}	Mean skin temperature
$T_{skin,p}$	Predicted mean skin temperature
τ	Time constant
ΔT_{skin}	Difference of actual mean skin temperate and neutral mean skin temperature

1 Introduction

1.1 Background

Population aging is a great challenge in many countries. Around the world, there are more than 906 million people who aged 60 or above in 2015, and this number will persistently increase to over 2080 million by the year of 2050 [1]. China, a country with more than 1.3 billion population, is facing an even more serious aging demographic challenge. Taking Shanghai for example, with over 4.83 million citizens aged 60 or above in 2017 [2], it is listed as the top city with the oldest average age in China [3]. Over 33.2% of Shanghai citizens belongs to the 'older people'. The importance of guaranteeing older people's healthy and thermal comfort cannot be overemphasized.

The topic of older people's thermal comfort in buildings has attracted many researchers' attentions to investigate how indoor thermal environment would affect older people's thermal responses. Researchers from Australia [4], Basil [5], China [6-10], Israel [11] Korea[12] and Portugal[13] conducted field studies in older people's residential buildings. Japanese [14-16] and Dutch [17] researchers studied older people's thermal responses to different thermal environments and corresponding differences compared with the young in laboratories. In warm environments, older people were found to have a desire for cooler temperatures than predicted by ASHRAE standard 55[4]. While in cold environment, they showed a lower neutral temperature than that predicted by EN15251 adaptive model [6]. All these results indicate that their subjective responses to thermal environments are different from those of young people.

However, most of previous studies mainly focused on thermal effects caused by uniform and stable thermal environments, while research about older people and transient environments have been absent. On the other hand, older people are very likely to experience transient thermal environments in their daily life. A previous survey study [6] showed that 84.3% of older Shanghai residents living in aged care houses would like to leave from their living-room to outside spaces regularly for exercising or breathing fresh air. When older people move from one space to another, the temperature differences may lead to transient subjective thermal comfort responses and even physiological variances.

1.2 Influences of temperature steps in thermal comfort and physiology

Many previous studies have discussed thermal comfort effects of sudden temperature changes on young people. The phenomena of 'overshoot' and 'transient thermal comfort' have been two widely discussed topics. For example, Gagge [18], Nagano [19], Chen [20] and Liu [21] conducted subject experiments investigating the comfort effects of temperature steps. All these studies found that subjects were much thermally sensitive in the first few minutes after a warm-to-neutral temperature step, then subjects gradually re-established a new thermal steady state because of the function of the thermoregulatory system of human body and consequently expressed relative stable thermal sensation. This phenomenon was named as 'overshooting' of thermal sensation. More recently, Xiong [22] conducted a series of experiments to test young adults' thermal responses to sudden cooling and heating. She found the instant changes of whole-body and local thermal sensations after temperature up-steps were less than its counterparts of down-step temperature changes. Similar asymmetric projections of thermal sensation to temperature up-step and down-step were also reported in Liu [21] and Ji's [23]studies, indicating human bodies are more sensitive to cold stimuli than warm ones.

The reasons behind the above changing patterns of subjective thermal perceptions can be human body's physiological adjustments. When the surrounding thermal environment changes, thermoregulation system can correct the body's microclimate by active adjustments like vasoconstriction, vasodilatation, sweating and shivering, to re-establish a new thermal balance between human beings and thermal environments [24, 25]. These internal changes will affect relevant physiological parameters like the skin and core temperatures, blood pressure, heart rate(HR), respiratory rate(RR), and blood oxygen saturation(SPO2) [26]. As these physiological parameters can largely reflect people's health condition (cardiovascular capacity, respiratory capacity, thermoregulatory capacity), it is reasonable to emphasize the variations of these physiological responses due to the transient thermal environment.

Among all these physiological parameters, the skin temperature is very sensitive to the changes of the surrounding thermal conditions [27]. Under a temperature step, the instant changing magnitude and the stabilizing time skin temperature needs to reach a new balance state can reflect the function of human thermoregulation system. Xiong [28] found that the instant variations of young adults' skin temperature caused by temperature up-steps were normally smaller than that caused by the same amplitude but opposite direction temperature steps. Nagano [19] demonstrated that subjects' thermoregulation systems suffered much more strain during a warm-to-cold step, compared with a warm-to-neutral step with the same magnitude. Zhang [29] tested subjects' skin temperature and thermal sensation in four different experiments and deduced a regression model to predict transient thermal sensation based on the value of skin temperature and its change rate.

1.3 Older people and temperature steps

Although previous studies have shed some light on temperature steps and thermal comfort, most of them focused on young adults. Only a small body of studies investigated the influences of sudden temperature steps on elderly people. Here, we introduce some studies alluding the potential effects of surrounding temperature changes on older people. Schellen [17] compared the skin temperature variations of older and younger people as responding to temperature steps. The results showed that young people's mean skin temperature was normally higher than that of older people when corresponding either temperature up or down steps. Elderly persons' blood pressure [30-32] was found to be associated with indoor and outdoor thermal environment. Through a three-year survey in Japan, Kimura [31] found that every centigrade decrement of mean outdoor temperature lead to the rises of 0.43mmHg in systolic blood pressure and 0.29mmHg in diastolic blood pressure. However, this study mainly focused on seasonal weather changes, not short-term or even instant temperature steps. Franklin [33] reported that systolic blood pressure(SBP) and diastolic blood pressure(DBP) were age-related. One of the causes inducing age-related blood pressure change and consequent cardiovascular diseases was thought to be the disordered control of baroreflex [34, 35].

By reviewing these literature, we realized that direct empirical data elaborating older people's thermal comfort and physiological responses to sudden temperature steps are yet to be produced. Given that the global demographic superpowers like China and other countries embarking upon worrying aging issues, the significance of ensuring older people's healthy and thermal comfort by providing better building thermal environment cannot be overstated. Bearing with these considerations in mind, this study aims to 1) understand the impacts of temperature steps' intensities and directions on older people's subjective perceptions and physiological responses; 2) establish a regression model to predict older people's overall thermal sensation after temperature steps; 3) compare older people's thermal responses to moderate temperature steps with those of young adults from previous studies.

2 Methods

2.1 Study design

Figure 1. Experimental conditions in the climate chamber

The initial idea of this study comes from older people’s common life experience that they regularly move from a living-room with a neutral temperature to a transient or outdoor space with non-thermoneutral environments and then come back to the living-room. In this study, experiments were conducted in a climate chamber located at Tongji University (see Fig. 1). The chamber was designed and constructed by China Academy of Building Research. It consists of two rooms, which are marked as room A (4.2m*2m*2.6m, L*W*H) and room B (4.2m*3.6m*2.6m, L*W*H). The two adjacent rooms are connected by a door. In these two rooms, air temperature (Ta), relative humidity (RH) and air velocity (Va) can be well-controlled by HVAC systems. The system can ensure air temperature varying within ±0.3℃ in the range of 18-28℃ and ±0.5℃ in the rest range of 10-40℃. The relative humidity can be controlled at ±5% accuracy in the range of 30-80%. The temperature in room A was set as a constant value of 26℃, simulating the neutral environment in a normal living-room. Accordingly, four different temperatures (21℃/23℃/29℃/32℃) were set in room B in four cases, representing typical temperatures in transient or outdoor spaces in Shanghai (see Fig.2). Note that although the typical maximum outdoor temperature is only near 30℃, it can easily excess this limit sometimes especially in the mid-summer time. In this study, the lower temperature limit of a transient space was set as 21℃, but not 5℃, because of healthy and safe concern. The temperature differences in these two rooms generated up and down temperature steps of 3℃, 5℃ and 6℃. Relative humidity was controlled in the range of 50-65%, and air velocity was less than 0.15m/s throughout the study.

