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The Thermal Responses between Young Adults and Preschool Children in a Radiant Floor Heating Environment

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Abstract: The thermal comfort of preschool children was assumed to be similar to that of young adults, which may cause inaccuracy. This study tested and analyzed the thermal response characteristics of young adults and preschool children (4–6 years old) and the differences in thermal sensation and thermal physiology between the two groups of participants in a room with a radiant floor heating system using the difference analysis methods (the paired data *t*-test, the Mann–Whitney U test and the Kruskal–Wallis H test). Participants were divided into two groups, young adults and preschoolers, and were sat in each condition while wearing winter clothing with a thermal resistance of 1.02 clo. The results showed that when the indoor temperature changed, there was a significant difference in the local skin temperature of the calf between the two groups of participants ($p < 0.05$). Preschool children adapt to the thermal environment better than adults, and the difference in metabolic rate is one of the influencing factors. The overall thermal sensation with mean skin temperature of the different populations was linearly correlated; correlation coefficients were 0.944 and 0.932, respectively. The overall thermal sensation of the participants was linear with respect to the indoor operative temperature. Preschool children have a higher thermal sensitivity to temperature change than young adults under low-temperature radiant floor heating systems, indicating that children have different thermal awareness from adults. There were significant differences in preschoolers' subjective assessments of thermal sensation when the predicted mean vote (PMV) model was used as the evaluation standard; the difference ranged from 0.77 to 2.33. Thus, the PMV-predicted percentage dissatisfied (PPD) model is not suitable for preschool children.

Keywords: floor radiation; thermal sensation; thermal comfort; difference analysis

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1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems aim to provide adequate thermal comfort and air quality to indoor occupants. HVAC systems generally account for approximately 50% of the primary energy consumption of buildings [1], closely related to thermal comfort [2]. The energy consumption due to thermal comfort corresponds to a significant part of the energy bill of a building, because of the rise of the occupant's expectations for thermal comfort level [3], so it is critical to achieve the goal of energy savings while maintaining interior comfort to the greatest extent possible. Fanger's PMV and PPD approach [4] has been widely used in academic research to describe human thermal comfort. PMV/PPD model predicts the overall thermal sensation of a group of people [5] and is based on the steady-state heat balance derived from measurements in controlled environments. The calculation of the PMV takes into account the thermo physiological properties of humans and their thermal balance with the environment. On a personal level, this includes the activity level and clothing insulation. The thermal environment is determined by the variables air temperature, mean radiant temperature, relative humidity, and air velocity [6]. However, physiological variation and psychological effects are not taken into account in the PMV model. J. van Hoof [7] noted that the PMV model applies to healthy young adults and thus, cannot be applied to preschool children, older adults (more than 60 years of age), or the disabled without modification of Fanger's PMV-predicted percentage dissatisfied (PPD) model. Being so, the same thermal environment may be perceived differently by different occupants or different occupants may perceive the same thermal comfort level at different thermal environments [8].

A literature survey reveals that studies on personal comfort models continue to focus largely on office environments and young adults [9–15], while others focused on the differences in thermal comfort, thermal sensation, and preference between older adults (more than 60 years of age) and young adults. The elderly were not sensitive to changes in temperature; they preferred neutral thermal environments. The thermal sensation of the elderly was generally 0.5 scale units lower than that of the younger adults [16]. The actual neutral temperature of elderly was lower than the PMV-predicted temperature in winter [17]. PMV for a thermoneutral environment of older females was higher than that for older males in the same age group [18]. To better predict the thermal needs of the elderly at home, Martins et al. [19] developed the personal comfort model with superior predictive performance.

Some researchers have discussed children's (aged 7–12 years) tolerance to a non-neutral thermal environment [20–23]. Yang [24] reported that the 8–10 years old children's thermal sensation vote (TSV) is always higher than the PMV prediction in a classroom. Those studies observed similar result [25,26]. Children aged 9–11 years old prefer lower temperatures than adults by comparing the calculation predicted mean vote (PMV) with the TSV [20]. Vanos et al. used the COMFA (Comfort Formula) model to study children aged 9–13 years and found that children's perception of "thermal comfort" may be different from that of adults due to experiential and cognitive limitations [27]. However, there are limited number of studies focusing on the thermal comfort of preschool children (4–6 years old), although the growth and well-being of children require a comfortable environment. The thermal comfort characteristics of preschoolers may differ from those of children of higher ages, and no study has clearly elucidated optimal thermal environments for preschool children, who have relatively weak self-decision-making abilities. Preschool children are a very important group among children of different ages. They usually have little control ability over the environment. The amount of clothes they wear is usually determined by their guardians; as the saying goes, "There is a kind of cold, that your parents think you are cold; there is a need, that your parents think you need". Qi et al. [28] found that preschool children and caregivers show different preferences in thermal adaptive behavior choices. Chen et al. [29] analyzed whether the inferences from parents are consistent with the preschoolers' real feelings. The results show that parents' post-touch inferences were closer to the actual state of their children.

