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The effect of local thermal sensation on overall thermal sensation in older people under warm conditions: a chamber room study

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Abstract. Global aging and climate warming have made scholars begin to pay attention to the thermal comfort of the elderly. The deterioration of the function of body organs and systems caused by aging affects the thermoregulatory system of the elderly, resulting in a narrowing of their thermoregulatory range. To ensure their thermal comfort, personalised thermal comfort systems can be used, for example. When designing a system or selecting equipment, the impact of local thermal sensation on the overall thermal sensation needs to be considered. Most of the existing studies are based on young people, however, the local thermal sensation of the elderly may not be consistent with that of the young. This study recruited 26 Finnish older adults to conduct a series of human thermal comfort experiments under warm conditions in a climate chamber. The local and overall thermal sensations of the elderly were analyzed, and the weights of the influence of different parts on the overall thermal sensation of the elderly were obtained. The study found that the head and torso had a greater impact on the overall thermal sensation in a warm environment.

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1 Introduction

Thermal comfort is one of the goals of architectural environment design. The majority of current building design standards are based on average adult needs. Physiologically, aging can weaken organ and system functions, causing older adults to have less capacity for thermal regulation than younger adults. In an extreme climate, the elderly may suffer health issues if the indoor environment is not properly controlled. Some researchers studied the differences in thermal sensation between young and old to meet the elderly's thermal comfort needs. In some studies, the elderly's thermal perception is identical to that of the young [1,2]. Others have found distinctions between these two groups [3,4]. The previous reviews analyzed the elderly and young's overall thermal sensations. According to several studies [5,6], local thermal sensations correlate with overall thermal sensations in humans. Also, researchers discovered that as people age, their thresholds for hot and cold sensations change [7]. So, in addition to studying the elderly's overall thermal sensation, local thermal sensation is important.

The purposes of this study are to: (1) explore the change of local thermal sensation in different warm conditions of the elderly and (2) find the relationship between local thermal sensation and the overall thermal sensation of the elderly.

2 Methodology

2.1 Experimental method

Five different conditions (26˚C, 28˚C, 29˚C, 32˚C, and 33˚C) were set in this experiment, and the indoor humidity was maintained between 40% and 60%. The room's indoor environment was controlled by heated windows, heat dummies, and humidifiers. Throughout the test of each condition, the indoor air temperature and relative humidity remained constant, and they were simultaneously detected by six sensors (Tinytag data logger with an accuracy of temperature: ± 0.5˚C and relative humidity: ± 3.0%). Table 1 summarized the average values for the physical parameters describing the chamber room environment.

26 healthy elderly local residents were enrolled in the experiment (19 females and 7 males, average age of 70.8 ± 5.8, average weight of 70.5 ± 10.5 kg, and average height of 166.1 ± 8.4 cm). Each participant was subjected to five tests in five distinct conditions with the same clothing insulation (0.5 clo). The temperature and relative humidity of the indoor air remained constant throughout the test. Each test consisted of 3 participants and lasted 4 hours. The entire procedure was divided into six stages (each lasting 40 minutes). The test procedure depicted in Figure 1(a). In the adaption phase and rest phases, elderly people were asked to stay sedentary, using a computer or reading, to adapt to the indoor environment. In the cooling phase, elderly people could flexibly use provided cooling devices according to their own demands.

Table 1. Physical measurements (mean ± s.d.) of the chamber room environment.

Condition (intended temperature)	Measured air temperature/°C	Measured relative humidity/%
26°C	25.7±0.7	42±2
28°C	28.3±0.8	62±5
29°C	29.0±0.8	42±3
32°C	31.7±0.6	48±3
33°C	32.6±0.5	38±2

Each participant was asked to complete a thermal sensation questionnaire once in the final five minutes of adaption phase and rest phases. The questionnaires included whole body thermal sensation and ten local thermal sensations (forehead, chest, upper back, lower back, pelvis, forearm, palm, thigh, calf, foot). Thermal sensation scale displayed in Figure 1(b).

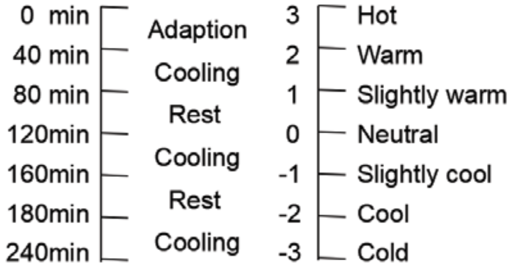


Fig. 1. a) Schematic of the experimental process; **b)**Thermal sensation vote scale.