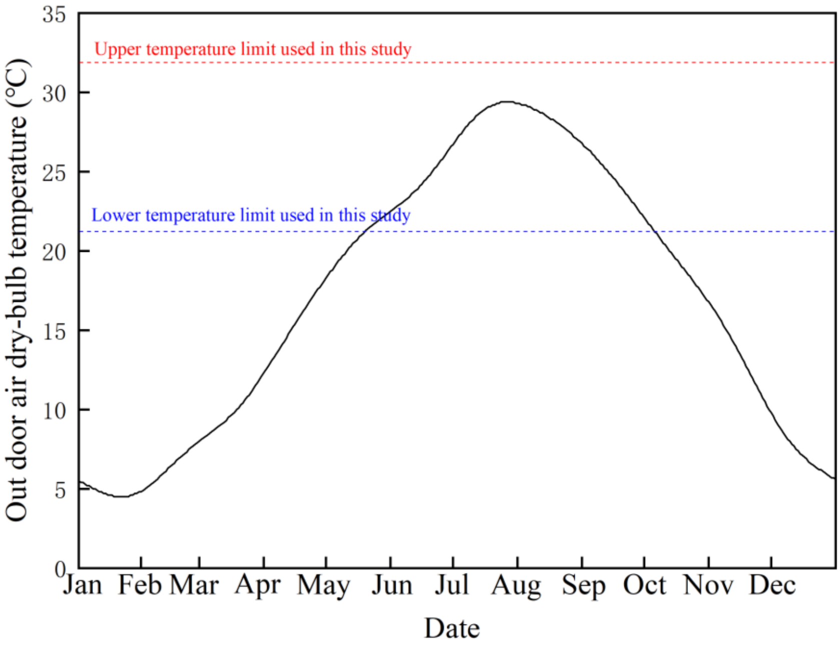


Figure 2 Typical annual outdoor air temperature in Shanghai

2.2 Test protocol

The overall experiment consisted of four separate 170-minute tests. Each test first had a 0.5-hour preparing period and 40-minute acclimation period followed by two 50-minute formal test periods (see Fig.3).

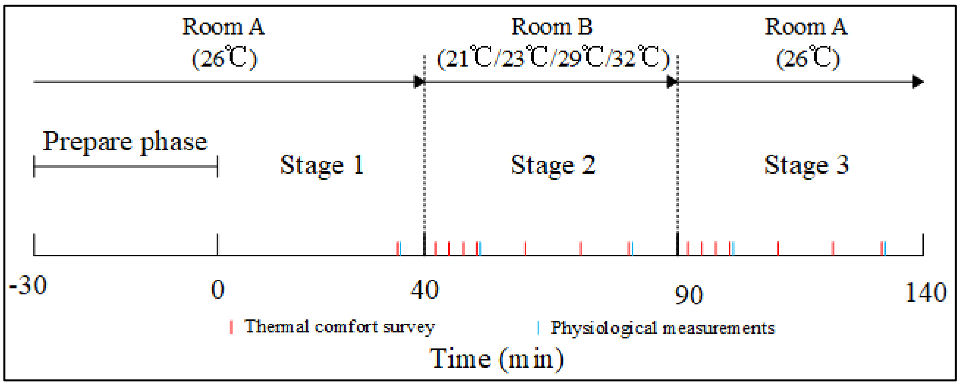


Figure 3. Experimental procedures

Preparing, training, and adapting. Upon arrival at the chamber, subjects stayed in room A for 30 minutes to prepare the test. During this period, they were asked to report their basic information like name, sex, age and diseases history etc. Researchers would help them to measure their heights and weights, and to wear wireless temperature sensors at seven body parts (i.e. forehead, chest, lower arm, left hand, left upper leg, left lower leg, and left foot) to continually record local skin temperatures with 1 minute interval. Once instrumented, subjects experienced a 40-minute adaptation period to adapt to the neutral temperature, while instructors explained to them the voting scale and the test procedures.

Test execution. The two 50-minuite formal tests were initiated right after the adaptation period (stage one). Subjects entered Room B and kept a sedentary activity for 50 minutes (stage two). After that, they moved back to Room A for another 50-minute exposure (stage three). In fact, we initially intended to set up a time period of 60 minutes considering older people's weakened thermoregulation ability. However, in our preliminary experiments, some subjects expressed too much complains to the coldness at the late period of 21℃, so we decided to cut down the time interval to 50 minutes. The survey of thermal comfort was conducted for the first time just before subjects entered Room B. Then, the survey became intensely in the first 10 minutes with the interval of every 3 minutes a vote in stage two. Afterward, participants filled out the thermal comfort questionnaire every 10 minutes. The same procedure was applied when older subjects moved back to Room A. Totally, each test ended with 15 times thermal comfort surveys. Physiological measurements, recording systolic blood pressure (SBP), diastolic blood pressure (DBP), heart rate(HR), respiratory rate(RR), blood oxygen saturation(SPO2) and tympanic temperature, were conducted at the 35th min, 51th min, 81th min, 101th min and 131th min. The test protocol has been reviewed and approved by Tongji University's Committee for the Protection of Human Subjects. Prior to the tests, subjects were informed that they were going to experience some cold/warm thermal conditions, but not harmful.

2.3 Subjects information

The study recruited 18 healthy Chinese older people (9 males and 9 females) as subjects. Their ages ranged from 65 years old to 83 years old, living in Shanghai for at least 1 year. They all had light-to-none caffeine, alcohol, smoking habits – less than 2 cups of coffee or 2 cigarettes a day.

Table 1 shows detailed information about these subjects. Before the day of taking experiments, subjects were suggested to have good rest and take no drinks containing caffeine or tea. Regarding the clothing insulation, we did not provide uniform clothes for subjects but told them to wear short sleeves, thin straight trousers and comfortable shoes (but not sandals or slippers). Estimated by ASHRAE standard 55-2013 [36], the total heat resistance of the clothing, including a wooden chair, was around 0.5clo (1clo=0.155m^2K/W). During the tests, they were allowed to read newspapers or listen to light music.

Table 1 Anthropometric data of subjects

Gender	Age(years) Mean±S.D.	Height(cm) Mean±S.D.	Weight(kg) Mean±S.D.	BMI(kg/m^2) Mean±S.D.
Male	68.3±6.2	168.4±4.1	63.5±10.3	22.4±3.7
Female	66.7±2.7	156.6±5.3	58.7±8.2	23.9±2.4

2.4 Measurement and questionnaire

Physical measurement. During the test, physical environmental parameters like air temperature, air velocity, relative humidity were monitored and recorded. The measuring site was placed near subjects at the height of 1.1 meters. Air temperature and relative humidity were measured automatically by data loggers with the interval of 1 minute. Air velocity and black-bulb temperature were tested using hand-held instruments every 10 minutes. Table 2 lists the detailed introduction of the instrument involved in this study.