There are differences between preschool children and adults on thermal comfort perceptions, and the quantitative differences are still not clear. Most of the existing studies focus on older children, and there is a lack of relevant studies on preschool children aged 4–6 years old. Therefore, it is necessary to carry out further studies on preschool children to better understand their thermal demands, and to establish corresponding "thermal comfort" evaluation criteria. To this end, we set up a laboratory test in a building in Mianyang to analyze the thermal response characteristics of young adults and preschool children with a radiant floor heating system, and to study the differences in thermal sensation and thermal physiology between young adults and preschool children in hot-summer and cold-winter areas. Our study will reveal the thermal sensation difference between adults and preschool children in the same heating environment and provide data for improving the thermal comfort model of preschool children in China.

2. Methods

2.1. Design

The experiments were carried out at the laboratory of the national university science park at Southwest University of Science and Technology in Mianyang. The laboratory size is 8.25 m × 7.89 m × 3.2 m, has three desks, a sofa, and a bookshelf. The experimental system was shown in Figure 1, which includes an air-source heat pump, convection terminal, radiation terminal, heat storage tank, water divider, pump, and other components. A household air-source heat pump unit (YVAG02RS) with a rated heating capacity of 12.6 kW and heating input power of 3.8 kW serves as the heat source. Two fan coil units (TFFL-56) with a rated heating capacity of 9.9 kW are installed at the convection terminal. Figure 2 shows the structure of the radiation terminal, which is a floor radiation system with a dry floor heating module.

Figure 1. Experimental system.

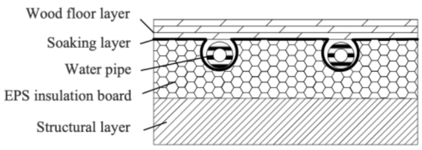


Figure 2. Radiant floor construction.

During the experiment, the water supply temperature of the heat source was set to 35 °C, and the indoor floor radiant thermostat was set to 22 °C. The 16 participants were separated into four groups: one male and one female preschool child and one male and one female adult, each in a sitting state and wearing 1.02 clo of winter clothing, were allocated to each condition. The main difference in each condition is the distance from external windows, as summarized in Table 1, which is to study the difference in thermal responses between people near the large glass windows and those located in the center of the room. The air temperature and relative humidity in Table 1 are the environmental test parameters around the human body under this heating system during the experiment. Table 2 provides essential information about the two groups of participants.

Table 1. Experimental conditions.

Condition	Air Temperature (°C)	Relative Humidity (%)	Distance from External Windows (m)
1	21.39	38.3	1.2
2	22.60	38.3	3.6
3	22.60	40.6	1.2
4	23.90	40.6	3.6

Table 2. Basic information for the two types of participants.

Participants	Number	Age	Height (cm)	Weight (kg)	BMI (kg/m^2)
Preschooler (male)	4	4.25 ± 0.50	116.33 ± 2.72	21.35 ± 0.90	15.78 ± 0.43
Preschooler (female)	4	4.00 ± 0.82	117.63 ± 3.29	20.90 ± 2.25	15.11 ± 0.87
Young adult (male)	4	23.50 ± 1.00	176.25 ± 4.86	73.55 ± 6.78	23.68 ± 0.91
Young adult (female)	4	24.25 ± 1.50	163.25 ± 8.06	54.40 ± 4.36	20.41 ± 2.83

Mean ± standard deviation; Body Mass Index BMI = W/H^2.

The subjective study of human psychological thermal response includes the local skin temperature, local and overall thermal sensation, and local and overall thermal comfort. The local temperature measurement sites on the human body include the forehead, back, abdomen, arm, hand, and calf. The ASHRAE seven-point [5] continuous scale was used for the local and overall thermal sensation, while the intermittent scale proposed by Arens E et al. [30], was employed for the local and overall thermal comfort; this comfort scale differs from that of most previous thermal comfort research in that it differentiates levels of comfort on the positive side as well as the negative side. As summarized in Table 3.

Table 3. Scale summary.

Thermal Sensation		Thermal Comfort	
Hot	+3	Very comfortable	+4
Warm	+2	Comfortable	+2
Slightly warm	+1	Just comfortable	+0
Neutral	0	Just uncomfortable	−0
Slightly cool	−1	Uncomfortable	−2
Cool	−2	Very uncomfortable	−4
Cold	−3		

2.2. Measurements

The experiments lasted 90 min, and the two types of participants entered the room 45 min before the beginning of the experiment to check their attire and explain the experimental requirements and experimental settings. The preschoolers were taught in kindergarten mode before the experiment began because their sensation and perceptual issues were strictly dependent on the educator's method [31]. Local and global thermal sensation votes were the emphasis of the two groups of participant's questionnaires, and the preschoolers' questionnaire was represented in the form of the image, as seen in Figure 3. The questionnaire for young adults also included local and global thermal comfort.

Figure 3. Expression form of thermal sensation questionnaire for preschool children.