2.2 Data analysis method

Each participant filled out a total of 3 questionnaires under each thermal condition, and the average thermal sensation vote of these 3 questionnaires was taken as the participant's thermal sensation under that condition, and the value was used for subsequent analysis.

A multivariate regression based on the least squares method was proposed in order to establish a regression model of local thermal sensation and overall thermal sensation. However, the thermal sensation between different segments may also have a linear relationship. In order to avoid the error caused by multicollinearity, the principal component analysis method was used to extract two factors, Z1 and Z2, which were:

$$Z_1 = a_1 Forehead + a_2 Chest + a_3 Upperback + a_4 Lowerback + a_5 Pelvis + a_6 Forearm + a_7 Palm + a_8 Thigh + a_9 Calf + a_{10} Foot \quad (1)$$

$$Z_2 = b_1Forehead + b_2Chest + b_3Upperback + b_4Lowerback + b_5Pelvis + b_6Forearm + b_7Palm + b_8Thigh + b_9Calf + b_{10}Foot \quad (2)$$

And the extracted factors, Z1 and Z2, can explain more than 85% of the original variance of thermal sensation with ten segments.

Then the factors Z1 and Z2 were used to construct a linear regression equation with the overall thermal sensation:

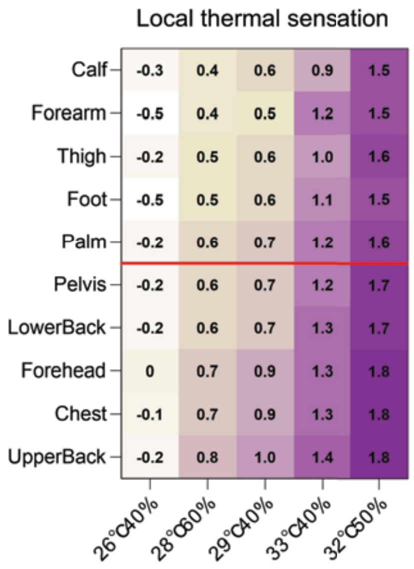
$$TSV(overall) = \mu_1Z_1 + \mu_2Z_2 + C \quad (3)$$

The focus of this study was on the weight of thermal sensation of different segments on the overall thermal sensation. Thus, the coefficients in equations (1) and (2) of each body segment were multiplied by the coefficients in (3), respectively, and then added together as the weight of the thermal sensation of this segment on the overall thermal sensation.

3 Results

The thermal sensations of different body parts under different working conditions are shown in Figure 2. The value in each cell represents the average thermal sensation vote for that part of all participants. Overall, thermal sensation at ten segments increased with increasing temperature. Under the 26˚C condition, the thermal sensation of each part was negative, but in the neutral range (-0.5 ~ 0.5). At 28˚C and 29˚C conditions, most parts began to feel slightly warm, and the thermal sensation vote began to exceed the neutral thermal sensation range. Under the 32˚C and 33˚C conditions, the thermal sensation of each part was warm. In addition, it can also be seen that the thermal sensation of the extremities and limbs (calf, forearm, thigh, foot, palm) were lower than that of the trunk (pelvis, lower back, forehead, chest, upper back).

Under different thermal conditions, the weight coefficients of different parts to the overall thermal sensation are shown in Figure 3. The value in each cell is the normalized percentage of that coefficient. Under the condition of 26˚C, the weight coefficients of the calf, thigh, forearm and foot were larger. As the temperature rises, the weight coefficients of the parts above the red line, including the extremities and limbs (calf, forearm, thigh, foot, palm) became gradually smaller, while the parts below the red line, including the trunk (pelvis, lower back, forehead, chest, upper back), the weight coefficients gradually increased. In the 28˚C condition, the sum of the weight coefficients of the segments above the red line was 0.45, and the sum of the weight coefficients of below parts were 0.55. In the 33˚C condition, the sum of the weight coefficients of the segments above the red line was 0.3, and the sum of the weight coefficients of below parts were 0.7.