Table 2 Information of instrument

Measurement	Instrument	Range	Accuracy
Air temperature	WSZY-1,Tianjianhuayi,China	0~+50℃	±0.1 °C
Relative humidity		10~90%	±2 %
Black-bulb temperature	TM200 black-bulb thermometer, KIMO, France	-50~+250℃	±0.2 ℃
Air velocity	Air velocity meter, TSI, USA	0~20m/s	±0.025 m/s
Skin temperature	Pyrobutton-L, OPULUS, USA	-40~+85℃	±0.2 ℃
Tympanic temperature	IRT6520, Barun, Germany	36~39℃	±0.2 ℃
SBP	Physiological parameters monitor MEC-1000, Mindary, China	40~270mmHg	±5 mmHg
DBP		10~210mmHg	
HR		15~300 BPM	±1 BPM
RR		0~120 BPM	±2 BPM
SPO2		0~100%	±1% (90~100%)

Figure 4 Diagrams of wireless temperature sensors and the physiological monitor

Physiological measurement. To test subjects' blood pressure, HR, RR, SPO2 before and after a temperature step, non-invasive multi-parameter physiological monitor (seen as Fig. 4) was used. Each measurement lasted for 5 minutes. During the period, subjects were told to hold a sedentary position and keep quiet. Before the measurement of blood pressure, the blood pressure cuff wrapped subjects' right upper arm with its lower edge 2.5cm above cubital fossa. Three electrodes attached on subjects' two wrists and left ankle were used to analyze and record HR. A pulse oximeter was attached on subjects' left middle fingertips to detect SPO2 and RR. The testing results could be stored in the monitor and easily be reviewed after experiments. Skin temperature sensors (seen as Fig.4) were attached on subjects' seven body parts with medical tape. An ear thermometer was utilized to test older people's left ear based tympanic temperature.

Thermal comfort survey. Subjects' thermal sensation, thermal comfort and thermal acceptability were recorded during the test. Thermal sensation is a subjective feeling in response to coldness or warmness, and the degree of these feelings can be sorted by a seven-point scale, as ASHRAE suggested, which are hot, warm, slight warm, neutral, slight cool, cool and cold. Thermal comfort is related to thermal sensation. An uncomfortable status usually comes with an extreme cold or hot feeling. However, in some circumstances, a cold feeling can also make people comfortable. For example, moving from a hot outdoor environment to a cool indoor environment could make people feel ‘cool’ but ‘very comfortable’. Another notable example is when people taking sauna or spa, the hot and humid environment will make them feel ‘hot’ but ‘very comfortable’.Thermal acceptability can further test if a specific thermal environment touch one’s bottom line of accepting to stay with it. For example, people may feel ‘cold’ and ‘slight uncomfortable’ outside buildings in winter, but the cold environment can be ‘clearly acceptable’. While an unacceptability to a thermal environment usually companies with an uncomfortable and extreme cold or warm sensation.

In this study, subjects’ thermal sensations were quantified using Chinese version scales translated from ASHRAE Standard 55 [36]. The questionnaire required subjects to grade their overall thermal sensation levels on a 7-point scale (i.e.+3,+2,+1,0,-1,-2,-3 corresponding to hot, warm, slight warm, neutral, slightly cool, cool and cold, respectively) and thermal comfort levels on a 6-point scale (i.e.+2,+1,+0.01, -0.01,-1,-2 corresponding to very comfortable, comfortable, just comfortable, just uncomfortable, uncomfortable and very uncomfortable, respectively). Meanwhile, thermal acceptability was accessed by a 4-point scale (i.e.+1, +0.01, -0.01 and -1 representing clearly acceptable, just acceptable, just unacceptable and clearly unacceptable, respectively).

2.5 Statistical analysis

To calculate the time subjects needed to stabilize thermal sensation after a temperature step, two-way ANOVA ($P<0.05$) was applied to compare mean thermal sensation votes collected from discrete time steps in a thermal environment. To figure out the effects of temperature steps on instant changes of subjective feelings and physiological parameters, index like ΔTSV, ΔTCV, ΔTAV, ΔHR, ΔRR, ΔSBP, ΔDBP, ΔSPO2 were calculated by subtracting the last average value before a temperature step from the first average value after the step. Then, paired t-test ($P<0.05$) was implemented to exam the significance of differences. The mean skin temperature was calculated on the basis of weighted 7-point local skin temperatures, seen as Equation 1 [37]. An exponential regression (Equation 2) [19] was performed to predict the variations of mean skin temperature in response to temperature steps.

$$\mathrm{T_{skin}} = 0.07\mathrm{T_{forehead}} + 0.35\mathrm{T_{chest}} + 0.14\mathrm{T_{lowerarm}} + 0.05\mathrm{T_{headback}} + 0.19\mathrm{T_{upperleg}} + 0.13\mathrm{T_{lowerleg}} + 0.07\mathrm{T_{foot}} \qquad (1)$$

$$\mathrm{T_{skin,p}} = \mathrm{A}\exp(-\mathrm{t}/\tau) + \mathrm{B} \qquad (2)$$

Where $T_{skin,p}$ means predicted mean skin temperature, and ‘t’ is the time after a temperature step. ‘A’ and ‘B’ are coefficients, and ‘τ’ is a time constant, therefore 3τ means the required time to achieve a 95% change on mean skin temperature. The regression models were computed by Levenberge-Marquardt algorithm.

For each individual, the influence of a temperature step on a specific physiological parameter can be calculated through dividing the values after a temperature step by the first value collected before the step. The following equation is used to calculate the mean relative physiological values.

$$\mathrm{RV_{parameters,PTi}} = mean(\textstyle\sum_{1}^{18} \frac{\mathrm{AV_{parameters,PTi,j}}}{\mathrm{AV_{parameters,PT1,j}}} * 100\%) \quad (3)$$

Where ‘RV’ and ‘AV’ are the abbreviations of relative value and absolute value, respectively. The parameters can be systolic blood pressure, diastolic blood pressure, HR, RR and SPO2. PT_i stands for the sequence of physiological tests. The subscript j represents a specific individual among the 18 subjects.

Skin temperature is a sensible thermal signal and therefore always a reliable index to predict human thermal sensation [24, 25, 27, 29, 38-40]. For the present study, we care about how older people’s thermal sensation changes after the transformation of thermal environments. For each individual, his or her unique physical and physiological characters may lead to the existence of differences in skin temperature compared with others, even being in the same thermal environment. To eliminate the side effect of subjects’ inconsistency of the thermoregulation system, the individual difference in skin temperature needs to be noticed and removed. Considering subjects’ TSV in the neutral thermal environment is near zero (thermal neutrality), we define that the corresponding mean skin temperature is neutral mean skin temperature. Accordingly, Equation 4 is used to calculate average individual discrepancy of actual mean skin temperature and neutral mean skin temperature ($\mathrm{m\Delta T_{skin}}$). Besides, the corresponding mean thermal sensation (mTSV) is also calculated.

$$\mathrm{m\Delta T_{skin,i}} = \frac{1}{18}\textstyle\sum_{1}^{18}\left(\mathrm{T_{skin,i,j}} - \mathrm{T_{skin,26℃,j}}\right) \quad (4)$$

$$\mathrm{mTSV_i} = \frac{1}{18}\textstyle\sum_{1}^{18} \mathrm{TSV_{i,j}} \quad (5)$$

Where $\mathrm{T_{skin,i,j}}$ means the jth subject’s mean skin temperature in the ith measurement. For a single test, j varies from 1 to 18, which means there are 18 subjects. The subscript i means the sequence of skin temperature measurement. In this study, we plan to develop a model to predict older people’s thermal sensation before mean skin temperature achieves stability. So only the data collected before the stable time is adopted to build the model. The symbol $\mathrm{T_{skin,26℃,j}}$ is the jth subject’s neutral mean skin temperature, which is calculated as the average of subjects’ mean skin temperatures measured in the stage one. $\mathrm{TSV_{i,j}}$ means the jth subject’s thermal sensation vote in the ith measurement.