During the experiments, indoor and outdoor air temperature and humidity, and indoor surface temperature data of each envelope were collected continuously via the temperature and humidity sensors (error ±0.3 °C and ±2%); wind speed data were measured using a hot-wire anemometer (±0.02 m/s). All measurement data were automatically transmitted to the computer using the RS-485 interface, and the monitoring system had a response time of <30 s for reading and storing real-time parameters. The local skin temperatures of both groups of participants were measured by the testers via the infrared thermometer every 15 min after the beginning of the experimental phase, and at the same time, questionnaires were submitted every 15 min. The questionnaires were completed by the participants. The two types of participants seated in the specified position, as shown in Figure 4. They were permitted to use cell phones and read books throughout the experiment; however, they were not permitted to talk to one another about the questionnaire, walk, eat, or drink, to reduce the impact on the experiment.

Figure 4. Two types of participants filling out questionnaires.

2.3. Calculations

2.3.1. Mean Skin Temperature

The mean skin temperature is a weighted average of the skin temperatures of different body parts, with the weighting factor determined by the area of the part. An infrared temperature gun is used to measure the skin temperature to ensure that the calculated skin surface temperature is at a more constant point and it may be utilized as a typical skin temperature. The six-point thermometry method [32] uses six different locations: the forehead, back, abdomen, arm, hand, and calf. The equation for estimating the average skin temperature is as follows:

$$T_{skin} = 0.07\ T_{forehead} + 0.26\ T_{back} + 0.35\ T_{abdomen} + 0.14\ T_{arm} + 0.05\ T_{hand} + 0.13\ T_{calf} \quad (1)$$

where T_{skin} is the mean skin temperature (°C); $T_{forehead}$, T_{back}, $T_{abdomen}$, T_{arm}, T_{hand}, and T_{calf} are the forehead, back, abdomen, arm, hand, and calf skin surface temperatures, respectively (°C).

2.3.2. Operative Temperature

The operative temperature (t_o) reflects the comprehensive effect of ambient air temperature (t_a) and mean radiant temperature ($\bar{t}_r$) [33], and its expression is:

$$t_o = \frac{h_r \bar{t}_r + h_c t_a}{h_r + h_c} \quad (2)$$

where h_r is the linear radiative heat transfer coefficient (W/m^2·°C); h_c is the convective heat transfer coefficient (W/m^2·°C)).

Mean radiant temperature is a key variable in thermal calculation for the human body. It is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual nonuniform enclosure. Mean radiant temperature can be calculated from the measured temperature of surrounding walls and surfaces and their positions with respect to the person [34]. All surfaces in the room can be assumed to be black; the following equation is then used:

$$\bar{t}_r = \sum_{j=1}^{k} \left(F_{P-j} t_j \right) \quad (3)$$

where F_{P-j} is the angle factor between a person and surface j; t_j is the surface temperature of surface j (°C).

2.3.3. Measure PMV

In this experiment, the monitoring system brings the measured values (indoor air temperature, wall temperature, etc.) and the input values (clothing insulation, metabolic rate, etc.) into the formula compiled in the system to calculate *PMV* and *PPD* values in the indoor thermal environment. The equations are as follows [4]:

$$\begin{aligned} PMV = {} & [0.303\exp(-0.036M) + 0.0275] \\ & \times\{M - W - 3.05[5.733 - 0.007(M - W) - P_a] - 0.42(M - W - 58.2) \\ & -0.0173M(5.867 - P_a) - 0.0014M(34 - t_a) \\ & -3.96 \times 10^{-8} f_{cl}\left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl}h_c(t_{cl} - t_a)\} \end{aligned} \quad (4)$$

$$PPD = 100 - 95exp\left[-\left(0.003353PMV^4 + 0.2179PMV^2\right)\right] \quad (5)$$

where M is the metabolic rate (W/m^2), W is the mechanical work (W/m^2), P_a is the water vapor pressure around the body (kPa), f_{cl} is the clothing area factor, t_{cl} is the clothing surface temperature (°C), t_a is the air temperature around the body.

2.3.4. Difference Analysis Methods

The purpose of a discrepancy study is to compare the differences between two or more sets of data. When the population distribution is normal or approximately normal, the parametric test can test whether there is a difference between the mean value of the population and a certain value, whether there is a difference between the mean values of the two populations, etc. [34]. However, in the process of data analysis, for various reasons, people often cannot make simple assumptions about the overall distribution pattern, and the parameter test method is no longer applicable. Based on this consideration, nonparametric tests are a kind of method that uses sample data to infer the population distribution pattern and so on when the population variance is unknown or little known.

The three difference analysis methods used in this study are the paired data *t*-test, which is the parametric test, and the Mann–Whitney U test and the Kruskal–Wallis H test, which are the non-parametric tests. The paired data *t*-test [35] can be regarded as an extension of the one-data *t*-test, but the object of the test is changed from a group of independent samples from normal distribution to the difference of observations of paired samples from two groups. The Mann–Whitney U test [36] is used to judge the proportion of two population distributions, and the Kruskal–Wallis H test [37] is used to test whether the distribution of multiple populations is significantly different.