	26℃40%	28℃60%	29℃40%	33℃40%	32℃50%
Calf	-0.3	0.4	0.6	0.9	1.5
Forearm	-0.5	0.4	0.5	1.2	1.5
Thigh	-0.2	0.5	0.6	1.0	1.6
Foot	-0.5	0.5	0.6	1.1	1.5
Palm	-0.2	0.6	0.7	1.2	1.6
Pelvis	-0.2	0.6	0.7	1.2	1.7
LowerBack	-0.2	0.6	0.7	1.3	1.7
Forehead	0	0.7	0.9	1.3	1.8
Chest	-0.1	0.7	0.9	1.3	1.8
UpperBack	-0.2	0.8	1.0	1.4	1.8

Fig. 2. Local thermal sensation under different conditions.

	26℃40%	28℃60%	29℃40%	33℃40%	32℃50%
Calf	12	9	9	7	7
Forearm	11	10	10	10	7
Thigh	11	9	10	9	8
Foot	10	8	6	0	5
Palm	6	9	8	4	7
Pelvis	10	10	11	14	12
LowerBack	10	10	12	15	11
Forehead	9	11	10	12	14
Chest	10	11	12	14	14
UpperBack	10	11	12	15	14

Fig. 3. Weight coefficients (%) of local thermal sensation on overall thermal sensation under differnet conditions.

4 Discussion

In most conditions, as it could be expected a higher air temperature resulted in a higher local thermal sensation. However, this study found that local thermal sensations at 28˚C， 60% were lower than thermal sensations at 29˚C,40%, and that local thermal sensations at 32˚C,50% were higher than 33˚C,40%, respectively. Changes in the main heat dissipation method could cause this. The elderly used sensible heat dissipation to dissipate heat when the air temperature was around 28˚C, and as the air temperature rose, sensible heat dissipation decreased, resulting in a high thermal sensation. When the air temperature reached around 32˚C, the elderly may have turned to evaporative heat dissipation (visible sweat evaporation and latent sweat evaporation). Because higher relative humidity slowed evaporative heat dissipation, the thermal sensation was higher at 32˚C, 50% than at 33˚C, 40%. This finding matched previous research on the human body's heat dissipation [8]. Human evaporative heat dissipation increases rapidly when the ambient temperature or water vapor pressure in the air exceeds a critical value.

Previous studies found that the lower of human body had little effect on the overall thermal sensation, and the overall thermal sensation was similar to that of the upper body [9]. That's because the lower body far from the core of human body. As a result, the effect on the entire body was negligible. Also, the head was considered to have a greater influence on the overall thermal sensation, due to its dense capillaries and blood supply that accounts for 14% of cardiac output. This study is consistent with these conclusions, with smaller weight coefficients for the lower body (thigh, calf, foot) and larger weights for the trunk and head. However, the results of this study indicated that the elderly have a small weight coefficient on hands, contrary to previous research findings. Previous studies approved that the hand has a dense and rich subcutaneous blood circulation and microcirculation, as well as a high density of nerve endings and temperature receptors, which contribute significantly to the overall thermal sensation [10]. On the one hand, this discrepancy may be due to the different participants. Previous studies had young adults, while the elderly have an increase in the hot and cold thresholds of many body parts, especially the limbs, due to weakened cardiovascular and neurological functions [11]. In addition, it may also be caused by different methods of calculating weights. Density of thermal receptors' distribution in different body parts and weighting factor of different parts were not considered in this study.

5 Conclusions

Thermal sensation increased with increasing temperature in ten segments chosen for this study. When the temperature is about 32˚C, the relative humidity has a greater influence on the local thermal sensation, that the higher the relative humidity, the higher the thermal sensation. In all five cases, the extremities and limbs were cooler than the trunk. The thermal sensation was lowest in the calf and forearm and highest in the forehead, chest, and upper back.

The weight coefficients of ten parts changed with temperature. When the temperature was lower, the weights of the extremities and limbs were larger. However, the weights of the extremities and limbs gradually decreased as the temperature increased, while the weights of the trunk and head gradually increased, until they reached 0.3 and 0.7 at 33˚C, respectively.

In conclusion, under lower temperature, the limbs and extremities had lower thermal sensation and greater weight, resulting in lower overall thermal sensation. When the temperature was higher, the trunk and head have higher thermal sensation and bigger weight, resulting in a high overall thermal sensation. The above conclusions can be used for future personalized comfort system design for the elderly.

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