The statistical analysis was performed by SPSS22.0 (IBM, USA), and the regression analysis was completed on the platform of Matlab R2018a (MathWork, USA).

3 Results

3.1 Subjective perceptions

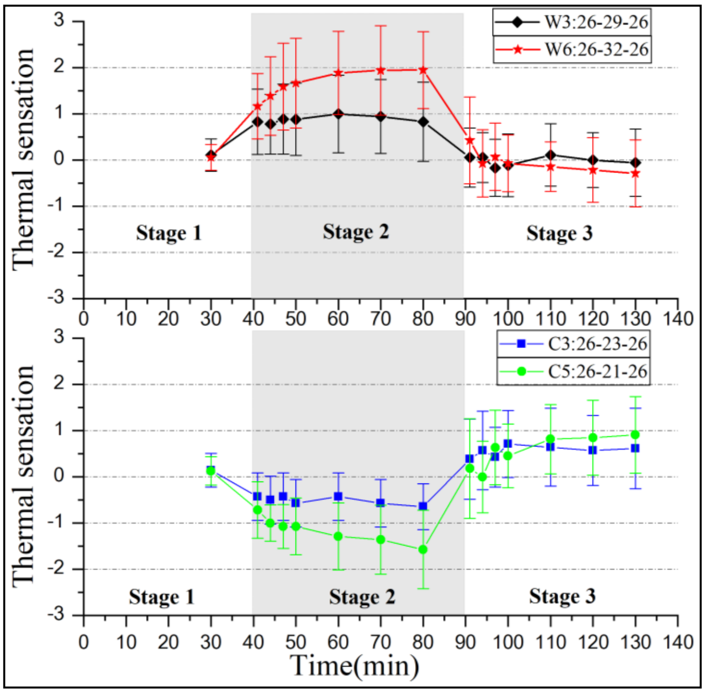


Figure 5 Variations of overall thermal sensation over temperature steps

Fig.5 depicts the changes in subjects' overall thermal sensation over time. The average values (C3: -0.64 ~ +0.71; C5: -1.57 ~ +0.91; W3: -0.17 ~ +1.00; W6: -0.29 ~ +1.95) and standard deviations (C3:0.36 ~ 0.87; C5: 0.31 ~ 1.08; W3: 0.35 ~ 0.86; W6: 0.28 ~ 0.97) are demonstrated with points and error bars separately. Clear overshooting phenomenon on TSV is neither observed in temperature up-step nor down-step. As a general trend, mean TSV gradually increases or decreases (depending on the direction of temperature step) after a temperature step.

Fig. 5 also shows the asymmetry of TSV, especially in cold tests. Taking the C5 test for example, the temperature in stage 1 and stage 3 are the same. But the mean TSV in stage one is 0.15, which is 0.8 scales lower than that of the last vote in stage three. Actually, the mean skin temperature in the late of stage 3 is even lower than that in the stage 1, which indicates that older people's thermal sensation may be influenced by a short-time thermal experience.

According to the ANOVA test with $P<0.05$, subjects only need less than 4 minutes to reach stabilized thermal sensation after moving from a neutral environment to a C5/W6 non-neutral condition. In other smaller temperature steps like C3 and W3, they only need less than 1 minute to get a stable thermal sensation.

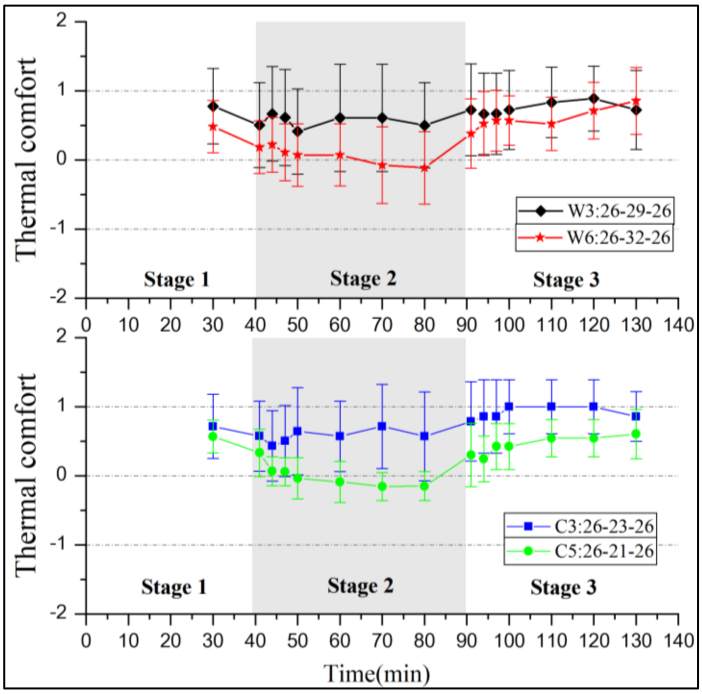


Figure 6 Variations of thermal comfort over temperature steps

Fig. 6 shows the variations of thermal comfort in response to temperature steps. In 3℃ temperature steps like C3 and W3 tests, subjects' mean TCVs are always higher than 0.01, which means they are comfortable to the environment. But in large temperature steps like C5 and W6, subjects' thermal comfortable votes exhibit a remarkable decreasing trend in the non-neutral environment, and then remained at uncomfortable status.

Older people's thermal acceptability (TA) in four tests is illustrated in Fig. 7. The standard deviations vary from 0.26 to 0.51 in C3, from 0.36 to 0.52 in C5, from 0.43 to 0.51 in W3 and from 0.39 to 0.51 in W6. The TAVs in cold or warm conditions (stage 2) are significantly lower than that in neutral environment (stage 1 and stage 3), with the largest differences of 0.43 in C3 (P=0.009), 0.57 in C5 (P=0.001), 0.35 in W3 (P=0.043) and 0.82 in W6 (P=0.000). At the same time, it is interesting to see that subjects are always acceptable to most of thermal environments in this study, except for the late stage two in 32℃.