3. Results and Discussion

3.1. Physiological Measurements

3.1.1. Local Skin Temperature

Figure 5 depicts the fluctuations in the local skin temperature of young adults (YA) and preschool children (PC) under variable conditions. The results clearly indicate that the skin temperatures differ at different body spots under the same conditions: local skin temperatures for both types of participants were maintained between 29 and 35 °C, and the hand and calf temperatures are the lowest.

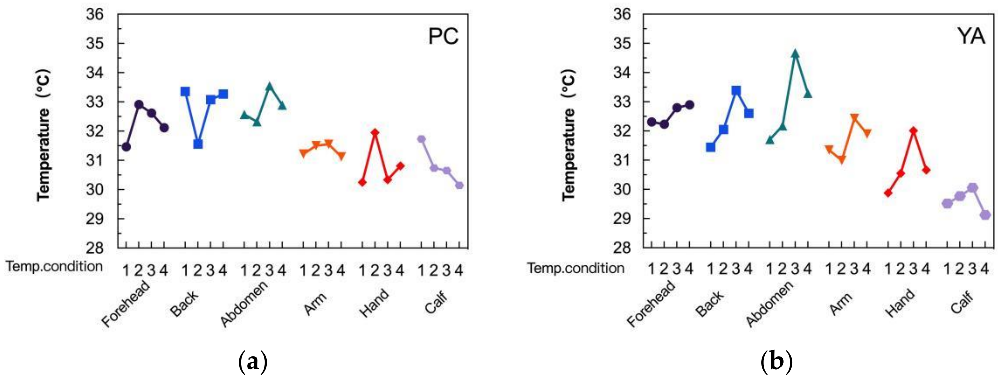


Figure 5. Local skin temperatures in two groups of participants: (**a**) Preschool children; (**b**) Young adults.

Comparing condition 1 and condition 3 with condition 2 and condition 4 reveals that the local skin temperature of the participants in condition 1 and condition 3 changed more than that of the participants in condition 2 and condition 4. Because condition 1 and condition 3 were adjacent to the west window, which has a large area of glass (Window Wall Rate 79%) that allows convective and radiative heat exchange with the outdoors, an uneven air temperature distribution occurred near the window according to the analysis. The local skin surface of the participants could exchange radiant heat with the west window glass and participate in convective heat exchange with the surrounding air, causing the local skin temperatures of the participants in condition 1 and condition 3 to differ significantly.

Table 4 summarizes the results of the paired data *t*-test used to compare the differences in local skin temperatures between the two groups of participants. Except for significant differences in the calf skin temperatures between preschool children and young adults in condition 1 and condition 4 and significant differences in the hand skin temperatures in condition 3, the local skin temperatures of the two types of participants were not significantly different, as summarized in Table 4. This indicates that calf sensitivity to floor radiation varied between the two groups of participants, with the children being closer to the ground.

Table 4. Paired *t*-test significance (two-tailed) values of local skin temperatures in preschool children and young adults.

Condition	Forehead	Back	Abdomen	Arm	Hand	Calf
1	0.150 >0.05	0.057 >0.05	0.218 >0.05	0.429 >0.05	0.727 >0.05	0.000 <0.05
2	0.166 >0.05	0.543 >0.05	0.769 >0.05	0.371 >0.05	0.088 >0.05	0.259 >0.05
3	0.785 >0.05	0.704 >0.05	0.060 >0.05	0.062 >0.05	0.003 <0.05	0.304 >0.05
4	0.126 >0.05	0.242 >0.05	0.405 >0.05	0.268 >0.05	0.651 >0.05	0.042 <0.05

3.1.2. Mean Skin Temperature

Figure 6 shows how the mean skin temperatures of preschool children and young adults vary depending on the condition. The range of the mean skin temperature is between 30 and 35 °C, varied by the local body spots. The mean skin temperature was lower in condition 1 and condition 2 than in condition 3 and condition 4; in condition 1 and condition 2, the preschool children had a higher mean skin temperature than the young adults, whereas in condition 3, the young adults had a higher mean skin temperature than the preschool children. The mean skin temperature of preschool children differed from that of young adults under various conditions; however, the difference was not significant.

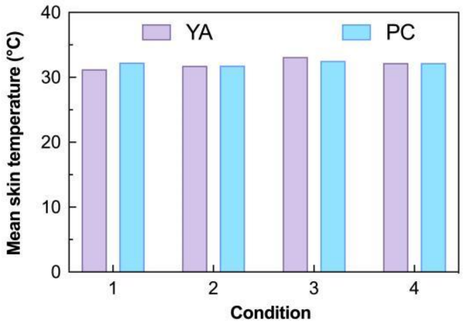


Figure 6. Mean skin temperature of two groups of participants.

The mean skin temperatures of preschool children and young adults are compared using a paired *t*-test. The results show that the difference in mean skin temperature between the two types of participants was greater in condition 1 (0.082) and condition 3 (0.166) than in condition 2 (0.604) and condition 4 (0.975), because the participants' position in condition 1 and condition 3 is close to the external window, which is greatly disturbed by the cold radiation from the external window and external wall, so that it has a significant impact on the skin temperature of the participants. However, there was no significant difference in the mean skin temperature between the two groups of participants in any of the four situations ($p > 0.05$).

3.2. Subjective Responses

3.2.1. Local Thermal Sensation Vote

Figure 7 shows a comparison of the local thermal sensation vote (LTSV) of preschool children and young adults. The LTSV of young adults in condition 1 and condition 2 were significantly lower than those of preschool children. In condition 4, the LTSV of preschool children and young adults were comparable. The LTSV of preschool children at the backs, arms, and calves in condition 3 were significantly higher than those of young adults, and the LTSV at the arms, hands, and calves of preschool children in condition 4 were significantly higher than those of young adults.

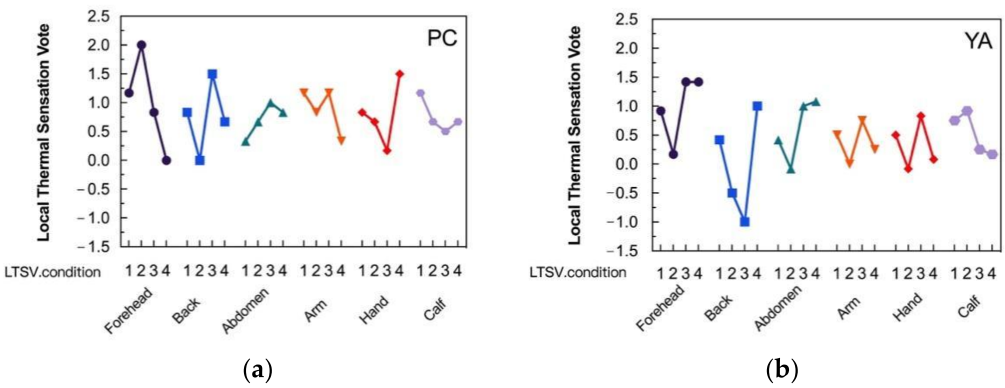


Figure 7. Local thermal sensation vote of two types of participants: (**a**) Preschool children; (**b**) Young adults.

The Mann–Whitney U test for the variability of the LTSV in preschool children and young adults is presented in Table 5. The results reveal that the variability of the LTSV was significantly lower in condition 1 and condition 3 than in condition 2 and condition 4. This finding shows that changes in the local skin temperature can affect local thermal sensation.

Table 5. Mann–Whitney U test of local thermal sensation vote in preschool children and young adults.

Condition	Forehead	Back	Abdomen	Arm	Hand	Calf
1	0.466 >0.05	0.265 >0.05	0.747 >0.05	0.267 >0.05	0.6798 >0.05	0.314 >0.05
2	0.002 <0.05	0.11 >0.05	0.039 <0.05	0.032 <0.05	0.123 >0.05	0.628 >0.05
3	0.261 >0.05	0.001 <0.05	0.844 >0.05	0.515 >0.05	0.307 >0.05	0.699 >0.05
4	0.008 <0.05	0.347 >0.05	0.552 >0.05	0.876 >0.05	0.014 <0.05	0.120 >0.05

3.2.2. Local Thermal Comfort Vote

Thermal comfort (TC) and thermal sensation (TS) are two different concepts. Thermal sensation evaluates the degree of the human subjective sensation of cold and heat, whereas thermal comfort evaluates the degree of comfort of human subjective sensations. Because preschool children have a limited cognitive sense of comfort level, the subjective evaluation of thermal comfort in this study solely focuses on the adult participants through a questionnaire survey.

Figure 8 shows the local thermal comfort vote (LTCV) of young adults under various conditions. The results show that under all four conditions, the LTCV of young adults between "slightly comfortable" and "comfortable" sate. This indicates that the room environment of the air-source heat pump low-temperature radiant floor heating system could meet subjective thermal comfort standards. Because of the influence of cold radiation from the west window, the LTCV in condition 1 and condition 3 were lower than those in condition 2 and condition 4. Consequently, young adults in condition 2 and condition 4 had higher local thermal comfort levels than they in condition 1 and condition 3. This indicates that young adults in the room's center experienced greater local thermal comfort than those closest to the window because of the effects of cold radiation on the human body.

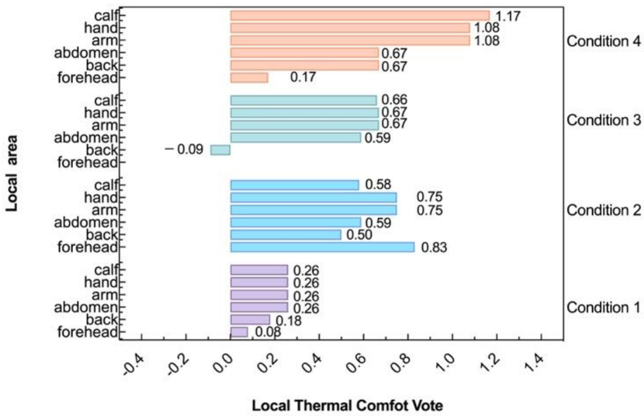


Figure 8. Local thermal comfort vote of young adults under different conditions.