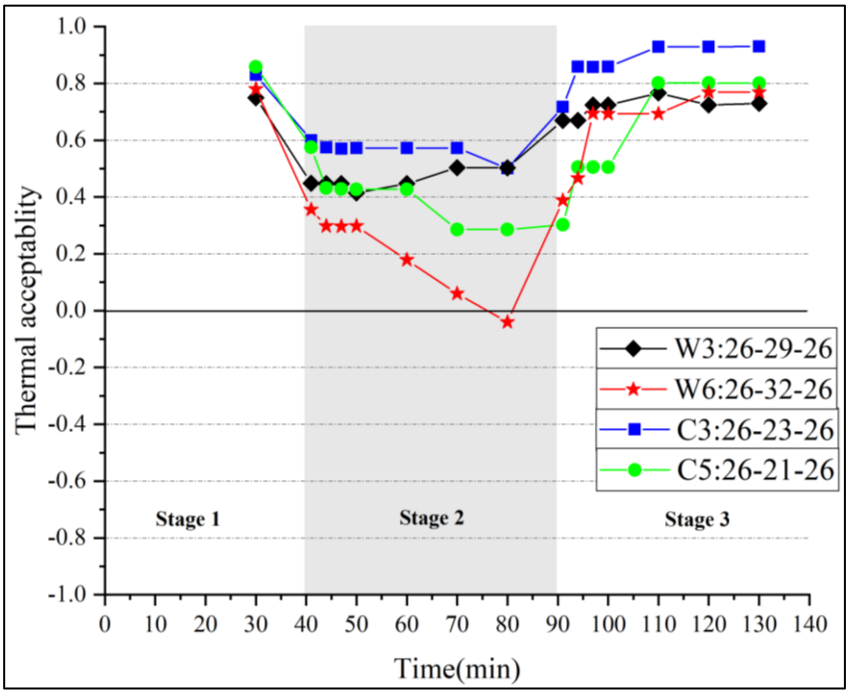


Figure 7 Variations of thermal acceptability over temperature steps

Table 3. Instant changes of TSV/TCV/TAV after a temperature step

	C3		C5		W3		W6	
	26-23	23-26	26-21	21-26	26-29	29-26	26-32	32-26
ΔTSV	-0.57*	1.02*	-0.85 *	1.75*	0.72*	-0.78*	1.10*	-1.52*
ΔTCV	-0.14	0.22	-0.36*	0.56*	-0.28	0.23	-0.45*	0.74*
ΔTAV	-0.07	0.20	-0.13	0.22	-0.05	0.10	-0.21	0.38*

Note: *P<0.05

Table 3 lists the instantaneous changes of TSV/TCV/TAV after temperature steps. It indicates the magnitude of temperature steps can significantly affect older people subjective perceptions. Generally, the larger magnitudes will lead to larger instant changes on TSV/TCV/TAV. Step directions also impose impacts on subjects' perceptions. When subjects moved from non-thermal neutral environments (21°C/23°C/29°C/32°C) to a neutral environment (26°C), the immediate changes of TSV/TCV/TAV are generally larger than the corresponding changes generated in the opposite transition. Besides, subjects' thermal sensation was sensitive to all the temperature steps in this study with significant changes occurred after any temperature step, while significant changes in thermal comfort were only found in large temperature steps like C5 and W6.

3.2 Physiological response

3.2.1 Skin and tympanic temperature

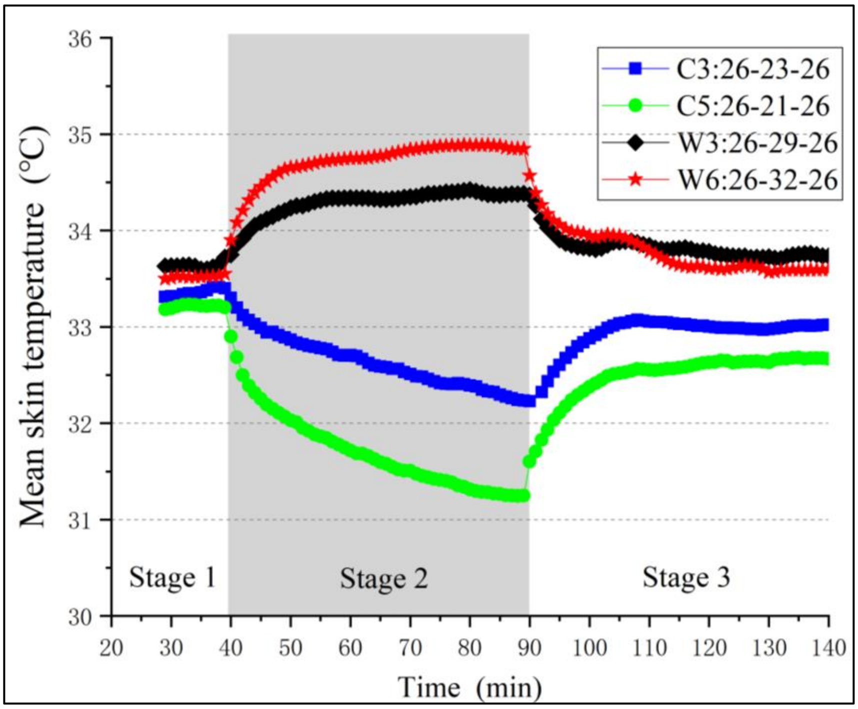


Figure 8 Changes of mean skin temperature in response to temperature steps

Fig.8 shows mean skin temperature's exponential changing trends after temperature up or down steps. The standard deviations vary from 0.39 to 1.12 in C3, from 0.46 to 0.73 in C5, from 0.33 to 0.46 in W3 and from 0.23 to 0.62 in W6. In the third stage of W3 and W6, mean skin temperature exhibits some fluctuations during the decreasing period, which may be caused by the physiological measurement implemented at the 100th minutes. The mean skin temperature can achieve new steady levels after either temperature up or down steps in warm tests. In contrast, mean skin temperature consistently drops after down side temperature steps in cold tests.

Table 4. Results of exponential models fitted by measured mean skin temperature

	C3		C5		W3		W6	
	26-23	23-26	26-21	21-26	26-29	29-26	26-32	32-26
A(°C)	1.22	-1.04	1.63	-1.21	-0.64	0.59	-1.27	1.20
B(°C)	32.13	33.02	31.10	32.65	34.37	33.74	34.84	33.60
3τ(min)	>50	14.4	>50	22.8	22.8	13.5	23.1	24.0
R^2	0.97	0.96	0.99	0.99	0.97	0.88	0.98	0.99
SSE	0.158	0.069	0.087	0.018	0.033	0.064	0.082	0.052

Table 4 presents the coefficients and time constants in skin temperature regression models. Based on these equations, we can predict mean skin temperature with time. As described above, the value of 3τ is the time subjects need to stabilize their mean skin temperature to a new steady state. A larger amplitude of temperature step usually causes a longer stable time. Besides, under cold stress, subjects require a longer time (more than 50minutes) to recover mean skin temperature, while they only need less than 24 minutes to get mean skin temperature stabilized again.