Table 6 presents the Kruskal–Wallis H test for the difference in K-independent samples of LTCV in young adults. There was a significant difference ($p < 0.05$) in LTCV in the overall comparison of the four conditions, except for at the abdomen. The Mann–Whitney U test was performed to investigate whether the difference in LTCV of two independent samples of young adults was affected by the difference in their locations, as summarized in Table 7. In the thermodynamic comfort of the window vs. the central position of the participants, there was a significant differe5nce in the LTCV on the exposed forehead and hand between condition 1 and condition 2. Between condition 3 and condition 4, there was a significant difference in the LTCV on the back and calf. Between condition 1 and condition 3, the participants had significant differences in the LTCV of the back, abdomen, and arm. Between condition 2 and condition 4, there was a significant difference in the LTCV on the back, abdomen, and arm. Between condition 2 and condition 4, there was a considerable difference in the LTCV on the forehead and back. In conclusion, owing to the varied positions of the young adults, there were substantial changes in the LTCV of the young adults' forehead and back under the four conditions.

Table 6. Kruskal–Wallis H test of k independent samples of adult local thermal comfort vote.

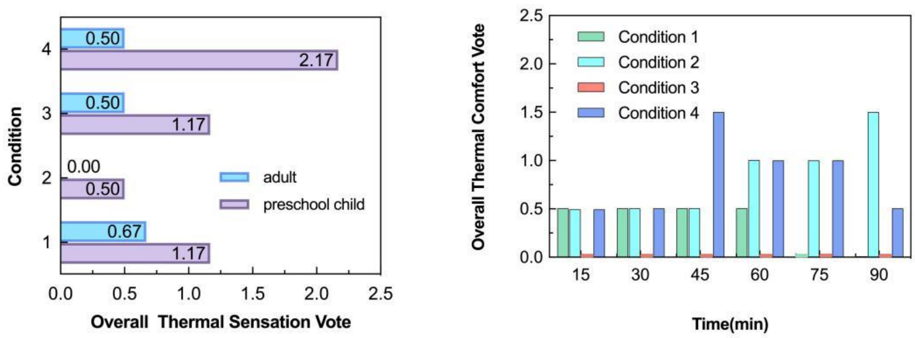
	Forehead	Back	Abdomen	Arm	Hand	Calf
***p*-Value**	0.002	0.001	0.158	0.012	0.006	0.013
	<0.05	<0.05	>0.05	<0.05	<0.05	<0.05

Table 7. Mann–Whitney U test for two independent samples of adult local thermal comfort.

Condition	Forehead	Back	Abdomen	Arm	Hand	Calf
1 and 2	0.003 <0.05	0.506 >0.05	0.300 >0.05	0.070 >0.05	0.031 <0.05	0.458 >0.05
3 and 4	0.051 >0.05	0.003 <0.05	0.598 >0.05	0.175 >0.05	0.180 >0.05	0.003 <0.05
1 and 3	0.924 >0.05	0.003 <0.05	0.043 <0.05	0.030 <0.05	0.070 >0.05	0.320 >0.05
2 and 4	0.021 <0.05	0.02 <0.05	0.548 >0.05	0.084 >0.05	0.080 >0.05	0.066 >0.05

3.2.3. Overall Thermal Sensation Vote

Figure 9a shows a comparison of the overall thermal sensation vote (OTSV) of young adults and preschool children. Preschool children had a higher OTSV than young adults in all four conditions, because preschool children have a higher metabolic rate than young adults and hence, they prefer a cooler environment; therefore, it may be argued that their OTSV is warmer in the same thermal environment with the same clothing thermal resistance [32].



(**a**) (**b**)

Figure 9. Comparison of the OTSV and OTCV in two groups of participants: (**a**) OTSV; (**b**) OTCV.

Table 8 presents the Mann–Whitney U test for differences in the OTSV of preschool children and young adults. The results indicate that there was no significant difference in OTSV between the two types of participants in condition 1, condition 2, and condition 3 ($p > 0.05$); however, there was a significant difference of OTSV between preschool children and young adults in condition 4. In other words, although the location of the indoor environment had effect on the local skin temperature of the two types of participants, but it had no effect on OTSV; even so, there was a slight difference in the OTSV of the two types of participants, preschool children adapt to the thermal environment better than young adults, which is consistent with the result of Chen [29] observed.

Table 8. Mann–Whitney U test for the overall thermal sensation vote and overall thermal comfort vote of preschool children and young adults.

Condition	Overall Thermal Sensation Vote	Overall Thermal Comfort Vote
1	0.124 >0.05	0.087 >0.05
2	0.959 >0.05	0.011 <0.05
3	0.312 >0.05	0.003 <0.05
4	0.003 <0.05	0.869 >0.05

3.2.4. Overall Thermal Comfort Vote

Figure 9b shows the evolution of the overall thermal comfort votes (OTCV) ratings of young adults under each condition over time. The OTCV of young adults in each condition was greater than zero, and all of the OTCV were in the state of "slightly comfortable" or higher. In condition 1, the OTCV decreased with time, and the comfort remained in the state of "slightly comfortable". In condition 2, the OTCV increased with time, and the comfort rose to between "slightly comfortable" and "comfortable". In condition 3, the evolution of the OTCV ranges 0–0.01, so in the condition 3 the "slightly comfortable" state was maintained over time. In condition 4, the comfort initially improved over time, then fell; however, it remained in the "slightly comfortable" range.

The Mann–Whitney U test for the variance is presented in Table 8 for two independent samples of the OTCV of young adults. There was no significant difference in the OTCV when condition 1 and condition 2 or condition 2 and condition 4 were compared. However, there were significant differences in the OTCV when condition 1 and condition 3 or condition 3 and condition 4 were compared. The OTCV for condition 3 differed significantly from that of the other conditions. This is due to the participants' lower sensitivity to the subjective thermal comfort evaluation in condition 3. Table 8 provides the results of the Kruskal–Wallis H test for K-independent samples of the OTCV in young adults. A significant difference ($p < 0.05$) was observed in the OTCV for the four conditions.

3.3. Correlational Analyses

3.3.1. Relationship between the Overall Thermal Sensation Vote and Mean Skin Temperature

The human body senses external temperature changes through temperature receptors on the surface of the skin. When the body's epidermal and core temperatures change, the temperature receptors are stimulated by heat and cold, producing instantaneous hot and cold sensations and sending impulse signals to the brain via the spinal cord, which promotes or inhibits heat production and heat dissipation processes. The thermal sensation is the body's subjective description of "cold" and "hot" surrounding environments. Although the "cold" and "warm" condition of a room is often used to establish the body's description of its surroundings, the body only feels the temperature of the nerve endings lying beneath the surface of the skin.

The change in human skin temperature has a statistical link with the evaluation of the thermal sensation according to EN ISO7730 [38]. According to Arens et al. [30], when the human skin temperature is between 29 °C and 34 °C, the mean skin temperature has a good linear association with the overall thermal sensation, regardless of whether the person is resting or active. When the mean skin temperature is less than the thermoneutral skin temperature of 3 °C to more than the thermoneutral skin temperature of 1 °C, Fiala [39] reported that the mean skin temperature has a good linear association with the overall thermal sensation. When the mean skin temperature is between 32.18 °C and 33.4 °C, the thermal sensation vote is in an appropriate environment according to Diao Chengyuzhuo [40].

Many studies have been conducted solely to determine the overall thermal sensation vote versus mean skin temperature in young adults, and the present study focuses on the relationship between OTSV and mean skin temperature in preschool children, as well as the differences between the two in comparison to young adults. Figure 10 shows the results of linear regressions for both types of participants. The correlation between OTSV and mean skin temperature showed that the R square of the preschool children was 0.892, while the one for the young adults was 0.868. This means there is a significant relationship between thermal sensation and mean skin temperature.

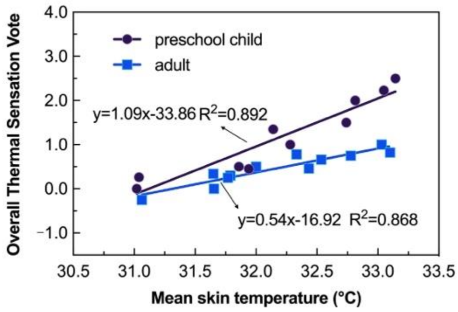


Figure 10. Changes in the OTSV with mean skin temperature.

The mean skin temperature for preschool children was 31.06 °C and that for young adults was 31.33 °C when the OTSV was "neutral" in this study. The difference in the OTSV between the two types of participants became more significant as the mean skin temperature exceeded 31 °C; when the mean skin temperature of the two types of participants was the same, the OTSV of preschool children was warmer compared to that of young adults. This is consistent with the previous comparison of the OTSV between the two groups of participants.

3.3.2. Relationship between the Overall Thermal Sensation Vote and Overall Thermal Comfort Vote

According to Fanger [4], the overall thermal sensation and thermal comfort are equivalent when the overall thermal sensation in an indoor environment with low wind speed and moderate relative humidity is "neutral," "slightly cool," and "slightly warm". Hou [41] identified a strong linear relationship between whole-body thermal comfort and whole-body thermal sensation in an asymmetric radiant heating environment. Zhang [42] discovered a strong linear relationship between whole-body thermal sensation and whole-body thermal comfort in a uniform thermal environment.However, in an unstable thermal environment with local air movement, a significant deviation between the whole-body thermal sensation and thermal comfort was reported.

In this study also examines the relationship between the OTSV and OTCV. Figure 11 shows the variations in the overall thermal comfort and thermal sensation of young adults. The results indicate that the OTSV has no obvious relationship with the OTCV; the reason may be that participants perceived a strong imbalance between heat and cold in unstable thermal environment. Uneven heat and cold may be another important factor affecting satisfaction; this is consistent with Zhang [42].