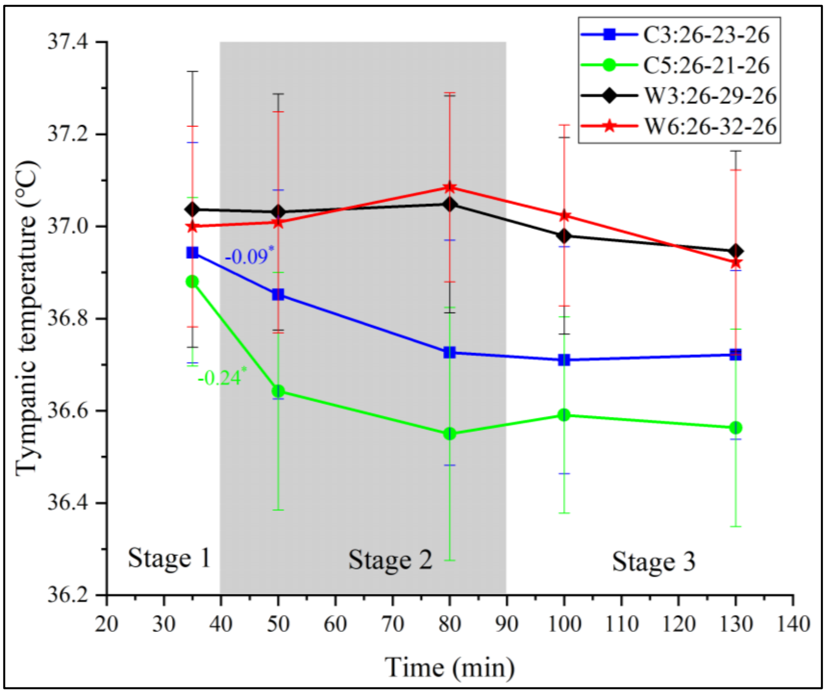
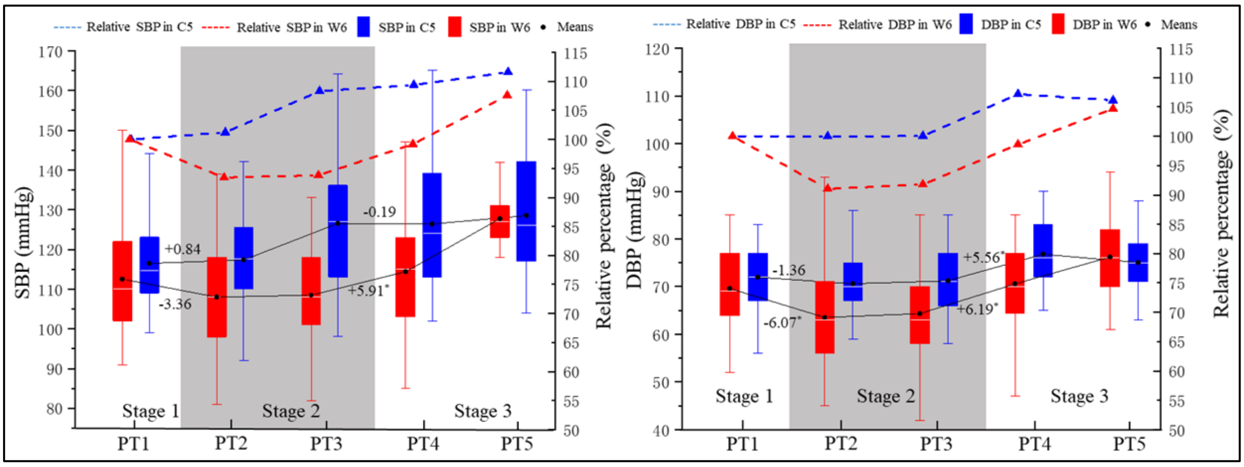


Figure 9 Changes of tympanic temperature in response to temperature steps

The variation trends of ear-based tympanic temperature in response to temperature steps are shown in Fig. 9. Both means (C3:36.71℃ to 36.94℃; C5:36.55℃ to 36.88℃; W3: 36.94℃ to 37.04℃; W6:36.92℃ to 37.08℃) and standard deviations (C3:0.18 to 0.25; C5:0.18 to 0.27; W3:0.22 to 0.29; W6:0.20 to 0.23) of tympanic temperature change in different tests. In warm tests, subjects' tympanic temperature shows no prominent changes, despite the direction and intensity of temperature steps. While in cold tests, tympanic temperature significantly drops ($P<0.05$) after downside temperature steps with the decrement of 0.09℃ in C3 and 0.24℃ in C5. Tympanic temperature is not easy to recover because even subjects moved back to the neutral thermal environment, their tympanic temperatures were still lower than the initial level.

3.2.2 Other physiological changes

Fig. 10 to Fig. 13 show the relative and absolute changes in blood pressure, HR, RR and SPO2 in C5 and W6. In these figures, box diagrams reflect the distributions, means, 25% and 75% quartiles of physiological parameters, and the dash lines show the variations of relative values.



(a)Systolic blood pressure (SBP)　　(b) Diastolic blood pressure (DBP)

Figure 10 Changes in blood pressure. 'PT' means a physiological test. PT2 and PT3 were conducted in 21°C/32°C, while PT1/4/5 were completed in 26°C.

Fig. 10 shows the changing patterns of SBP and DBP. Means and standard deviations of SBP (mean:116.39mmHG to 128.44 mmHG in C5 and 108.03 mmHG to 127.74 mmHG in W6; SD: 11.05 to 16.04 in C5 and 5.74 to 14.96 in W6) and DBP (mean:70.61 mmHG to 76.80 mmHG in C5 and 63.53 mmHG to 76.22 mmHG in W6; SD: 6.09 to 7.05 in C5 and 7.97 to 9.30 in W6) vary among different tests. The results show that cold environment stimulates SBP to a higher level with about 10% increment in PT3, and SBP consistently maintains at this level even after subjects moved back to the neutral environment. Unlike the effects imposed on SBP by a sudden cold stimulus, a warm one depresses blood pressure with the decrements of 3.36mmHg in SBP and 6.07mmHg in DBP in PT3.

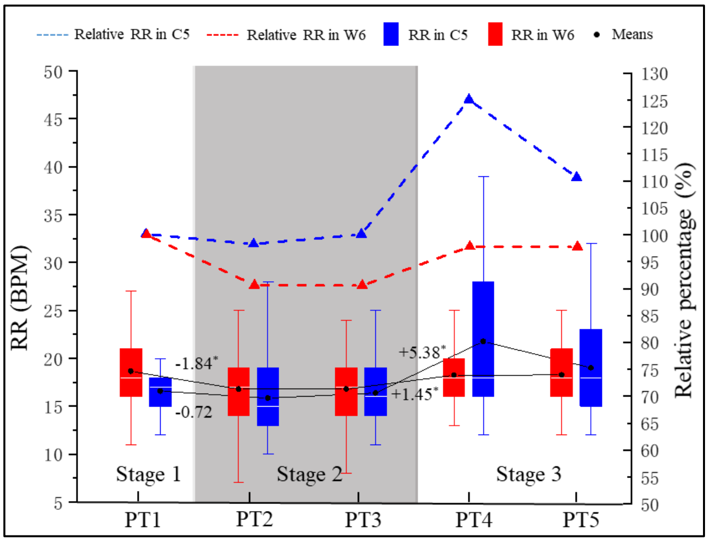


Figure 11 Changes in respiratory rate

Fig. 11 illustrates the fluctuations of respiration rate during temperature steps. Means (C5:15.86BPM to 21.76BPM; W6:16.79BPM to 18.64BPM) and standard deviations (C5:2.11 to 7.32 ;W6: 2.61 to 4.11) of RR are shown in the figure. It is very noticeable that RR signally increases by 5.38BPM in PT4, reaching at 22.2BMP with the relative percentage peaking at 125 %, after a 5°C up-step in C5. Unlike the prompting effects caused by the cold exposure, a warm stimulus depresses RR with a decrement of 1.84BPM.

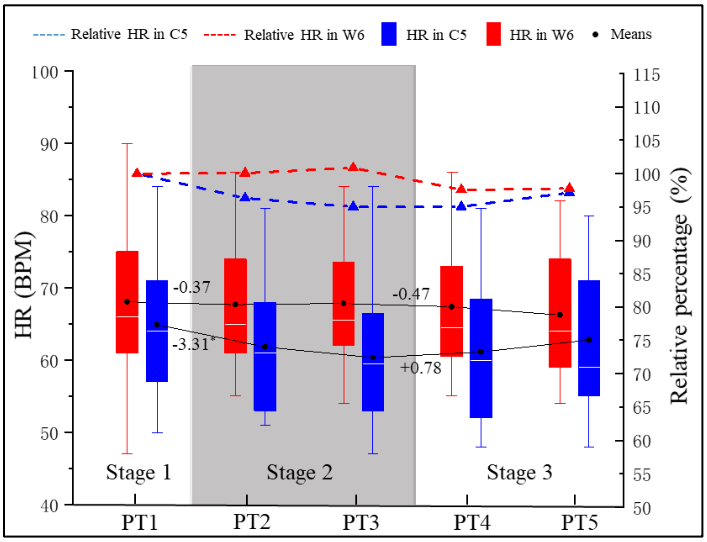


Figure 12 Changes in heart rate

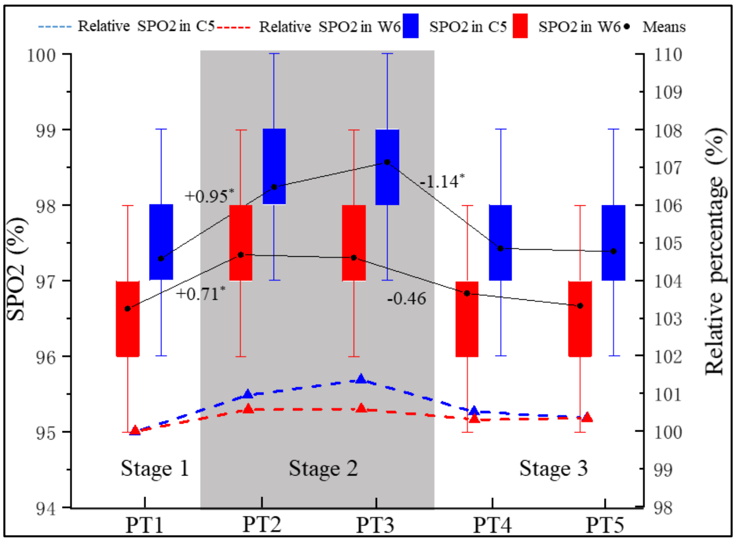


Figure 13 Changes in SPO2

Fig. 12 shows the changes in heart rate. The mean values of HR change from 60.35BPM to 64.90BPM in C5 and 66.25BPM to 68.06BPM in W6, and the standard deviations alter from 8.63 to 9.10 in C5 and from 8.04 to 8.98 in W6. HR shows no significant changes in most temperature steps, except for an obvious reduction of 3.31BPM occurred at the down-step of C5 ($P<0.05$). As subjects went back to the neutral environment from a cold or warm exposure, HR gradually recovers to the original levels with relative percentage of HR being around 97.5% at the end of tests.

In Fig. 13, the mean values of SPO2 change from 97.28% to 98.56% in C5 and from 96.62% to 97.34% in W6, and the standard deviations alter from 0.63 to 1.44 in C5 and from 0.73 to 0.95 in W6. The changing trends of SPO2 in C5 and W6 consistently show that both the absolute and relative values of SPO2 get increased significantly ($P<0.05$) in non-neutral thermal environments and then return to near original status at the end of tests.

3.3 Correlation between thermal sensation and skin temperature

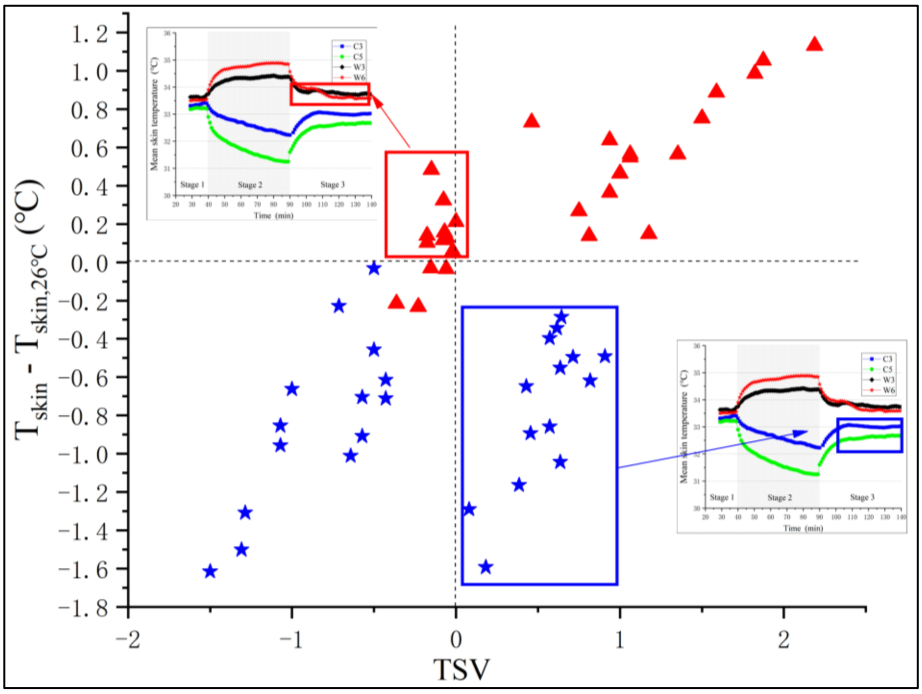


Figure 14 Correlation between ΔT_{skin} and TSV

Fig. 14 depicts the correlation between $m\Delta T_{skin}$ and mTSV. In the figure, red triangles and blue stars stand for the values in warm tests (W3 and W6) and cold tests (C3 and C5), respectively. Generally, the larger the discrepancy of neutral skin temperature and actual skin temperature is, the stronger thermal sensation (cooler or warmer) subjects will feel. Correlation tests verify that ΔT_{skin} is strongly related to older people's thermal sensation in warm tests (R^2=0.85). However, no such correlation is found in cold tests. The points circled by red and blue rectangles seem to be outliers. For example, in the red rectangle, although the points refer to positive ΔT_{skin}, the corresponding TSVs are negative. That situation occurred in stage three when subjects came back to the neutral environment from non-neutral environments. At this time, we can see from Fig. 8 that subjects' mean skin temperatures after the 120th minutes are slightly higher than the values in stage one, while the TSV in the late of stage three is slightly lower than the TSV in stage one (seen as Fig. 5). The contrary phenomenon is also seen in cold tests. The influences caused by short-term or long-term thermal history on thermal perception have been noticed and reported by Luo [41], Ning [42] and Palma [43]. Hence, one more factor is needed to explain the bias originated from the dynamic process. In this study, the change rate of mean skin temperature is picked as the other index to build our model. That is reasonable as the change rate is normally steeper at the first few minutes after a temperature step and then gradually reduces to or near zero. And the same variation trend can also be observed in subjects' thermal sensation, shown as Fig.5. The average changing rate of mean skin temperature in each test is deduced by equation 6.

$$\mathrm{m}\frac{\mathrm{d}T_{skin,i}}{dt} = mean\left(\sum_{1}^{18}\frac{T_{skin,i,j,t+1}-T_{skin,i,j,t-1}}{2}\right) \qquad (6)$$

Where the subscript 't+1' and 't-1' represent a minute after and before the time when subjects' thermal sensation is collected.