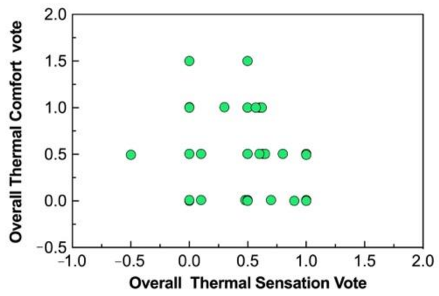


Figure 11. Changes in the OTSV and OTCV.

3.3.3. Relationship between the Overall Thermal Sensation Vote and Indoor Operative Temperature

As the sum of the mean radiation temperature and the indoor air temperature, the t_o is a useful metric for assessing the comfort of indoor thermal environments. Figure 12 shows a linear regression analysis of the relationship between the OTSV and the t_o.

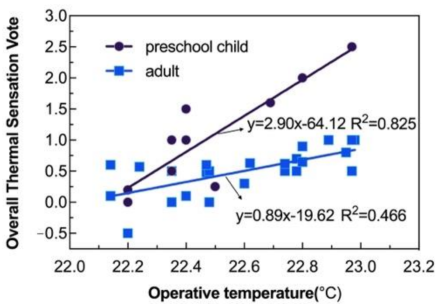


Figure 12. Change in the OTSV with the t_o.

The correlation between OTSV and t_o showed that the R square of the preschool children was 0.825, while that for the young adults was 0.466, and the difference between the regression lines of preschool children and young adults became apparent with the increase in temperature. It can be seen that children have relatively smaller ranges of thermal sensation than young adults because of their higher metabolic rates per unit weight. The differences in thermal sensitivity between young adults and preschool children are also revealed. Figure 12 shows the OTSV regression equations of preschool children and young adults, respectively. The slope of the regression line represents the subject's sensitivity to temperature change. The preschool children's slope (2.90) of OTSV against t_o is more than half of that of the young adults (0.89), which indicates that the preschool children have a higher thermal sensitivity to temperature change than young adults under the low-temperature radiant floor heating system.

When the measured t_o were the same, the OTSVs of the preschool children were warmer than those of young adults.

3.3.4. Relationship between OTS and Measured PMV

Professor Fanger's PMV-PPD model and the OTS are compared in this study, and the difference between the measured PMV and the OTS of the two types of participants is presented in Table 9. The difference between the measured PMV and the OTS for young adults ranged from 0.27 to 0.94 for the four conditions; for preschool children, the difference between the measured PMV and the OTS ranged from 0.77 to 2.33. Because of the significant bias of the measured PMV model as a criterion for thermal sensation evaluation in preschool children, the measured PMV/PPD model is not suitable for preschool children. The findings of this study are in agreement with those of J. van Hoof [7].

Table 9. Difference between measured PMV and overall thermal sensation vote.

Condition	Participants	Air Temperature (°C)	Mean Radiant Temperature (°C)	Indoor Wind Speed (m/s)	Measured PMV	Measure PPD (%)	Overall Thermal Sensation Vote	Difference between PMV and OTS
1	Young adults	21.39	22.50	<0.01	−0.273	6.6	0.67	−0.94
	Preschool children	21.39	22.50	<0.01	−0.273	6.6	1.17	−1.44
2	Young adults	22.60	22.50	<0.01	−0.273	6.6	0.00	−0.27
	Preschool children	22.60	22.50	<0.01	−0.273	6.6	0.500	−0.77
3	Young adults	22.60	22.35	<0.01	−0.162	5.7	0.500	−0.66
	Preschool children	22.60	22.35	<0.01	−0.162	5.7	1.167	−1.33
4	Young adults	23.90	22.35	<0.01	−0.162	5.7	0.500	−0.66
	Preschool children	23.90	22.35	<0.01	−0.162	5.7	2.167	−2.33

4. Conclusions

This study investigated subjective and objective thermal comfort evaluation methods for 16 young adults and preschool children in an environment of low-temperature radiant floor heating. Difference analysis methods were applied to analyze the thermal reactions of the participants. The following conclusions could be drawn:

(1) The sensitivity of the calf to radiant floor heating system differed between the two groups of participants as preschool children are closer to the floor.
(2) The OTSV of preschool children was higher than those of young adults in each condition, because preschool children have relatively higher metabolic rates than young adults, children feel slightly warmer than young adults under identical microclimate conditions.
(3) Young adults in the room's center experienced greater local thermal comfort than those closest to the window because of the effects of cold radiation on the human body.
(4) The OTSV of the two groups of participants had a strong linear correlation with the t_o, but preschool children have a higher thermal sensitivity to temperature change than young adults under low-temperature radiant floor heating systems.
(5) For preschool children, the PMV model as a thermal sensation evaluation criterion had a considerable bias, and the measured PMV/PPD model is not suitable for preschool children and needs to be modified if it is to be used.

The results of this study found that there were some differences between preschool children and young people in terms of local skin temperature and thermal sensation voting, which could enhance the understanding of children's (4–6 years old) thermal sensation. In the future, in-depth research could be carried out to further develop a new child PMV model for the existing adult-based thermal environment assessment methods.

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