A polynomial regression model is used to fit the variation trend of thermal sensation after a temperature step, with the discrepancy of actual mean skin temperature and neutral mean skin temperature and mean skin temperature's change rate as independent variables. Considering that the asymmetry of human thermal sensitivity to cold and warm stimuli may occur [39], two regression models are developed based on the data in C3/C5 and W3/W6 separately, seen as Table 5. In this study, subjects neutral mean skin temperature ($T_{\text{skin,26°C}}$) is 33.6°C. The fitness of the regression model for cold conditions is not as good as that for warm conditions. That is a hint that only using mean skin temperature and its changing rate to predict dynamic cold-side thermal sensation may be not enough. More other complex factors, such as heat loss from skin, should be considered in the future studies to develop a more accurate model. Note that this study did not consider outdoor related attributors like wind speed, sunlight and view-related factors. Also, the models may not accurately predict the transient thermal sensation of those who will involve high-intensity physical activities after experience a transition of thermal environments.

Table 5 Regression models of thermal sensation after temperature steps

Condition	Equation	Adjusted R^2	RMSE
Warm	$\text{TS} = -0.051 + 1.78(T_{\text{skin}} - T_{\text{skin,26°C}}) + 5.78\frac{\mathrm{d}T_{skin}}{dt}$	0.94	0.16
Cold	$\text{TS} = 0.81 + 0.94(T_{\text{skin}} - T_{\text{skin,26°C}}) + 7.61\frac{\mathrm{d}T_{skin}}{dt}$	0.66	0.42

4 Discussion

4.1 No 'overshooting' phenomenon on older people

Some previous studies reported the observations of overshooting phenomenon on TSV after subjects experienced a temperature step. Zhang [29] found a clear evidence of heating overshoot in his experiments when young students moved from 26°C to 29°C [29]. Liu [21] also reported both heating and cooling overshoots after young subjects experienced a 3°C/5°C/7°C temperature step. Du [44] found subjects showed cooling overshoots on thermal sensation in response to temperature steps in the range of 5°C to 10°C. However, in the present study, we did not find any overshoot on thermal sensation after subjects experienced sudden temperature steps, no matter what the directions or amplitudes of temperature steps are.

One possible reason to explain the discrepancy can be the magnitude of temperature steps. In our study, to avoid wide temperature steps resulting in some damages on older people's health, we only selected the temperature steps lower than 6°C. These temperature steps are also very close to the real temperature changes older people may experience in their daily life. In previous studies, the magnitudes of temperature steps were usually larger than that. For example, Du et al. [44] tested a cold step of 10°C in their study. However, the amplitude sometimes seems to be not as a vital factor to determine the existence of a warm-side overshooting phenomenon. Zhang [29] observed a clear heating overshoot in his warm test with an only 3°C temperature step.

Another possible cause can be related to the changes in older people's thermal sensitivity and perception. Joseph [45] detected young and older adults' thresholds to warming and cooling. He found that thermal sensitivity declined with age, and the most serious deterioration of thermal sensitivity existed in the extremities, such as toes and soles. The possible underlying mechanisms of elderly people's reduced thermal sensitivity were summarized into three aspects by Slava and André [46]. One of the mechanisms is the age-related change in the density of sensory epidermal nerve fibers. Both Chang [47] and Goransson [48] demonstrated that the intraepidermal nerve fiber (IENF) in some specific body parts decreased as age-related, and Slava suggested that IENF could be associated with the reduction of older people's thermal perception. Another possible mechanism is related to the compromised functional properties. Nerve fibers were validated to be functional with the microvasculature in the dermis [49]. Therefore, the reduced vascular network in older people can somehow restrain the functionality of nerve fibers and consequently influences their thermal perception. The third possible mechanism of loss of thermal sensitivity may be the alternation of the peripheral nerve system, which has the property of transmission signals, for example, thermal stimuli. The nerve conduction velocity of older persons was found to be markedly slower than that of younger persons [50]. That may contribute to weaken older people's thermal sensitivity.

4.2 Cold/warm stimuli and older people's responses

In this study, we found that cold and warm stimuli induce distinct changes in older people's subjective thermal perceptions and physiological responses like skin temperature, tympanic temperature, blood pressure, RR, HR and SPO2. For thermal perceptions, subjects showed thermal discomfort both in warm and cold exposures with the temperature steps above 5 °C. But thermal unacceptability only occurred at the end of W6 where subjects' tympanic temperature reached at the highest level-37.08°C, which is 0.1°C away from the tympanic temperature of a neutral status. By contrast, a 5°C cold stimulus reduced tympanic temperature to 36.55°C (0.33°C deviating from a neutral status) and no cold unacceptability was observed. That suggests high core temperature may be a key factor for older adults to feel warm thermal unacceptability.

Another finding is that older people's mean skin temperature did not get steady even at the end of cold exposures, while they took less than 24 minutes to recover skin temperature to new steady levels in warm exposures. That is a signal that cold stimuli are more likely a 'challenge' than warm stimuli to older people's thermoregulation system.

In addition, an instant cold exposure is verified by this study that it could be a serious threat to older people's cardiovascular system and respiratory system. That because it imposes strong and obvious influences on systolic blood pressure, respiratory rate, heart rate and SPO2. Our results indicate that instant cold exposures can induce significant increment of systolic blood pressure. The similar results were reported by some previous studies [30, 51]. These studies proved that long-term cold exposures could also increase systolic blood pressure. But a higher systolic blood pressure is not good for healthy condition. On the contrary, an average decrement of 12 to 13mmHg in systolic blood pressure is related to a 21% reduction in coronary heart disease, 37% reduction in stroke, 25% reduction in total cardiovascular mortality, and 13% reduction in all-cause mortality rates [52].

On the other side, a cold environment forces subjects' heart rate to reduce to a lower level. That may be a synergistic effect regulated by thermoregulation system and cardiovascular system to constrict blood flow to minimize the heat loss from body[24]. In this study, after subjects experienced an instant cold exposure, their respiratory rates rise to a high level with the average rate up to 22.2BPM. By contrast, a recent study suggests that a respiratory rate of over 20BPM is probably unwell [53]. Considering the above analysis, cold exposures, especial intense cold stimuli, deserve to be avoided in older people's daily life.

5 Conclusions

A series of climate chamber tests were conducted to examine the effects of four moderate temperature steps on older people's thermal perceptions and physiological parameters. Older people's subjective thermal perceptions like thermal sensation, thermal comfort and thermal acceptability were collected. Their physiological parameters, including blood pressure, heart rate, respiratory rate, and blood oxygen saturation were measured before and after a temperature step. Some main conclusions are listed below:

(1) Older people's thermal sensation is sensitive to any moderate temperature steps larger than 3°C, while their thermal comfort only alters significantly to sudden temperature steps beyond 5°C.
(2) Two regression models, aiming to predict older people's thermal sensation after cold-side and warm-side temperature steps, are proposed with actual mean skin temperature and its change rate as independent variables.
(3) No thermal sensation overshooting phenomenon is observed on older subjects, which is probably due to older people's reduced thermal sensitivity.
(4) Instant cold exposures are more dangerous than warm exposures to older people. Older people's thermoregulation system does not work effectively to help their bodies achieve a new thermal balance in response to sudden cold stimuli. Meanwhile, instant cold exposures could be a serious threat to older people's cardiovascular system and respiratory system, by boosting systolic blood pressure and respiratory rate and depressing heart rate.

Acknowledgments

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